FLOW OVER TRIANGULAR BROAD-CRESTED WEIR

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ABSTRACT

Broad-crested weir with triangular cross section allows wide range of stream flow measurement while the discharge remains independent on tail water level up to high submergence ratio. Study of flow characteristics over such weir leads to optimal design, and operation. Theoretical study based on the energy equation is presented. Theoretical equations are developed for; velocity, and discharge coefficients, depth of flow over the weir, depth- discharge relationship, and the brink depth. Experimental study is carried out using weir models with different shapes. Predicted equations are checked by the experimental measurements and good agreement is found to exist. Head-discharge equations are presented in mathematical formulas and charts applicable to field engineering situations are given .

Keywords: Weir, Broad-Crested, Triangular weir.

NOTATIONS

A Area of the flow cross section,
A_c Area of critical flow cross section,
C_d Discharge coefficient,
C_v Velocity coefficient,
g Gravity acceleration,
H Head on weir,
H_o Total head on weir, $H_o = H + \frac{\alpha_1 v_a^2}{2g}$,
k Pressure coefficient at the brink section,
L Length of weir crest,
P Apex height,
Q Discharge passing over weir,
T_c Top width of critical flow cross section,
v_a Approach velocity,
v Velocity of flow over weir,
y Depth of flow over weir,
y_b Brink depth,
y_c Critical depth, for triangular section, $y_c = \left(\frac{2}{g} \cdot \frac{Q^2}{\tan^2 \frac{\theta}{2}}\right)^{1/5}$,
α_1, α_2 Energy correction coefficients,
θ Notch angle of triangle,
η Coefficient of head loss.

1 - INTRODUCTION

Triangular or V-shaped broad-crested weir has triangular cross-section and broad crest in longitudinal section as shown in Figure (1). The characteristics of such weir meet modern demands of water resources development, particularly in; irrigation, water supply, and hydrologic studies.

Broad-crested weir of triangular cross section is characterized with higher accuracy and wide range of flow measurement. It possesses the following two main advantages over other weirs of exponential sections; rectangular and parabolic. (1) broad-crested weir of triangular cross section takes greater submergence than rectangular or parabolic cross section before its capacity is affected. For ideal flow, the critical depth for triangular section is 0.8 H, while it equals 0.667 H, and 0.75 H for rectangular, and parabolic sections, respectively (2), triangular cross section is more sensitive to small heads. Hence, better accuracy for measuring discharges is achieved in comparison to rectangular, and parabolic cross sections. For triangular cross section $Q \alpha H^{2.5}$ while $Q \alpha H^{1.5}$ for rectangular cross section, and $Q \alpha H^{2.0}$ for parabolic cross section.

Triangular broad-crested weir has been investigated in few works. Bos [1,2] introduced combination of broad crested and triangular shape profile in Netherlands. Neglecting the loss of flow energy, Smith, and Liange [3] predicted a discharge equation for the weir. Pitlo, and Smit [4] analyzed the data of experiments conducted in Wageningen Agricultural University, Netherlands. Pitlo, and Smit showed that submergence ratio decreases as discharge increases. Also they predicted that the discharge coefficient is independent on the weir notch angle, θ. The agricultural University carried out laboratory study to measure the boundary layer displacement thickness on a V-shaped broad-crested weir with $\theta = 90°$ [5]. Boiten [6] improved the discharge equation predicted by Smith and Liange. Accounting for the energy loss, Boiten introduced a correction coefficient, and defined it as characteristic discharge coefficient. Boiten, and Pitlo [7] presented some design rules and limits of application including free and submerged flow conditions.

