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An Approach to Analyze the Flow Characteristics of Sharp-Crested Triangular Planform Contracted Weirs

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Abstract: Weirs are a barrier across a river to amend its flow characteristics. Conventional weirs pose problems of submergence upstream of the weir due to large afflux required to pass the discharge downstream. The capacity of the weirs can be enhanced by increasing the crest length of the weir. Labyrinth weirs are folded in plan view to provide a longer crest length and which can easily be constructed on any existing conventional weir or spillway. The capacity and hydraulic design of labyrinth weirs depends on various factors such as aspect ratio, side wall angle, channel conditions and other geometric parameters of the weir etc. which has not been yet completely established. In this paper the results of the experimental study carried out to investigate the discharge characteristics of a sharp-crested contracted triangular planform weir under free flow conditions in a rectangular channel is presented. The efficiency of the triangular planform weirs is found better than the normal weir. A generalized discharge equation has been proposed for the given range of data and compared with Ghodsian and Ghare equations. The proposed equation is found within ±5% of the observed ones. Sensitivity of the weir, i.e., change of discharge due to unit change in head is also carried out which indicates that the weir is more sensitive at the low head and high *L*/*B* ratios.

Key words: Triangular planform weir · Flow measurement · Sensitivity · Discharge coefficient and open channel

INTRODUCTION

A weir is built across a stream in order to raise level of water on the upstream side and to allow the excess water to flow over its entire length to the downstream side. Conventional weirs are inherited with afflux and submergence of area upstream of the weir. Labyrinth weirs have been used to enhance their discharging capacity with minimum head over the weirs and to restrict the afflux.

Labyrinth weirs are folded in plan view (i.e. the weir crest is not straight in planform) to provide a longer crest length compared with a normal weir having the same lateral space to increase the discharge for a given operating head. Since labyrinth weirs passes large flood at a comparatively low head, they can therefore be widely used to a particular advantage in situations where a weir is required to pass a range of discharge with a limited variation in upstream water levels and also where the width of a channel is restricted.

Discharge (Q) over a sharp-crested suppressed weir under free flow condition in a channel is expressed in terms of the following mathematical expression

$$Q = \frac{2}{3} C_d \sqrt{2g} L H^{\frac{3}{2}} \tag{1}$$

where C_d = coefficient of discharge, L = crest length of the weir, g = acceleration due to gravity, H = head over the crest. The C_d depends on flow characteristics and geometry of the channel and the weir (Bagheri and Heidarpour [1]).

For a sharp crested weir with end contraction, if velocity of approach is considered then equation (1) is modified as

$$Q = \frac{2}{3} C_d \sqrt{2g} \left[L - 0.1n \left(H + \frac{V_a^2}{2g} \right) \right] \left[\left(H + \frac{V_a^2}{2g} \right)^{\frac{3}{2}} - \left(\frac{V_a^2}{2g} \right)^{\frac{3}{2}} \right] \tag{2}$$

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where n is the numbers of end contractions, $V_a = \frac{Q}{B(H+P)}$ is velocity of approach, B is width of the flume and P is weir height.

Taylor [2] studied the behavior of the labyrinth weirs and presented his results in the term of a magnification ratio i.e., ratio of discharge over labyrinth weir and normal weir for the same head over the crest. Hay and Taylor [3,4] tested various plan shapes in the form of labyrinth weirs and presented the results in the form of curves between the ratio of discharge over labyrinth weir (Q) to corresponding normal weir (Q_n) and h/w. where, w = weir height. They found that the triangular planform weir is more efficient than the trapezoidal plan form.

