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Experimental studies on the use of mobile cylinders for measurement of flow through rectangular channels

A. D. Ghare[1,*], A. M. Badar[2]

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Abstract

The objective of field water measurement is to conserve water by improving management of its distribution and field application. A simple mobile flume to measure a discharge through small rectangular open channels in agricultural fields has been experimentally investigated. The flume consisting of a vertical cylinder inserted axially into the horizontal prismatic rectangular channel, referred as a simple cylindrical flume, has been calibrated. The flow rate in rectangular channel can be measured by constricting the flow due to presence of cylinder, resulting in critical flow conditions. Experiments have been performed on two simple cylindrical flumes of different diameters, to evaluate the hydraulic characteristics of subcritical incoming flow under free flow conditions. The results of laboratory experiments on the flume have been analysed and two different discharge prediction models have been developed. The two models developed for the prediction of discharge for simple cylindrical flumes developed for use in rectangular channel sections, are based on the energy concept and the direct regression approach, respectively. Both the proposed models have been validated using the limited experimental data available in the literature. Formation of critical depth at the throat section has also been verified. Plots have also been developed for the dimensionless column head and the corresponding Froude number of the incoming flow. The discharge prediction model giving the least error has been proposed for use in practice.

Keywords: *Flume, Discharge measurement, Rectangular channel, Critical flow.*

1. Introduction

Among all the natural resources, water is the most precious and now, a scarce resource for survival of life on the globe. Agriculture uses more than two thirds of water reserves in order to produce food for the world, but it may fail to make efficient use of water unless it is metered. The field water measurement is an important phase to conserve water. Attention to measurement and consequent management of water, would be advantageous to farmers' water and can help to prevent the reduced yields and other crop damages caused by under or over watering.

Weirs and other types of flumes are usually fixed devices used for channel flow measurement and these are sensitive to sediment deposits and hence require regular maintenance. A simple cylinder inserted vertically in the channel flow is called as simple cylindrical flume and it works on the principle of constriction of flow and the resulting critical flow conditions.

* *Corresponding author: adghare@yahoo.co.in*

1 Associate Professor, Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, India

2 Resarch Scholar, Deparment of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, India

This arrangement serves as a mobile or portable flume and the flow rate can be measured at any desired location in the channel reach. Such mobile flume offers the advantages of its inexpensive construction, simple operation, less maintenance, accuracy of flow rate measurement and negligible sand, silt or floating trash troubles.

Flumes are primarily the devices that constrict an open channel flow for its measurement. Once the flow is backed up behind the constriction, there is a definite relationship between the up-stream depth and the flow through the constriction. The discharge measurement is based on the principle of existence of a unique depth–discharge relationship for critical flow. For a particular flume, a unique relationship exists between the discharge and the head causing flow.

In case of simple cylindrical flume, flow movement through the flume can be defined by the energy equation and Froude number relationship. Assuming a uniform velocity distribution and a level flume, the energy at the upstream of the critical flow section, considering a flow upstream of the cylinder and flow at the cylinder, will be equal to the energy at critical section (at the narrowest cross section as shown in Fig. 2), neglecting losses. As the upstream flow is subcritical, the water surface drops due to width contraction as the flow passes around the cylinder. At the chocking condition, the upstream depth of flow increases to allow for increased specific energy to make the flow possible. Fig. 2 shows the photograph of an experimental run in the laboratory and plan of the research flume.

In 1915, experiments performed in the hydraulics laboratory at Fort Collins, Colorado; on measuring devices led to the development of the so-called Venturi flume [1]. The bottom configuration of the Parshall flume [2] does not allow an easy installation into an existing channel and the downstream back slope of bottom can induce sedimentation processes of the solid particles transported by the flow. Since then attempts have been made to simplify the construction and improve the accuracy of water – measuring devices in open channels.