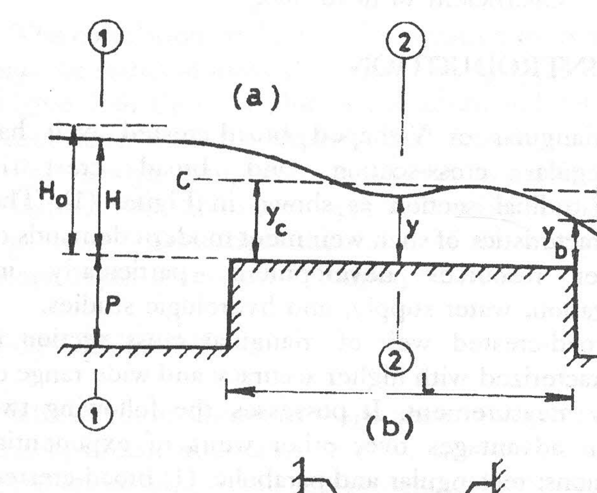

Figure 1. Definition Sketch for flow over triangular brood-crested weir, (a) Longitudinal section (b) Cross section.

However, in previous studies, evaluation of the velocity coefficient, C_v, accounting for energy loss at the control section has not been included. The depth of flow over the weir has not been investigated previously. It was assumed to be equal to the critical depth. However, critical depth assumption is valid only for ideal flow in which the energy loss is neglected. Actually, in real flow, a part of the flow energy is lost due to lateral and vertical contractions. This makes the flow depth to be lesser than the critical depth. This fact was confirmed by the author [8,9] through studying rectangular, and parabolic broad- crested weirs.

Consequently, for accurate discharge measurement,the depth- discharge relation should be based on the actual depth, and not on the critical one. This fact is taken into consideration, in the present work, to develop the discharge equation of triangular broad-crested weir.

The brink depth of triangular broad-crested weir has not been sufficiently investigated in previous studies. Diskin [10] developed an equation for the brink depth assuming zero pressure at the brink section. Diskin obtained a theoretical value, for the brink depth, equals to 0.775 of the critical depth. Rajaratnam [11], and Replogle [12] improved Diskin's work by deriving equations for non-zero pressure at the brink section. Considering a value of the pressure coefficient, k, equals to 0.175, Replogle obtained brink depth ratio y_b/y_c, equals to 0.7943. An average experimental value for y_b/y_c equals 0.795 was given by Rajaratnam, and Maralidhar [13]. Assuming a free vortex formation at the brink section, Kamil, and Sykes [14] applied the free vortex theory resulting a brink depth ratio equals 0.798.

Obviously, in previous studies, energy equation is not employed to evaluate the brink depth ratio. On the other hand, theoretical evaluation for the pressure coefficient at the brink section has not been presented. Experimental evaluation of pressure coefficient is subjected to measurement accuracy. Thus, using $k = 0.175$ in Rajaratnam equation results a brink depth ratio equals 0.788 which differs than Replogle value for the same k. Furthermore, Rajaratnam, and Replogle equations are quintet and need a trial and error technique in order to be solved.

The present study is intended to investigate the characteristics of flow over triangular broad-crested weir which have not been sufficiently studied. The problem is investigated theoretically by applying the energy equation taking the energy loss into account. Experimental study was conducted to check the predicted equations.

2 - THEORETICAL STUDY

Equating the specific energy equations at section 1-1, where the head H is measured, and section 2-2, where the flow is contracted, considering the apex line as a datum we get;

$$H_o = y + \frac{\alpha_2 v^2}{2g} + h_L \qquad (1)$$

Substituting for the $h_L = \eta \frac{v^2}{2g}$, equation (1) becomes;

$$H_o = y + \frac{v^2}{2g}(\alpha_2 + \eta), \qquad (2)$$

where,

$H_o = H + \frac{\alpha_1 v_a^2}{2g}$,

η - is the coefficient of head loss,

v_a - is the velocity of approach, $v_a = \frac{Q}{A1}$,

A_1 - is the cross section area at section 1-1.

Considering $\alpha_1 = \alpha_2 = 1.0$, and introducing the velocity coefficient, C_v, to account for the energy loss, where, $C_v = 1/\sqrt{1+\eta}$, in Eq (2), yields;

$$H_o = y + \frac{Q^2}{2gA_2^2C_v^2}, \qquad (3)$$

where, A_2 is the cross section area of the flow at the contracted section, 2-2, $A_2 = y^2 \tan\frac{\theta}{2}$.