Tullis *et al*. [5] found the capacity of a labyrinth weir is a function of the total head, the effective crest length and the coefficient of discharge. The coefficient of discharge depends on weir height, total head, weir wall thickness, crest shape, vertex configuration and the angle of the side legs. On the basis of experiments on three submerged labyrinth weirs of different geometries with half-round crest shapes Tullis *et al*. [6] described the submerged labyrinth weir head–discharge relationship using the dimensionless submerged head parameters and found that the relationship is independent of labyrinth weir sidewall angles. Ghare *et al*. [7] proposed a methodology for the optimal hydraulic design of trapezoidal labyrinth weirs. Ghodsian [8] conducted experiments on sharp, quarter round, half round and flat top crest shape weirs and using dimensional analysis, he proposed an equation for calculating discharge over labyrinth weir. Kumar *et al*. [9, 10] conducted an experimental study to investigate the discharging capacity of a sharp-crested suppressed triangular and curved plan form weir under free flow conditions in a rectangular channel. They found that the efficiency of the triangular and curved plan form weirs was better than the normal weir.

Experimental Work: The experiments were conducted in a horizontal rectangular tilting flume of length 5.360 m; width 0.262 m and depth 0.450 m in the hydraulics lab of Graphic Era University, Dehradun, India. Sharp-crested triangular planform weirs were fabricated of mild steel plates and were located at 5.150 m downstream from the head of the flume. Head over the crest was measured using the point gauge of accuracy ± 0.1 mm and discharge by means of an orifice meter provided in the inlet pipe and connected to the pressure gauges. Water was guided to a sump provided at the end of the flume in the downstream of the weir to ensure free flow condition. Regulating gate and wave suppressors were provided at the upstream of the flume to control the discharge and to dissipate the surface disturbances, respectively.

The experiments were performed for weirs of different L/B ratios and varying discharges. Figure 1 shows the definition sketch of a sharp crested triangular planform weir with end contraction and Figure 2 shows the layout of the experimental set-up. For each run, the head over the crest of the weir was measured at about 4–5 times upstream of the weir using point gage to avoid the curvature effect. The ranges of the data collected in the present study are given in Table 1.