Hager [3] presented the discharge-head relations for a vertically immersed cylinder in a rectangular channel. This investigation dealt with a modified Venturi channel having the constriction along the channel axis. This flume enabled a mobile registration of discharge at any section of the channel. The discharge was analytically expressed by accounting slope and curvature of the surface profile i.e. for parallel and horizontal streamlines and sloped-curved streamlines. A few experimental observations were presented on a graph with water surface profiles. It was concluded that the results based on the observed upstream flow depth underestimated the predicted discharge. This was attributed to the streamline slope and curvature effects. Hager [4] also measured discharge from a rectangular channel by placing a circular cone as a deliberate obstruction to the flow. Hager [5] as well measured the discharge through a circular channel by using a circular (cylindrical) flume and a computer model was proposed for the prediction of discharge. A pipe flume was used by Kohler et al. [6] for determination of discharge through pipe under free surface condition and the effects of device distortion, device position, bottom slope of pipe and submergence were evaluated. Oliveto et al. [7] introduced the Sector Venturi for highly polluted sewage. Peruginelli et al. [8] presented a kind of measuring flume, whose throat section is obtained by placing a mobile pier-shaped prism in the centre of a rectangular channel. Samani et al. [9] proposed a simple flume, wherein two semi-cylinders of polyvinyl chloride (PVC) were attached to each of the side walls at the downstream end of a rectangular channel, combining the concept of cutthroat and circular flumes and also presented dimensionless calibration curves for the three different contractions. A modified discharge prediction model using dimensional analysis for trapezoidal canal, with simple cylindrical portable flume was proposed by Badar et al. [10]. Thus, it is evident that a portable device can be used for flow measurements in small agricultural field canals. However, in the literature, experimental observations by only one investigator viz. Hager [3] for a simple cylindrical vertical obstruction used in the rectangular canal section are found. Hence, a need was felt to collect more experimental data with different contraction ratios and consequently, develop a mathematical model for prediction of discharge, which would be applicable to a wider range of contraction ratios.

The purpose of the present laboratory experimental study was to develop a calibrated mobile discharge measuring structure, referred to as simple cylindrical flume, which would be suitable for the short-time use. Hence, experimental investigations were carried out on the cylindrical flumes in a rectangular channel under free flow conditions and discharge models have been developed. For this study, cylindrical flumes of diameter 25.25 cm and 26.80 cm have been used in a rectangular channel of base width 30 cm. At the downstream, a gate was installed to study the effect of submergence on the flume operation, if desired. The schematic representation of simple cylindrical flume in rectangular channel is as shown in Fig. 1.

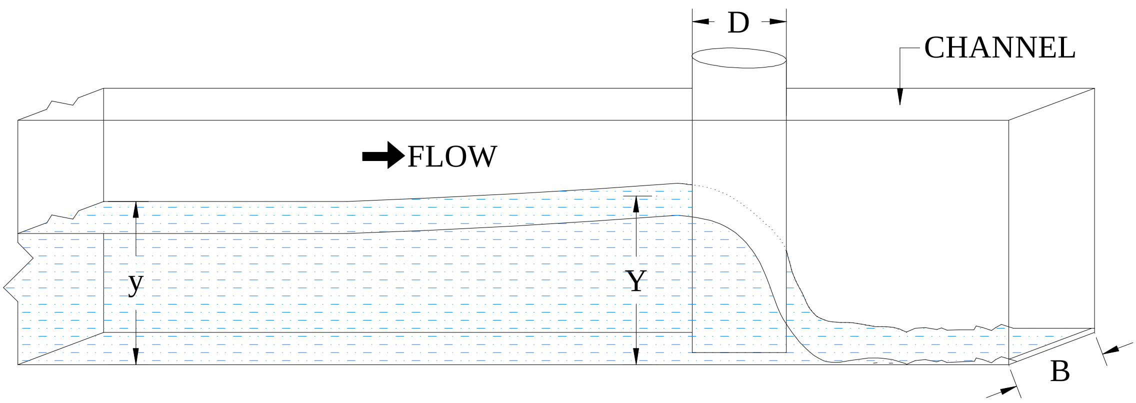

Fig. 1 Schematic representation of simple cylindrical flume in rectangular channel

2. Experimental Facility and Test Procedure

Indian Standard M. S. Angles, M. S. Sheets and Transparent Acrylic Sheets were used to fabricate the experimental Model of a rectangular channel in Hydraulics Laboratory at K. D. K. College of Engineering, Nagpur, India. The horizontal rectangular channel was 4.90 metre long and had cross section of 30 cm × 60 cm. Two cylinders of diameter 25.25 cm and 26.80 cm were used as mobile flumes for the study. The actual dimensions corresponding to two flumes are shown in Table 1.