The critical depth, y_c, for triangular cross section may be expressed as;

$$\frac{Q^2}{g} = \frac{A_c^3}{T_c} = \frac{Y_c^5}{2}\tan^2\frac{\theta}{2}, \qquad (4)$$

where, A_c and T_c are the cross section area, and the top width of critical flow. Substituting for $\frac{Q^2}{g}$ from Eq (4) in Eq (3) we get;

$$y^5 - H_o y^4 + \frac{y_c^5}{4c_v^2} = 0. \qquad (5)$$

Equation (5) is a quintet equation for y. Solution of Eq (5), to obtain depths of flow in polynomial form, is not existed. However, another approach can be developed to obtain the flow depth. Referring to Eq (4) we get;

$$Q = \sqrt{\frac{g}{2}}.(\tan\frac{\theta}{2})\, y_c^{5/2}. \qquad (6)$$

The discharge equation for triangular sharp crested weir is,

$$Q = \frac{8}{15}C_d\sqrt{2g}(\tan\frac{\theta}{2})H_c^{5/2}. \qquad (7)$$

where, C_d is the discharge coefficient. Equating Eqs. (6), and (7) we get

$$y_c^5 = (\frac{16}{15})^2 C_d^2 H_o^5. \qquad (8)$$

Substituting from Eq. (8) in Eq (5), we get;

$$(\frac{y}{H_o})^2(1-\frac{y}{H_o})^{1/2} = \frac{8}{15}\frac{C_d}{C_v}. \qquad (9)$$

The velocity coefficient, C_v, was evaluated theoretically, by the author [8,9], for rectangular, and parabolic broad crested weirs through analytic solution of cubic and quartic equations, respectively. For triangular broad-crested weir, analytic solution of quintet equation, (5), is not available. However, theoretical equation of C_v for triangular shape may be analogously obtained with respect to equations of C_v for rectangular, and parabolic shapes, predicted by the author, as follows;

1. for rectangular broad-crested weir; the energy equation is,

$$y^3 - H_o y^2 + \frac{y_c^3}{2C_v^2} = 0. \text{ Hence,} \tag{10}$$

$$C_v = (\frac{3}{2})^{3/4} (\frac{y_c}{H_o})^{3/4}, \tag{11}$$

and $$C_d = 0.57735\, C_v^2. \tag{12}$$

2. for parabolic broad-crested weir; the energy equation is,

$$y^4 - H_o y^3 + \frac{y_c^4}{3C_v^2} = 0. \text{ Hence,} \tag{13}$$

$$C_v = (\frac{4}{3})^{4/4} (\frac{y_c}{H_o})^{4/4}, \tag{14}$$

and $$C_d = 0.55111\, C_v^2. \tag{15}$$

By analogy, for triangular broad-crested weir,

$$C_v = (\frac{5}{4})^{5/4} (\frac{Y_c}{H_o})^{5/4}, \tag{16}$$

and $$C_d = 0.53666\, C_v^2. \tag{17}$$

Substituting for C_v and C_d from Eqs (16), and (17) in Eq (9) we get;

$$(\frac{y}{H_o})^{1.6} (1 - \frac{y}{H_o})^{0.4} = = 0.4595\, (\frac{y_c}{H_o}). \tag{18}$$

Solving Eq. (18), using trial and error technique, the depth of flow over weir, y, can be calculated. To facilitate calculations, Eq (18) is represented by the curve shown in Figure (2). substituting for y_c from Eq (6) in Eq. (18), yields,

$$Q = 4.941\, \sqrt{g} (\frac{y}{H_o})^4 (1 - \frac{y}{H_o}) (\tan \frac{\theta}{2}) H_o^{2.5}, \tag{19}$$

and hence,

$$Q = 4.941\, \sqrt{g} (\frac{y}{H})^4 (1 - \frac{y}{H}) (\tan \frac{\theta}{2}) H^{2.5}. \tag{20}$$