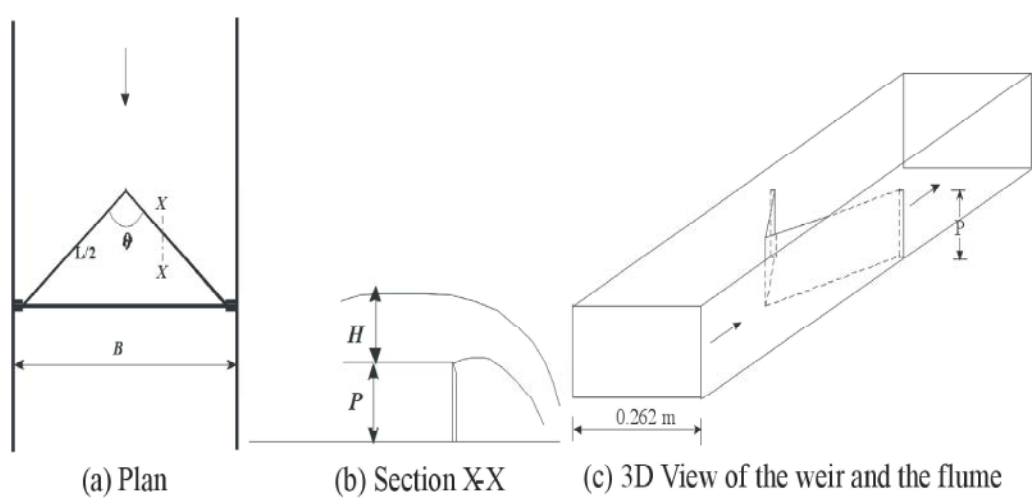

Fig. 1: Definition sketch of sharp crested triangular planform contracted weir

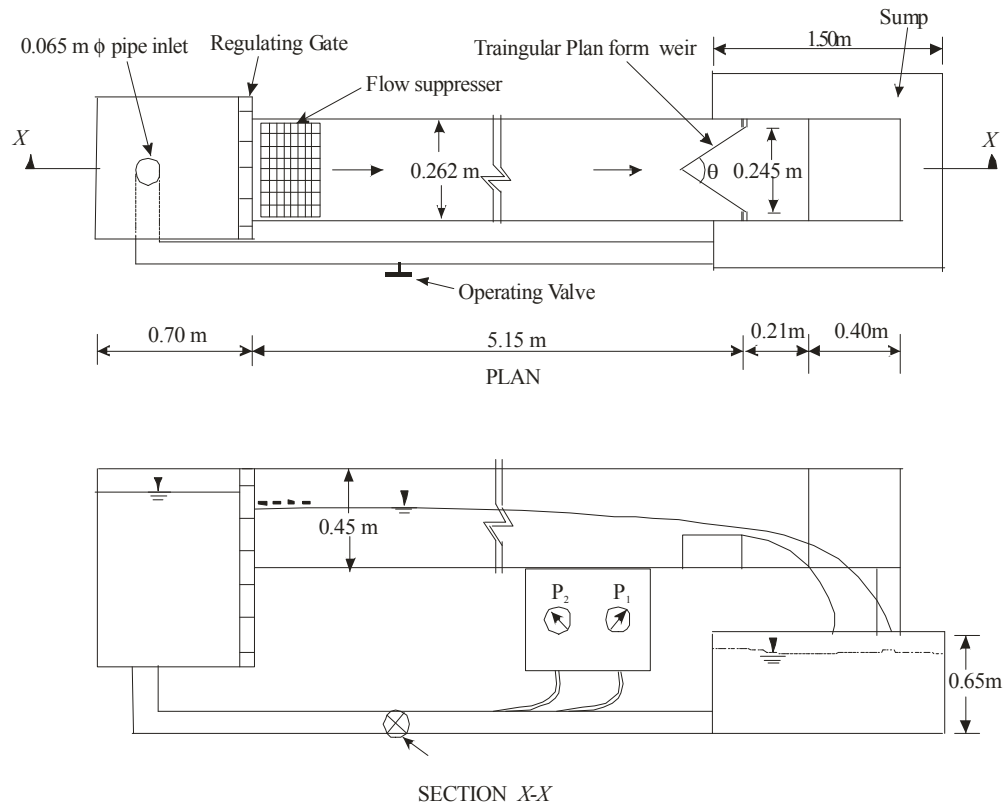

Fig. 2: Layout of the experimental set-up

Table 1: Range of parameters for triangular planform contracted weirs

S.no.	L/B	P (m)	H (m)	Q_o (m^3/s)	No. of Runs
1	1.000	0.1043	0.0314 - 0.0777	0.0022 - 0.0091	10
2	1.023	0.1040	0.0362 - 0.0834	0.0031 - 0.0101	14
3	1.069	0.1033	0.0273 - 0.0812	0.0022 - 0.0094	13
4	1.140	0.1022	0.0259 - 0.0847	0.0022 - 0.0103	12
5	1.245	0.0992	0.0237 - 0.0754	0.0022 - 0.0094	12
6	1.397	0.1009	0.0224 - 0.0721	0.0022 -0.0096	13
7	1.623	0.1019	0.0309 - 0.0690	0.0038 - 0.0099	12
8	1.976	0.0995	0.0248 - 0.0541	0.0031 - 0.0094	13

Analysis of Data

Data Presentation and Analysis: Data collected in the present study is analyzed to obtain the functional relationship of discharge coefficient for all tested triangular planform contracted weirs in a free flow situation in the form of Rehbock's [11] equation. i.e.

$$C_d = a + b\left(\frac{H}{P}\right) \tag{3}$$

where a and b are the coefficients to be found using experimental data. The most general values for these coefficients are proposed by Rehbock [11] as a = 0.611 and b = 0.075.