Table 1 Description of the experimental flumes

Flume	Base width B (cm)	Diameter of cylinder D (cm)	Throat width W_c (cm)	Contraction ratio η (%)
1	30	25.25	04.75	84.17
2	30	26.80	01.77	89.33

At a distance of 1.50 metre from the downstream end, initially a polyvinyl chloride (PVC) pipe of diameter 25.25 cm was installed vertically and centrally, to function as a simple cylindrical flume. The piezometric head at the upstream side of the cylinder and upstream depth was measured by a vernier type point-gauge having an accuracy of ±1 mm. The assembly was mounted on a mobile cart that traversed along the sides of the flume. Horizontal centrifugal pump of 5 H.P. was used to deliver a continuous flow of water with a re-circulating arrangement. In order to stabilize the flow, baffle walls were provided at the upstream end of the channel.

Flow was initiated and slowly increased to the desired flow rate and then it was allowed to stabilize. The required discharge was controlled by a flow regulating valve. Uniform flow depths (i.e. piezometric heads) on the upstream side of cylinder (y) and upstream depths just on the upstream side of the cylinder (Y) for various discharges were recorded. The actual discharge was measured by volumetric collection of water. The discharge was varied between 0.00278 m^3/s to 0.01388 m^3/s. The experimental procedure was repeated for the second cylinder. Table 2 and Table 3 show the details of observations recorded for Flume -1 and Flume -2. Water surface profile pattern is as shown in Fig. 2.

Table 2 Experimental observations for Flume - 1

Experimental Run	Flow depth on upstream side Y (cm)	Flow depth on cylinder at upstream side Y (cm)	Measured Discharge Q (m^3/s)
1	8.80	09.35	0.00278
2	10.60	11.10	0.00345
3	12.60	13.10	0.00465
4	14.90	15.50	0.00649
5	16.00	16.45	0.00704
6	22.20	23.00	0.01351

Table 3 Experimental observations for Flume - 2

Experimental Run	Flow depth on upstream side Y (cm)	Flow depth on cylinder at upstream side Y (cm)	Measured Discharge Q (m^3/s)
1	12.40	12.70	0.00313
2	13.65	14.00	0.00376
3	17.30	17.70	0.00556
4	18.25	18.60	0.00610
5	25.40	25.90	0.01090
6	29.10	29.20	0.01388

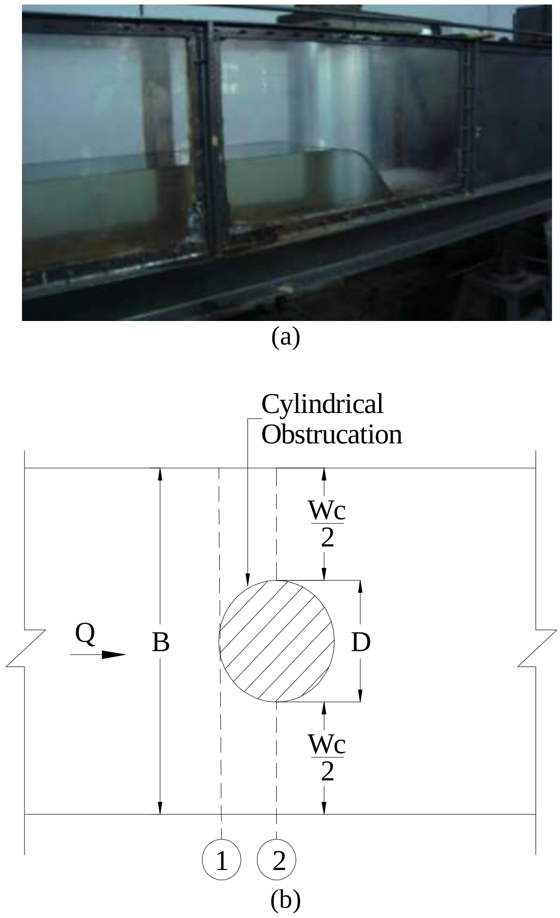

Fig.2. (a) Photograph showing a water surface profile due to simple cylindrical flume in the laboratory. (b) Plan of the Flume

3. Analysis of Experimental Data and Development of Models

Two different mathematical models have been developed for the computation of discharge. The depth measured on the upstream side of the cylinder is also termed as column head and is the single quantity that has to be measured on field, when such a flume is put to use after calibration. The depth of water at the cylinder would be equal to upstream energy if the velocity distribution on a cross section of the flow is uniform for parallel flow lines. It is seen that velocity distribution on a cross section was non uniform and streamlines were curved in nature due to presence of inserted cylinder. Hence, a relationship between upstream energy and the upstream depth of water at the cylinder is developed. The upstream energy was calculated using the measured discharge and observed upstream depth.

