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Design of compound cross-section critical flow flumes for PT channel by using WinFlume software

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ABSTRACT : Accurate discharge measurement in open channels is essential for water resources planning, water and sediment budget analysis, hydrologic modeling, reservoir operation, flood mitigation. Long-throated flumes are coming into general use in discharge measurement because they can be easily fitted into complex channel shapes as well as simple shapes. And also provide cost-effective, practical and flexible capabilities for measuring discharge. 'Winflume' software allows the user to calibrate the existing design and to make new design of long throated flume. Based on channel dimensions and conditions of canal an attempt is made to theoretically design a new flume to measure the discharge accurately. With so many iterations, three acceptable designs were considered with compound cross-sections. The three designs were further studied for hydraulic flow conditions. Among the three flumes, the flume with trapezoidal compound cross-section resulted the best performance.

KEY WORDS : WinFlume, Discharge, Canal

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Growing populations induces the more withdrawal of water towards agriculture, industry and domestic sectors putting water resources under deficit situations. An accurate water measurement at different locations (at all outlets and field) is important in efficient water management in an irrigation system (Raza *et al.*, 2007). Accurate water measurement is also required in ensuring equity delivery of water. The prediction of discharge in open channels is important in irrigation engineering for different hydrological applications. It can help engineers and practitioners to provide essential information regarding the water resources planning, water and sediment budget analysis, hydrologic modeling, reservoir operation, flood mitigation, and as far as planning for effective control and preventive measures (Al-Khatib *et al.*, 2014). Several types of structures have been used for a long time in performing discharge measurement in open channels such as flumes, gates, and weirs (Boiten, 2002 and Vatankhah and Mahdavi, 2012).

Examples of such structures used in the past two decades are weirs and flumes. Flumes can be categorized in to short-throated flume and long-throated flume. Long-throated flumes are coming into general use because they can be easily fitted into complex channel shapes as well as simple shapes (Replogle, 1975). And also provide cost-effective, practical and flexible capabilities for measuring discharge. The terms ''long-throated flume'' and 'broad-crested weir'' comprises a large family of structures used to measure discharge in open channels. Long-throated Flumes are extremely flexible devices in that any throat section geometry may be used, as long as the throat is horizontal in the flow direction. This forces uniform flow conditions through the structure and a unique relationship exists between the head and flow rate. Another characteristic of the Long-throated flume is that the designer may utilize compound throat shapes for special applications requiring a wide range of flow measurement.

■ METHODOLOGY

The WinFlume computer programme :

WinFlume is the latest in a series of long-throated flume design tools originally developed through the co-operative research efforts of the Agricultural Research Service (ARS) and the International Institute for Land Reclamation and Improvement (ILRI). The newest version of the software was developed through the co-operative efforts of the U.S. Bureau of Reclamation's Water Resources Research Laboratory and ARS's U.S. Water Conservation Laboratory, with funding from Reclamation's Water Conservation-Field Services (Wahl 2001:WinFlume User's Manual).

The WinFlume programme serves two primary purposes (Wahl 2001:WinFlume User's manual). Calibration of existing flow measurement structures fitting the criteria for analysis as long-throated flumes and design of new structures for new and existing canal systems. Designs can be developed manually by the user and analyzed using WinFlume to ensure proper operation, or WinFlume's design module can be used to develop designs that have desired head loss characteristics and meet other performance requirements. The model has good ability to simulate the flow and to estimate discharge passing through long-throated flume. The average error in the estimation of discharge was 10 per cent (Samad *et al.*, 2009)

In designing the new structure for a canal, the user must specify the flume and canal geometry. In addition to these, it is required to define hydraulic properties of the structure and the site, and design requirements to be used for later evaluation and review of flume designs. Specific information needs include (Wahl *et al*., 2000) are the hydraulic roughness of the material used for construction of the flume, range of flows to be measured and the associated tail water levels at the site, allowable flow measurement uncertainty at minimum and maximum discharge and required freeboard in the approach channel at maximum flow. The programme facilitates the computation of the tail water levels by permitting the user to specify a tail water calculation scheme. The programme then makes the calculations automatically.