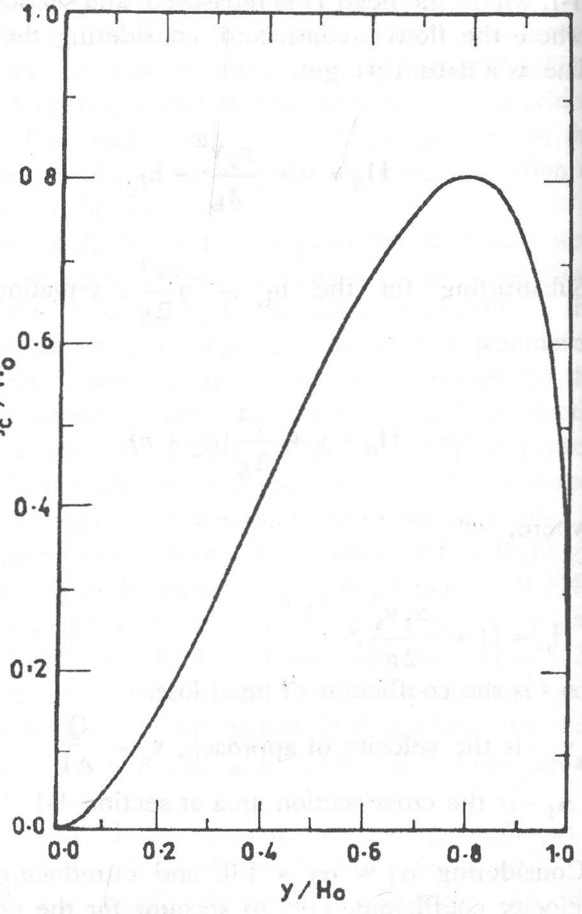

Figure 2. Relation between y/H_o and y_c/H_o.

Equation (20) is considered depth - discharge equation since it depends on the direct measured values of H, and y. For various notch angle, θ, Eq. (20) is plotted in Figure (3). The figure shows that, the flow has two depths for the same discharge. The first is the depth of free flow since it is lesser than the critical depth. The second, is higher than y_c, indicates the depth of submerged flow. The depth of free flow, y, has a maximum value when, $y = y_c = 0.8$ H ($C_v = 1.0$) or just before submergence. correlating Eqs. (6) and (16) with each others, results discharge equation over the weir in the form,

$$Q = (\frac{4}{5})^{5/2} (\frac{g}{2})^{1/2} (\tan \frac{\theta}{2}) C_v^2 H_o^{2.5}, \quad (21)$$

or

$$Q = 1.26778 (\tan \frac{\theta}{2}) C_v^2 H_o^{2.5}. \quad (22)$$

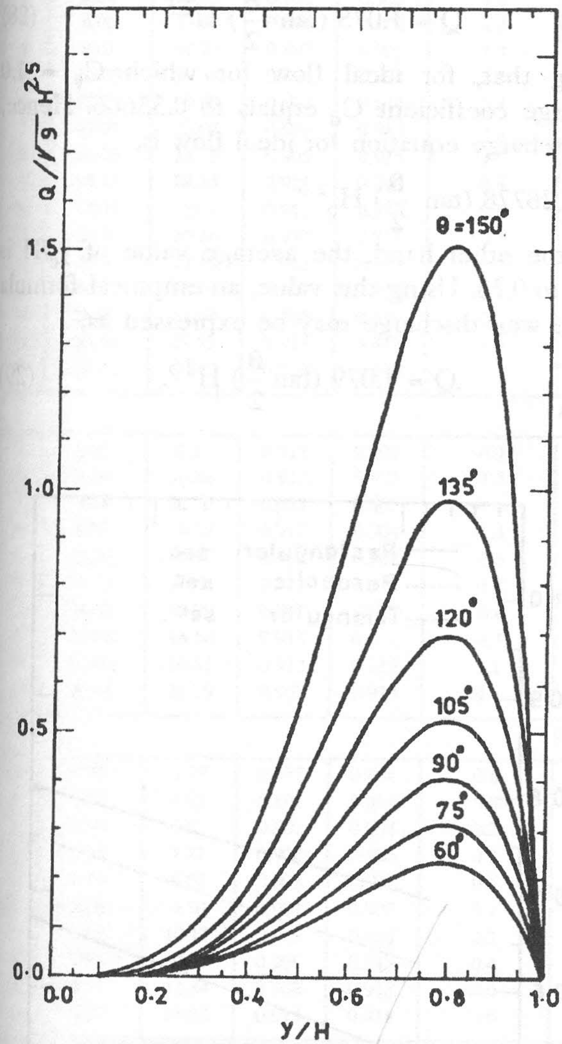

Figure 3. Head-Discharge relationship.