A graph is plotted between the depth of water at the cylinder recorded for the two afore mentioned flumes and the corresponding upstream energy, H as shown in Fig. 3. The resulting relationship between the depth of water on the upstream side of the cylinder and the upstream energy is as follows:

$$H = 1.011Y - 0.005 \quad \text{with} \quad R^2 = 0.999 \tag{1}$$

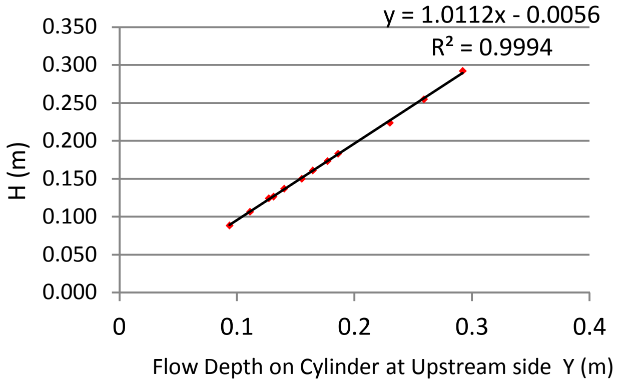

Fig. 3 Relationship between flow depth on cylinder at upstream side and upstream energy

Measured depth of the water at the cylinder was used to calculate the upstream energy by using Equation 1 and the theoretical discharge (Q_{th}) through the critical section (width, W_c) can be calculated by assuming uniform velocity distribution and neglecting energy loss between upstream and the critical flow section. For critical flow conditions i.e. for Froude number to be unity, it is known that

$$\frac{Q_{th}^{2}}{g} = \frac{A^3}{T} \tag{2}$$

As Area = BY_c, $\frac{Q_{th}^{2}}{g} = B^2 Y_c^3$ (3)

$$Q_{th}^{2} = g\, B^2 Y_c^3 \tag{4}$$

Hence,

$$Q_{th} = B\sqrt{g\,(Y_c)^3} \tag{5}$$

For minimum specific energy, $Y_c = \frac{2}{3}H$ which results in

$$Q_{th} = B\sqrt{g\,(\tfrac{2}{3}H)^3} \tag{6}$$

As the streamlines in the vicinity of critical section are curved, Equation 6 does not estimate the actual flow rate accurately, hence the theoretical discharge should be multiplied by a coefficient. A dimensionless curve was plotted between dimensionless energy (H/D) and discharge ratio (Q/Q_{th}), based on the laboratory observations taken on two different flumes mentioned in Table 1 and is as shown in Fig. 4.

The resulting linear regression equation from Fig. 4 is as follows:

$$\frac{Q_p}{Q_{th}} = 0.521\,\frac{H}{D} + 1.052 \tag{7}$$

This is the first mathematical model (Equation 7) developed to calculate the predicted discharge for free flow conditions. Computations for development of this model (Model-1) are shown in Table 4.

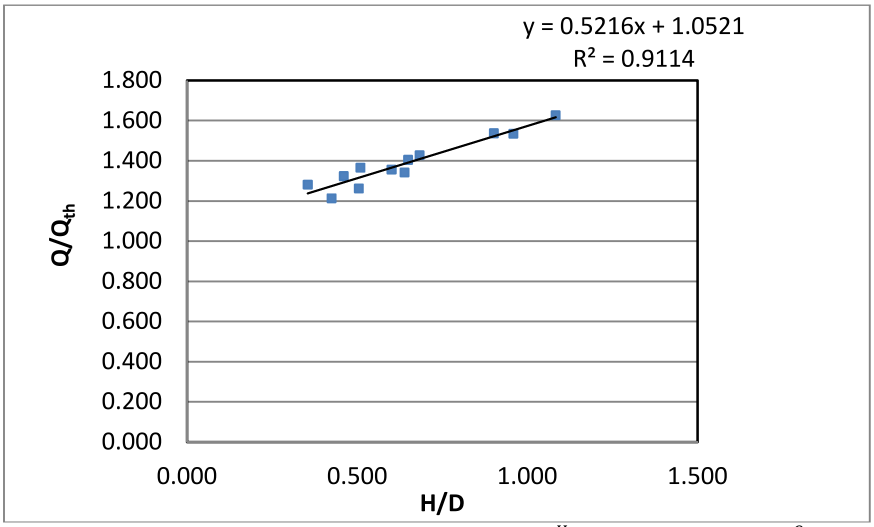

Fig. 4 Relationship between dimensionless energy ($\frac{H}{D}$) and discharge ratio($\frac{Q}{Q_{th}}$)