WinFlume uses six design criteria to evaluate the suitability of a given structure for flow measurement. In the automated design module, four of these considered primary criteria that must be satisfied within the design module. In addition, two secondary design criteria related to the flow measurement accuracy of the structure. From the reports and graphs menu is used to create flume data report, flume review report, Flume drawing, rating tables and graphs of rating table data, Rating Equation for the flume that can be used in a data logger at the flume site to automate discharge measurements, create wall gages and reports of the data needed to construct wall gages. Keeping the above points in view, the following studies are taken up to design compound cross-section critical flow flumes for PT channel by using WinFlume software

Description of study area and flume design :

Perali-Thimmaraju channel (PT channel) takes off at 65.7 km on left bank on Commamuru canal with a head discharge of 9.6 cumecs. The study area starts from the head situated at Uparapalem, Prakasam district and ends at Pedapuluvaripalem. It runs for a length of 13.12 km (Fig. A) and irrigates an extent of 6437ha.

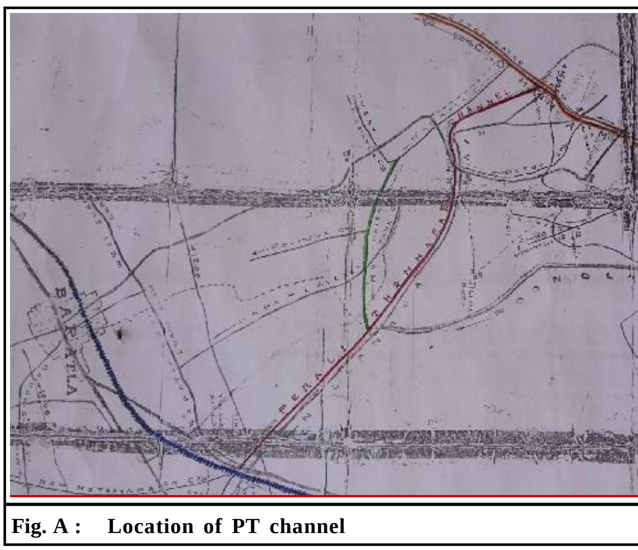

Fig. A : Location of PT channel

The existing structure for flow measurement is a regulator orifice (Underflow gate) (Fig. B). The structure area consists of two surpluses (old and new) to drain

Fig. B : Regulators at the head reach of PT channel

the excess water during floods. The canal water release data for 10 years (2005-2014) were collected from Irrigation and Command Area Development (I and CAD) Department at Bapatla and analyzed for further investigation. Maximum possible flow in the channel was assumed to occur when the outlet gates of the regulator are fully open is 340 cusecs as per the records of I and CAD department.

The physical characteristics for the channel reach under study includes channel widths range from approximately 13.41m at the water surface to approximately 14.0 m at an elevation of 50 cm above the water surface elevation, the shape of the channel is rectangular with vertical sides, the channel banks contain grass and brush and materials in the channel bed are mainly rocks, pebbles and sand.

For designing the broad crested weir, a range of discharge is selected as 10-340 cusecs, the shape of weir/flume is rectangular, the Minimal ponding or damming action in order to allow the flow is 30 cm and ability to pass the maximum channel flow without washing out the structure. Reasonable accuracy for flow measurement is considered as ±5 per cent. Utilizing this information, preliminary calculations were made to determine the size of structure required to measure the desired range of flow. After entering some initial values, the programme performed an evaluation of the flume and indicated that the flume design was not acceptable. In other terms, the preliminary dimensions would not allow the structure to accurately measure the desired flow range. The programme also detailed which problems were encountered during the flume evaluation and recommended changes to find a suitable structure.

After the first flume evaluation was performed, numerous changes were made in succession by one of the five methods until an acceptable design was achieved. Next, the values were manually adjusted in an effort to minimize the expected measurement errors and reduce the structure size. The iterations started with contracting only sides or only bottom. Initially it was started with side contraction of 20 per cent, 40 per cent, 60 per cent. At 20 per cent contraction WinFlume indicated that the flume design was not acceptable due to tail water area too small compared to control area and for width-contracted flumes, L/W $\geq$ 0.75 is recommended for throat section. This indicates that the contraction is not sufficient or goes for compound cross-section. Later at 30 per cent and 40 per cent contraction, the errors of submergence exceeds modular limit. Critical flow will not occur, for width-contracted flumes, L/W $\geq$ 0.75 is recommended for throat section. In all the cases, there is a common warning that uses a compound control section shape.