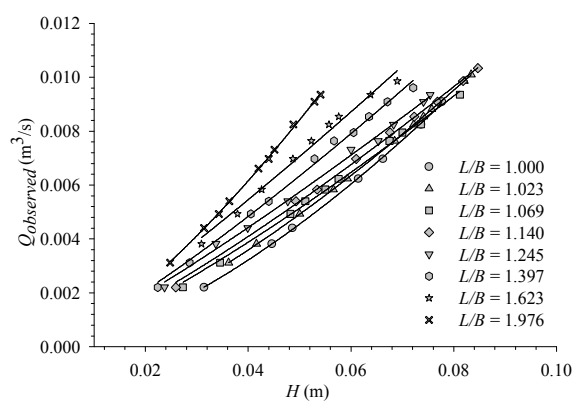

Fig. 3: Variation of $Q_{observed}$ with H for weirs of different L/B ratios.

Variation of observed discharge with head over the crest for the triangular planform contracted weirs of different L/B ratios is shown in Figure 3. All the plots are curvilinear, co-focal with the best one being for the largest L/B ratio, i.e. 1.976. Figure 3 clearly indicates that for the same value of H, discharge increases with the increase of L/B ratios due to increases of the crest length of the weir. For each data set, the C_d was computed using Eq. (2) for known value of discharge, head over the crest and the

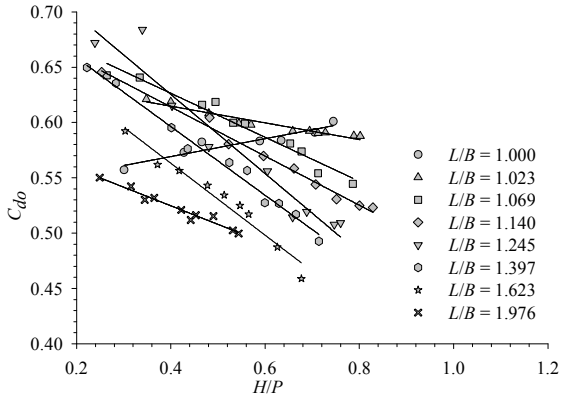

Fig. 4: Variation of C_d with H/P for weirs of different L/B ratios.

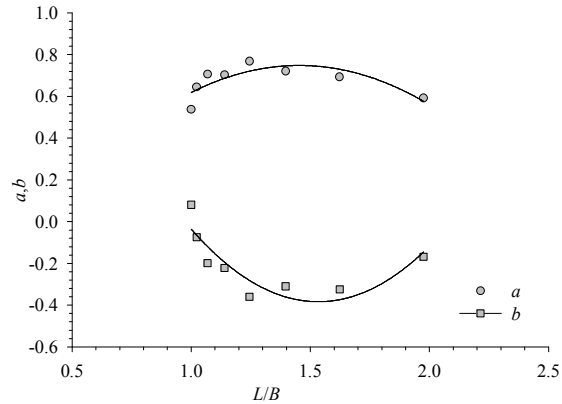

Fig. 5: Variation of 'a' and 'b' with L/B

crest length for weirs of different L/B ratios. Variation of C_d with H/P is shown in Figure 4. It can be noted that C_d decreases with an increase of L/B ratios due to interference of the falling jets for high value of H/P. However, for the low value of H/P, the interference of jets is not so severe, resulting in high C_d. The value of C_d decreases with increase in H/P for different L/B ratios and for the $L/B = 1.0$ i.e., the normal weir, the C_d increases with H/P, which satisfies the Rehbock [11] equation for C_d.