Table 4 Computations for development of Model -1

Flow Depth on Upstream side y	Flow Depth on Cylinder at Upstream side Y	Upstream Energy H=y+v²/(2g)	Q_{th}	Q	H/D	$Q/(B^{5/2} g^{1/2})$
(m)	(m)	(m)	(m³/s)	(m³/s)		
0.088	0.09	0.090	0.0022	0.00278	1.281	0.355
0.106	0.11	0.107	0.0028	0.00345	1.213	0.425
0.126	0.13	0.127	0.0037	0.00465	1.262	0.505
0.149	0.16	0.152	0.0048	0.00649	1.356	0.601

0.16	0.16	0.161	0.0052	0.00704	1.342	0.639
0.222	0.23	0.228	0.0088	0.01351	1.537	0.901
0.124	0.13	0.123	0.0024	0.00313	1.324	0.460
0.137	0.14	0.137	0.0028	0.00376	1.366	0.509
0.173	0.18	0.174	0.0040	0.00556	1.405	0.649
0.183	0.19	0.183	0.0043	0.0061	1.428	0.683
0.254	0.26	0.257	0.0071	0.0109	1.535	0.958
0.291	0.29	0.290	0.0085	0.01388	1.627	1.083

Another mathematical model is developed by the direct regression approach. For this purpose, a graph is plotted between the dimensionless quantities $\frac{Y}{D}$ and $\frac{Q}{B^{5/2}g^{1/2}}$ as shown in Fig. 5.

The resulting regression equation was obtained based on the data in Fig. 5 and the resulting mathematical model (Model - 2) is as follows :

$$Q_P = 0.081B^{5/2}g^{1/2}(\frac{Y}{D})^{1.623} \quad (8)$$

Equation 8 is thus the second model (Model-2) developed for the prediction of discharge for use of Simple Cylindrical Flume in rectangular open channel flow. Table 5 exhibits the computations for Equation 8.

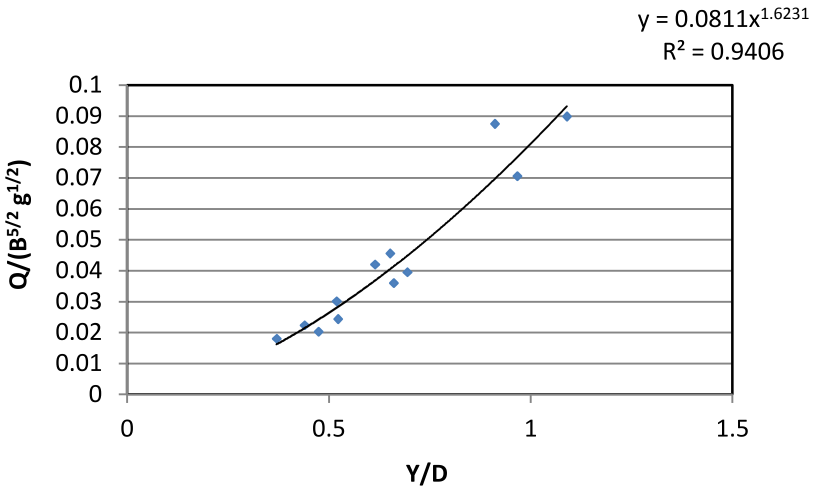

Fig. 5 Variation of $\frac{Q}{B^{5/2}g^{1/2}}$ with $\frac{Y}{D}$ based on the writers' experimental data