RESULTS AND DISCUSSION

The flume got acceptable design with all adjustments of components at 70 per cent contraction. With further increase in contraction to 80 per cent, the upstream energy head exceeds channel depth. This error message indicates that the approach channel energy head (water level plus velocity head) is above the banks of the upstream channel. If the velocity head is a large part of the total energy head, the water level may actually be within the channel banks, but this is an undesirable flow condition because there is so little freeboard in the approach channel that it could conceivably spill over the banks if the flow were brought to a stop by a local offset in the canal lining or an obstruction in the approach channel. To eliminate this error message, reduce the contraction in the control section or increase the size or top elevation of the approach channel.

The iterations with bottom contraction with suitable upstream and downstream ramp not attained the acceptable design in any case. After many iterations with combinations of both bottom and sides, three separate design options were found that minimized the expected measurement error and provided the most practical fit in the existing channel. The final design values for each of the proposed Long-Throated Flume options are shown in Table 1. In addition, the final shapes of designed flumes are presented in Fig. 1 and 2.

Using the graphs, illustrations and tables, the proposed Long-Throated Flume can proceed to structural design and construction without further hydraulic analysis. To study the best model among the three models, the hydraulic parameters of flumes are compared and presented in Fig. 3-6. The H_1/L vales for all three flumes are in close agreement with each other. There is no significant difference between the three flumes.

The value of H_1/L value varied between 0.141 and 0.699. From the result it has been concluded that there is no flow separation and the throat length is sufficient and critical flow conditions created within the flume throat. For flume 3 with trapezoidal compound cross section, H_1/L value varied from 0.07 to 0.691.

The discharge verses C_d for the three accepted flumes are presented in Fig. 4. The value of C_d values of

Table 1 : Dimensions of acceptable flumes designed by WinFlume software

	Flume-1	Flume-2	Flume-3
Units			
Length and height	Meter	Meter	Meter
Water velocity	Meter/second	Meter/second	Meter/second
Discharge	Cusec	Cusec	Cusec
Flume properties and canal data			
Crest type	Stationary	Stationary	Stationary
Crest material	Concrete - smooth	Concrete - smooth	Concrete - smooth
Roughness height of flume	0.000150 m	0.000150 m	0.000150 m
Minimum discharge	10.000 cu. ft/s	10.000 cu. ft/s	10.000 cu. ft/s
Maximum discharge	340.000 cu. ft/s	340.000 cu. ft/s	340.000 cu. ft/s
Tailwater calculation method	Manning's equation using n and S	Manning's equation using n and S	Manning's equation using n and S
Manning's n	0.0130	0.0130	0.0130
Hydraulic gradient	0.001000 m/m	0.001000 m/m	0.001000 m/m
Head detection method	Staff gage in stilling well, Fr=0.2 [custom]	Staff gage in stilling well, Fr=0.2 [custom]	Staff gage in stilling well, Fr=0.2 [custom]
Expected measurement uncertainty	±0.002000 m	±0.002000 m	±0.002000 m
Allowable error at minimum discharge	±8%	±8%	±8%
Allowable error at maximum discharge	±4%	±4%	±4%
Minimum free board	20% upstream head	20% upstream head	20% upstream head
Bottom profile			
Channel depth	1.5 m	1.5 m	1.5 m
Sill height	0	0.1 m	0.1 m
Approach	2.000 m	1.100 m	1.100 m
Converging transition	12.250 m	12.835 m	12.835 m
Control section	1.760 m	1.490 m	1.490 m
Diverging transition	29.400 m	0.600 m	0.600 m
Bed drop	0	0	0
Cross sections			
Approach section shape	Rectangular	Rectangular	Rectangular
Bottom width	14.000 m	14.000 m	14.000 m
Control section shape	Rectangular	Rectangular	Simple trapezoid
Bottom width	4.200 m	5.433	11.000
Side slopes	0	0	1.00:1
Tail water section shape	Rectangular	Rectangular	Rectangular
Bottom width	14.000 m	14.000 m	14.000 m
Side slopes	0	0	0

all flumes increases with increase in flow in the channel. For flume 3 that is the flume with trapezoidal compound cross-section the value of C_d is more than other flumes. The C_d values for flumes 1 and 2 (only side contracted and rectangular compound sections) are almost same. This may be due to the frictional loses of vertical walls in first two weirs. From this graph, it has been concluded that the discharge measurement of side contracted weir and compound weir are same. With change in the throat cross section to trapezoid, flume can pass the flow with less loss the results are in agreement with Fateme *et al*. (2013).