Discharge Equation for Triangular Planform Contracted Weir: As per the Rehbock [11] equation, the variation of C_d with H/P is fitted to linear equations for weirs of L/B ratios as follows:

$C_d = 0.537 + 0.081(H/P)$	For $L/B = 1.000$	$R^2 = 0.89$	(4a)
$C_d = 0.645 - 0.075(H/P)$	For $L/B = 1.023$	$R^2 = 0.94$	(4b)
$C_d = 0.706 - 0.199(H/P)$	For $L/B = 1.069$	$R^2 = 0.96$	(4c)
$C_d = 0.703 - 0.222(H/P)$	For $L/B = 1.140$	$R^2 = 0.98$	(4d)
$C_d = 0.768 - 0.358(H/P)$	For $L/B = 1.245$	$R^2 = 0.94$	(4e)
$C_d = 0.721 - 0.310(H/P)$	For $L/B = 1.397$	$R^2 = 0.98$	(4f)
$C_d = 0.693 - 0.325(H/P)$	For $L/B = 1.623$	$R^2 = 0.95$	(4g)
$C_d = 0.592 - 0.168(H/P)$	For $L/B = 1.976$	$R^2 = 0.96$	(4h)

A high correlation between C_d and H/P may be noted for all the weirs. Variations of constants 'a' and 'b' with L/B ratios are shown in Figure 5. A third order polynomial has been fitted to the data for 'a' and 'b' as follows:

$$a = 1.51\left(\frac{L}{B}\right)^3 - 7.31\left(\frac{L}{B}\right)^2 + 11.375\left(\frac{L}{B}\right) - 4.99, \quad R^2 = 0.82 \tag{5a}$$

$$b = -2.23\left(\frac{L}{B}\right)^3 + 11.11\left(\frac{L}{B}\right)^2 - 17.88\left(\frac{L}{B}\right) + 9.015, \quad R^2 = 0.89 \tag{5b}$$

Out of 99 data sets for triangular planform contracted weirs, 75 data sets were used to develop the relationship for coefficient of discharge. The generalized equation of C_d for the triangular planform contracted weir to be used in Eq. (2) for the computation of discharge can be written as:

$$C_d = \left(1.51\left(\frac{L}{B}\right)^3 - 7.31\left(\frac{L}{B}\right)^2 + 11.375\left(\frac{L}{B}\right) - 4.99\right) + \left(-2.23\left(\frac{L}{B}\right)^3 + 11.11\left(\frac{L}{B}\right)^2 - 17.88\left(\frac{L}{B}\right) + 9.015\right)\left(\frac{H}{P}\right) \tag{6}$$

This equation is valid in the range $0 < H/P < 0.83$ and $1.00 = L/B = 1.976$.

Validation of the Proposed Discharge Equation: The remaining 24 data sets, not used in the derivation of Eq. (6), were used next to validate the proposed relationship for C_d i.e., Eq. (6). The computed discharge is compared with the corresponding observed ones in Figure 6, which shows that the computed discharge is within ±05% of the observed ones for the weirs of all L/B ratios studied herein. Figure 6 also shows the comparison between Q values calculated using Eq. (6) in the present investigation and the equations proposed by Ghodsian M. [8] (i.e. Eq. 7) and Ghare *et al*. [7] (i.e. Eq. 9).

$$Q = \left[0.703\left(\frac{H}{P}\right)^{0.928}\left(\frac{l}{w}\right)^{-0.383} P\right]^{\frac{3}{2}} g^{\frac{1}{2}} L \tag{7}$$

Eq. (7) holds good for a sharp crested triangular labyrinth suppressed weir which can be modified for a sharp crested contacted weir as

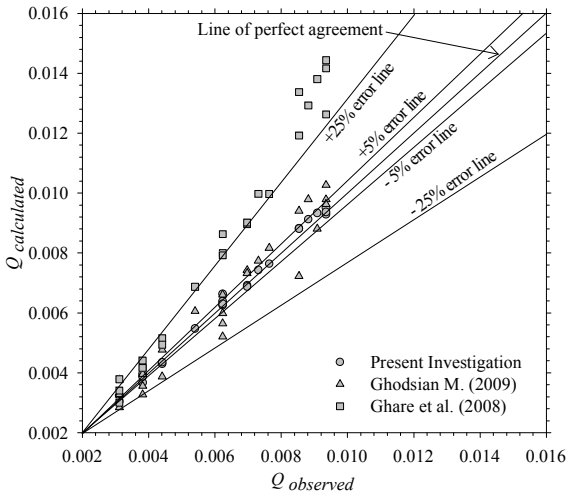

Fig. 6: Comparison of computed discharge using Eqs.(2, 6, 8 and 10) with the observed ones