Table 5 Computations for development of Model - 2

Contraction	Flow Depth on Cylinder at Upstream side	Measured Discharge	$\frac{Y}{D}$	$Q/(B^{5/2}g^{1/2})$
η	Y	Q		
(%)	(cm)	(m^3/s)		
84.17	9.35	0.00278	0.3703	0.01801
	11.1	0.00345	0.4396	0.02235
	13.1	0.00465	0.51881	0.03012
	15.5	0.00649	0.61386	0.04203
	16.45	0.00704	0.65149	0.0456
	23	0.01351	0.91089	0.0875
89.33	12.7	0.00313	0.47388	0.02027
	14	0.00376	0.52239	0.02435
	17.7	0.00556	0.66045	0.03601
	18.6	0.0061	0.69403	0.03951
	25.9	0.0109	0.96642	0.0706
	29.2	0.01388	1.08955	0.0899

Measured flow rates were compared with predicted discharge obtained by both the mathematical models. The results of the comparison are shown in Table 6. It shows that the Model -1, (Equation 7), predicts the discharge with less than 5% error whereas the errors with Model-2 (Equation 8) are found to be higher. Therefore, it is concluded that prediction of discharge by Model-1, (Equation 7), is more accurate as compared to prediction of discharge by Model-2, (Equation 8).

Table 6 Comaprison of measured and predictated discharges in simple cylindrical flumes

Contraction	Measured Discharge	Froude No on the Upstream side of the Cylinder	Predicted Discharge by proposed Model -1 Equation 7	% Error of Predicted Discharge by proposed Model -1	Predicted Discharge by proposed Model -2 Equation 8	% Error of Predicted Discharge by proposed Model -2
η	Q	Fr	Q_p	Q_p	Q_p	Q_p
(%)	(m^3/s)		(m^3/s)	(%)	(m^3/s)	(%)
84.17	0.00278	0.113	0.00268	3.492	0.00249	10.29
	0.00345	0.106	0.00362	4.930	0.00329	4.50
	0.00465	0.111	0.00484	4.187	0.00431	7.29
	0.00649	0.120	0.00653	0.644	0.00566	12.72
	0.00704	0.117	0.00727	3.207	0.00624	11.38
	0.01351	0.137	0.01337	1.017	0.01075	20.44
89.33	0.00313	0.076	0.00306	2.392	0.00372	18.90
	0.00376	0.079	0.00363	3.555	0.00436	15.94
	0.00556	0.082	0.00550	1.039	0.00638	14.72
	0.0061	0.083	0.00602	1.392	0.00691	13.33
	0.0109	0.091	0.01102	1.074	0.01183	8.55
	0.01388	0.094	0.01379	0.684	0.01437	3.56

The variation of measured discharge with predicted discharge (Q_p), Model -1, (Equation 7), is shown in Fig. 6. The data points of predicted discharge found to lie within ± 5 % error zone with referance to measured discharge.

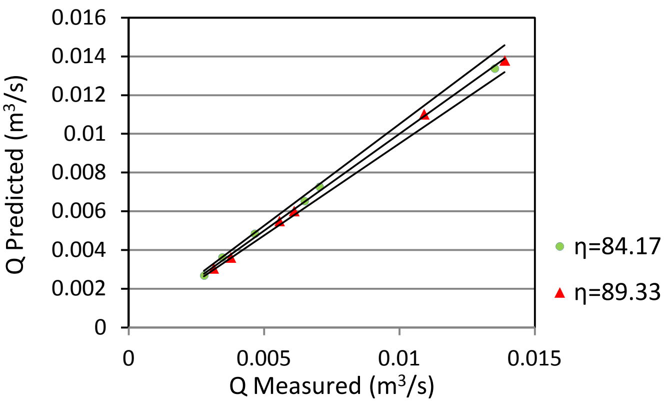

Fig. 6 Variation of predicted discharge with measured discharge

4. Model Validation

Hager [3] proposed an iterative Model relating upstream energy and discharge. It was expressed in terms of cylinder diameter and channel geometry. The details of the experimental flume of Hager [3] are as shown in Table 7.

Table 7 Description of the Hager [3] experimental flume

Flume	Base width (B) (cm)	Diameter of Cylinder (D) (cm)	Throat width (W_c) (cm)	Contraction (η) %
Hager (1985)	30	11.42	18.58	38.07

Experimental runs for different discharges in terms of water profile plots were presented by Hager [3]. These experimental observations have been compared with the results obtained by the two developed mathematical models in the present study. Comparison of both the models are made by plotting the Hager [3] observations. These comparisons of the two models are shown on Fig. 7 and Fig. 8, respectively. It is found that both the models compare well with Hager [3] observations and thus stand validated. It is interesting to note that there is significant difference between the contraction ratios used in the present experimental study and that presented by Hager [3]. Hence the proposed model (Model -1) can be considered to be applicable for contraction ratio, η ranging from 38% to 89% and is reasonably accurate.