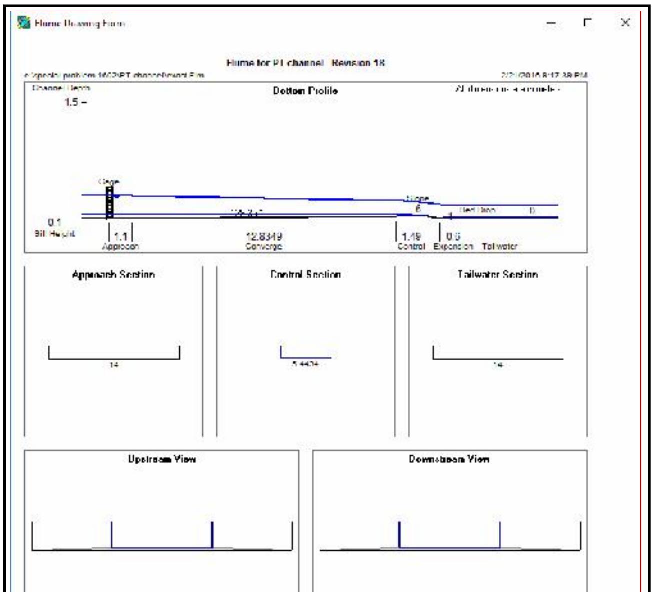

Fig. 1 : Flume diagram of designed Flume 2

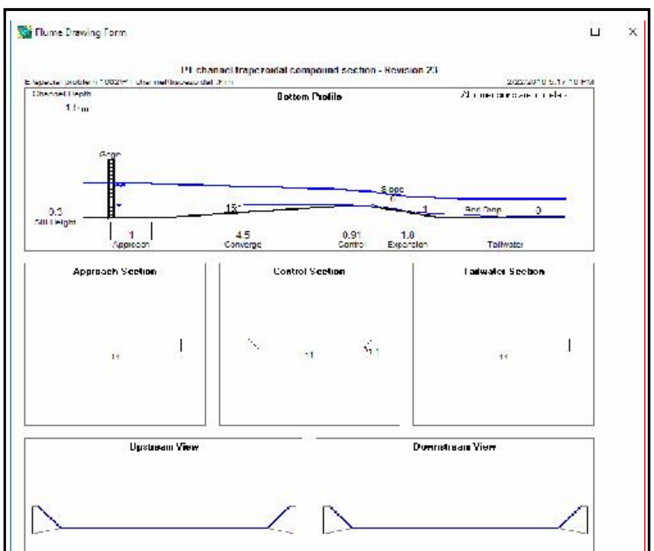

Fig. 2 : Flume diagram of designed Flume 3

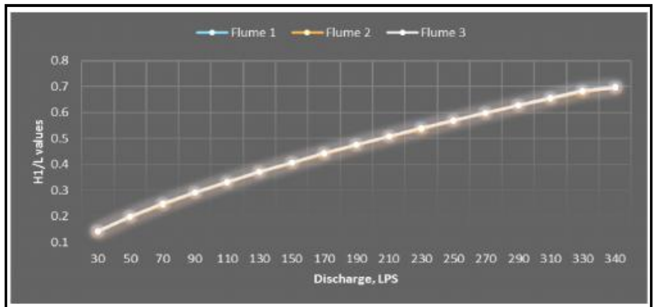

Fig. 3 : Variation of 'H_1/L' with discharges of three acceptable flumes

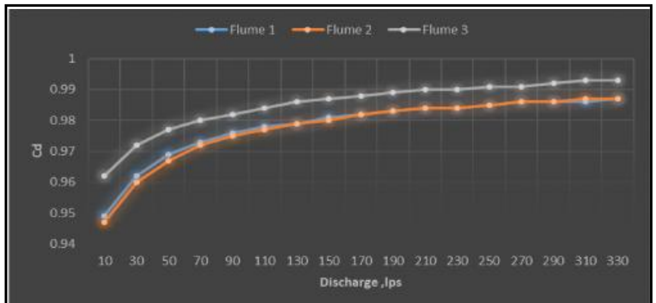

Fig. 4 : Variation of 'C_d' with discharges of three acceptable flumes

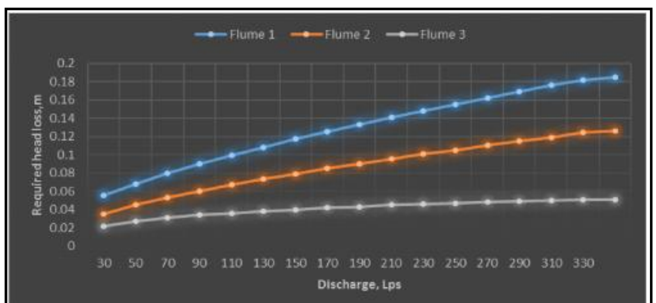

Fig. 5 : Variation of required loss with discharges of three acceptable flumes

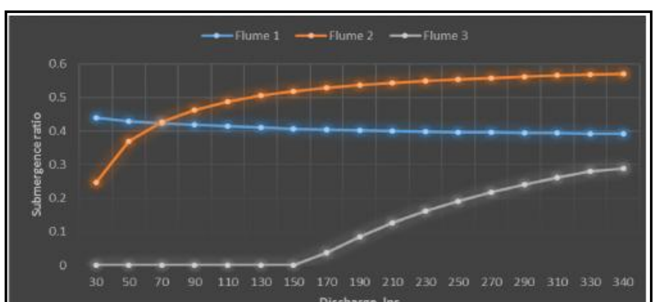

Fig. 6 : Variation of submergence ratio with discharges of three acceptable flumes

Table 2 : K_1 and U co-efficient in different scenarios

Sill height, m	Crest length, m	Crest width, m	K_1	U	C_d
0	1.76	4.2	254.4	1.525	0.99998030
0.1	1.49	5.443	334.3	1.536	0.99997579
0.3	0.9	Bottom width: 11 m Side slopes: 1;1	760.4	1.578	0.99997131

The loss of head required for the three accepted flumes are presented in Fig. 5. The three flumes are in acceptable range. The head loss requirement of 70 per cent side contracted flume is more compared to compound cross-sections. In compound cross-sections, the loss of head requirement is less with trapezoidal throat compared to rectangular throat. This concludes that for big channels with less height and more width, compound cross-sections are more suitable.