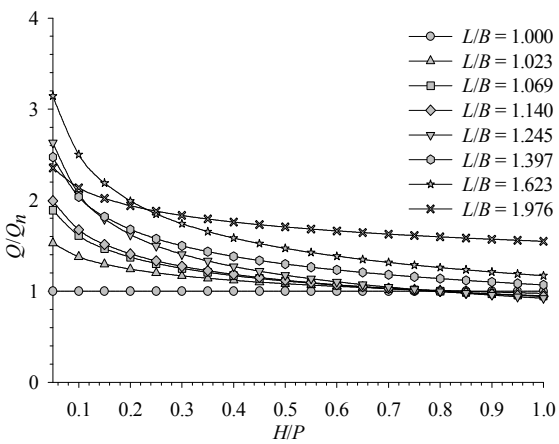

Fig. 7: Variation of Q/Qn with H/P for the weirs of different L/B ratios.

$$Q=\left[0.703\left(\frac{H}{P}\right)^{0.928}\left(\frac{l}{w}\right)^{-0.383}P\right]^{\frac{3}{2}}g^{\frac{1}{2}}\left(L-0.1nH\right) \tag{8}$$

$$Q=\frac{2}{3}\times\left(0.1714\ln\left(\frac{H}{P}\right)+0.8671\right)\sqrt{2g}\times L\times H^{\frac{3}{2}} \tag{9}$$

Eq. (9) can be modified for a sharp crested contacted weir as

$$Q=\frac{2}{3}\times\left(0.1714\ln\left(\frac{H}{P}\right)+0.8671\right)\sqrt{2g}\times\left(L-o.1nH\right)\times H^{\frac{3}{2}} \tag{10}$$

For a numerical measure for error between the observed and computed values, an average percentage error term e is defined as (Ghodsian M., [12]):

$$e=\frac{100}{N}\sum_{i=1}^{N}\left[\frac{Q_{computed}-Q_{observed}}{Q_{observed}}\right] \tag{11}$$

The average percentage error in the computation of discharge over the weir using Eqs. (2) and (6) is found in the range 0%–05% for weirs of different L/B ratios where as discharge calculated by Eqs. (8) and (10) over estimates the observed ones.

Efficiency of the Weir: To examine the efficiency of the triangular planform contracted weir for different L/B ratios, ratio of discharges over the triangular planform contracted weir and normal weir, i.e., Q/Q_n is plotted with H/P in Figure 7.

The efficiency of triangular planform contracted weir is high for high L/B ratios and decreases with increase of H/P due to interference of the jets downstream. For $H/P = 0.05$, the weirs of L/B ratios 1.023, 1.069, 1.140, 1.245, 1.397, 1.623 and 1.976 are respectively 1.53, 1.88, 1.99, 2.63, 2.47,3.14 and 2.35 times more efficient than the normal weir. However, for $H/P = 1.0$, the efficiency of triangular planform contracted weir is low and even for $L/B = 1.976$, the efficiency is only 1.55 times the normal weir.