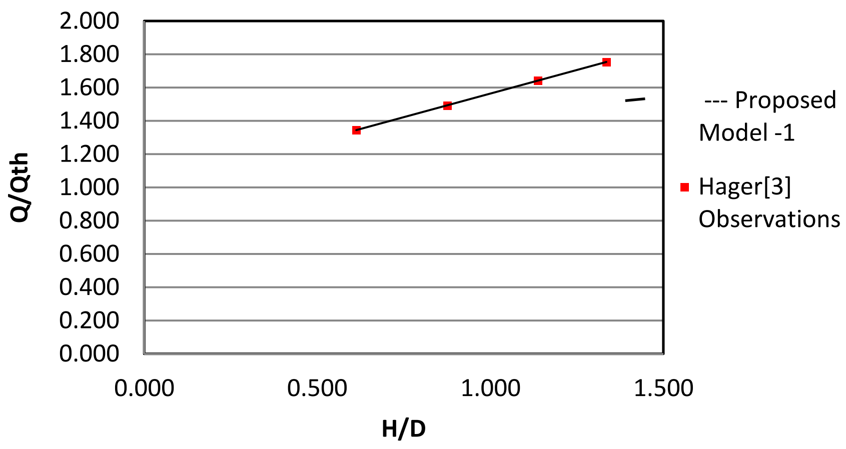

Fig. 7 Comparison between Model-1 and Hager [3] data

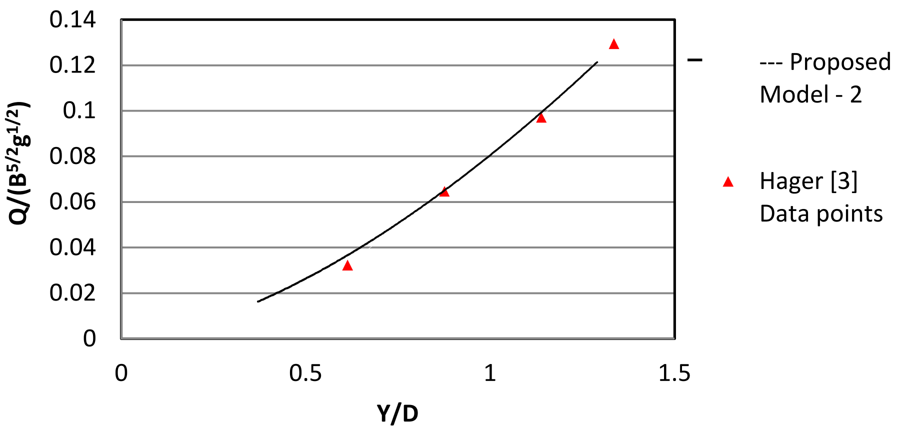

Fig. 8 Comparison between Model-2 and Hager [3] data

5. Verification of Critical Depth

The water surface profile is plotted along the length of the channel where the cylinder is positioned in the rectangular channel. For every section, the flow depth is plotted and Froude number is also determined. It is observed that the Froude number is unity at the center of the cylinder. Hence, it is concluded that the critical depth forms at the center of the cylinder and the flow is subcritical on the upstream side and supercritical on the downstream side, as anticipated. The water surface profile and variation of critical depths along the length of the channel where the cylinder is present in the rectangular channel for one experimental run, is shown in Fig. 9.