The submergence ratio for the three accepted flumes are presented in Fig. 6. The three flumes are in acceptable range. The submergence ratio of flume-1 decreases with increase in discharge, indicates that the flume works well at high discharges. At lower discharges, the submergence ratio of the flume-1 is higher than the remaining two flumes. At higher discharges the flume-2 shown higher submergence ratio than the remaining two flumes. The flume-3 shown zero submergence up to 70 cusecs later the submergence ratio increase drastically with increase in discharge. From the results it has been concluded that the side contracted flumes are works well at higher submergence which is in agreement with Krupavathi *et al*. (2012).

Rating equations :

WinFlume determines a curve-fit equation of the form

$Q = K_1(h_1+K2)^u$

The K_1 and U values and the co-efficient determination for different designed flumes are given in Table 2.

Conclusion :

An accurate water measurement at different locations (at all outlets and field) is important in efficient water management in an irrigation system. Accurate water measurement is also requiring in equity delivery of water. Broad crested weir and Long-throated flumes are a well-developed technology that provides economical and flexible water measurement capabilities for a wide variety of open-channel flow situations. Winflume software allows the user to calibrate the existing design and to make new design. Based on channel dimensions and conditions of canal an attempt is made to design a new flume to measure accurately. With so many revisions finally three designs that are acceptable were considered. The three designs were further studied for hydraulic conditions.

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