Sensitivity Analysis of the Triangular Planform Contracted Weir: Sensitivity analysis, i.e., change in discharge due to unit change in the head of water is carried out for the proposed discharge equation of the triangular planform contracted weir, which can be written as:

$$Q=\frac{2}{3}\left[a+b\left(\frac{H}{P}\right)\right]\sqrt{2g}\left[L-0.1n\left(H+\frac{V_a^2}{2g}\right)\right]\left[\left(H+\frac{V_a^2}{2g}\right)^{\frac{3}{2}}-\left(\frac{V_a^2}{2g}\right)^{\frac{3}{2}}\right] \tag{12}$$

The values of 'a' and 'b' can be obtained from the Eqs. (5a) and (5b) respectively. Differentiating Q with respect to H and arranging the terms, one can get

$$\frac{dQ}{dH}=\frac{3}{2}Q\left[\frac{\left(H+\frac{V_a^2}{2g}\right)^{\frac{1}{2}}}{\left(H+\frac{V_a^2}{2g}\right)^{\frac{3}{2}}-\left(\frac{V_a^2}{2g}\right)^{\frac{3}{2}}}-\frac{n}{\left\{L-0.1n\left(H+\frac{V_a^2}{2g}\right)\right\}}+\frac{2b}{3P\left\{a+b\left(\frac{H}{P}\right)\right\}}\right] \tag{13}$$

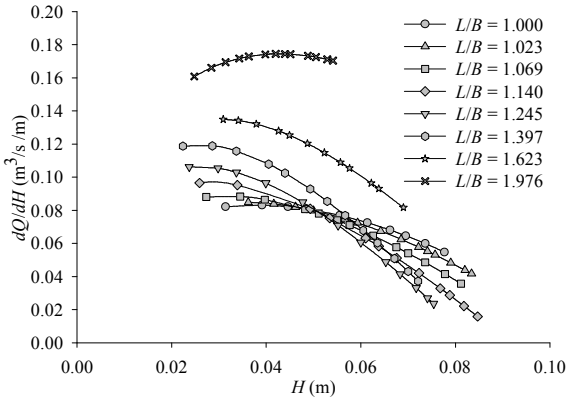

Fig. 8: Sensitivity of the weirs as function of head

The larger value of dQ/dH implies higher sensitivity. Data collected in the present study was used to compute dQ/dH for different values of the L/B ratios. The variation of dQ/dH with H is shown in the Figure 8. Figure 8 indicates that the discharge through triangular planform contracted weir is more sensitive to the low head. As the head increases, the sensitivity decreases due to interference of the water jet downstream of the weir crest. Further, sensitivity is higher for the high L/B ratios of the triangular planform contracted weir due to large weir crest length.

CONCLUSION

An experimental study was carried out to investigate the discharging capacity of a sharp-crested triangular planform contracted weir under free flow conditions in a rectangular channel. The coefficient of discharge of the triangular planform contracted weir decreases with increase of L/B ratios due to interference of falling jets for high value of H/P. However, for low values of H/P and lower values of L/B ratios, the C_d is high. The computed discharge using the proposed equation is within ±05% of the observed ones. The efficiency of the weir is high for high L/B ratios and decreases with increase of H/P due to interference of the jets downstream. For H/P = 0.05, the weirs of L/B ratios 1.023, 1.069, 1.140, 1.245, 1.397, 1.623 and 1.976 are respectively 1.53, 1.88, 1.99, 2.63, 2.47,3.14 and 2.35 times more efficient than the normal weir. However, for H/P = 1.0, the efficiency of triangular planform contracted weir is low for all L/B ratios. Sensitivity analysis indicates that the discharge through triangular planform contracted weir is more sensitive to the low head and high L/B ratios. As the head increases, the sensitivity decreases due to interference of the water jet downstream of the weir crest.

Notations:

B = Flume width
C_d = Coefficient of discharge for triangular planform contracted weir
g = Acceleration due to gravity
H = Head over the weir
l = Total length of one cycle
L = Crest length
n = Numbers of end contractions.
P = Weir height above the bed of flume
Q = Discharge over triangular planform contracted Weir
Q_0 = Observed Discharge
Q_c = Computed Discharge
Q_n = Discharge over corresponding normal weir
V_a = Velocity of approach
w = Width of a cycle
θ = Vertex angle
a, b = Coefficients

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