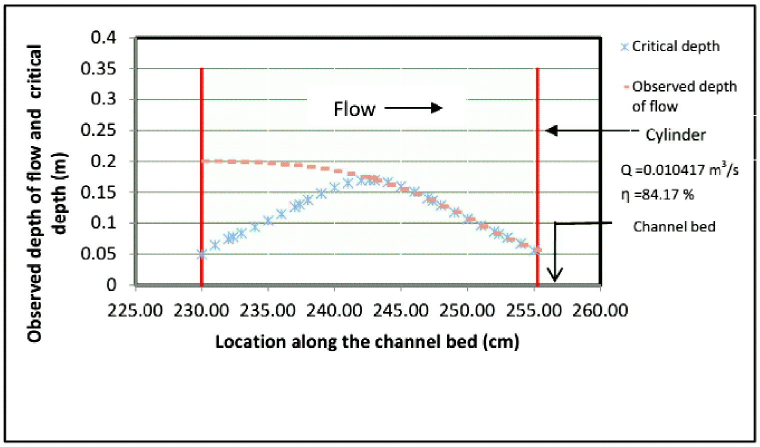

Fig. 9 Variation of water surface profile and critical depths along the cylinder

6. Variation of Froude Number with Dimensionless Column Head (Y/D)

Graph is also plotted between dimensionless column head (Y/D) and Froude number (F_r) of flow, upstream side of the cylinder, for the two diferent contractions corresponding to two flumes and observed linear variation as shown in Fig. 10.

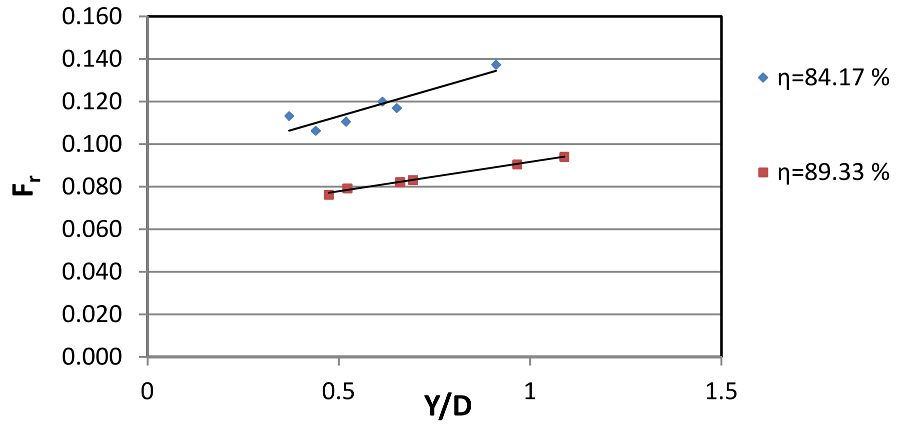

Fig. 10 Relationship between Froude number (F_r) and dimensionless column head (Y/D)

7. Conclusions

For systematic water management, the accurate measurement of flow in irrigation and drainage channels is essential. A simple cylindrical flume can be suitable for the rectangular channel for accurate measurment of free flow at any location on field. Two simple cylindrical flumes have been calibrated in laboratory for measuring discharge through rectangular field channel. Flumes with contraction ratios 84.17% and 89.33% were used in the experiments. This particular device has considerable advantages over the other devices, as it can be quickly installed and removed for use in small irrgation channels. By determining the Froude number, it is concluded that flow is critical at the central location of the cylinder where the minimum width for flow is available. Two mathematical models have been developed for the calibration of the simple cylindrical flume. The predicted flow rates based on the proposed discharge models were compared with the corresponding measured ones and Model -1(Equation 7) showed a good agreement as compared to Model -2 (Equation 8). The proposed model i.e. Model -1(Equation 7) predicted the flow rates with a maximum error within 5% whereas Model -2 (Equation 8) predicted discharge with maximum error within 20%. Hence Model -1 (Equation 7) has been proposed for prediction of discharge. The results of both the models have been validated by comparing these, with the limited experimental data of Hager [3] available in the literature. The proposed model can be recommended for use in the flumes with a wide range of contraction ratios between 38% to 89%. The graph plotted between dimensionless column head (Y/D) and Froude number (F_r) of flow indicated that there exist a definite relationship with dimensionless column head and Froude number of the incoming flow, for different contraction ratios (η).

NOTATIONS

The following symbols are used in this paper:

A	= cross-sectional area of flow at critical section
B	= channel bottom width
D	= diameter of cylinder pipe
F_r	= Froude number
g	= acceleration due to gravity
H	= upstream energy
T	= top width of flow
Q	= measured discharge
Q_p	= predicted discharge
Q_{th}	= theoretical discharge
q	= discharge per unit width
R^2	= coefficient of determination
W_c	= throat width of the channel
y	= upstream depth of flow
Y	= water depth at upstream side of cylinder
Y_c	= critical depth
η	= % contraction = $\frac{D}{B} \times 100$

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