substituting for C from Eq (17) in Eq (22), discharge equation in terms of discharge coefficient C_d may be expressed as,

$$Q = 2.3624 C_d (\tan \frac{\theta}{2}) H_o^{5/2}. \quad (23)$$

Brink depth equation for triangular broad crested weir can also be analogously predicted with respect to brink depth equations, derived by the author (8,9), for rectangular, and parabolic broad crested weir. Thus,

$$\frac{y_b}{y_c} = \frac{2}{3} \sqrt[3]{\frac{1}{C_v^2}}, \quad (24)$$

for rectangular cross section,

$$\frac{y_b}{y_c} = \frac{3}{4} \sqrt[4]{\frac{1}{C_v^2}}, \quad (25)$$

for parabolic cross section, and hence, by analogy, for triangular cross section,

$$\frac{y_b}{y_c} = \frac{4}{5} \sqrt[5]{\frac{1}{C_v^2}}. \quad (26)$$

3 - EXPERIMENTAL PROGRAM

Experiments were conducted in horizontal rectangular channel, 9.0 m long, 0.395 m wide. The channel was fabricated from perespex sheets supported by a steel frame. Three wooden and coated models for the triangular broad crested weir were inserted into the channel. The first model has crest length L = 60 cm, and notch angle $\theta = 60°$. The second model has L = 60 cm and $\theta = 90°$, while the third model has L = 40 cm and $\theta = 120°$. Models were installed in the channel with apex height, P = 10.50 cm above the channel bed.

Different discharges were allowed to pass over each weir model covering a range of L/H from 2.0 to 12. For each discharge, head on weir H, contracted depth y, and brink depth y_b were measured, with respect to the center line (apex line), by point gauge. Discharges were measured by V-notch weir.

4 - RESULTS AND DISCUSSION

Results of the experimental tests were used to verify predicted equations for depth of flow over the weir, velocity coefficient C_v, depth-discharge equation, and the brink depth.

4.1. Depth of flow over the weir

Results showed that the ratio y_c/H_o has minimum value equals 0.725, for free flow condition. Hence values of $y_c/H_o > 0.725$ were used in Eq (18) to calculate depth of flow y. calculated values of y were compared to measured ones. Good agreement is obtained with maximum deviation of 1.5 %, as shown in Table (1).

4.2. Velocity coefficient C_v

Experimental values of C_v were obtained by substituting for the measured values of H, and y in Eq (5), which is expressed as,

$$C = \frac{y_c^{2.5}}{2y^2\sqrt{H_o - y}}. \tag{27}$$

Theoretical values of C_v were calculated using values of $y_c/H_o > 0.725$ in Eq (16). Comparison between experimental and theoretical values of C_v indicates good agreement with maximum deviation of 1.6 %, as shown in Table (1).

Free flow condition over broad crested weir with exponential sections; rectangular, parabolic, and triangular, has minimum values of the ratio y_c/H_o, which are, 0.53, 0.65, and 0.725. This corresponds to minimum C_v values as, 0.84, 0.86, and 0.88, respectively.

Comparative graphics describing the relations, $C_v - (\frac{y_c}{H_o})$ and $C_v - C_d$, for broad crested weir with exponential sections, are shown in Figure (4), and (5), respectively.

4.3. Depth-Discharge Equations

Depth - discharge relationship expressed by Eq. (20) is verified using the measured values of H, and y. Resulting discharges are in very close to measured discharges with maximum deviation of ±3.0 % as shown in Table (1).

As mentioned in Ref. [7], for values of L/H from 2.5 to 7.0, characteristic discharge coefficient has constant value 0.948, and 0.957 for $\theta = 90°$, and 120°, respectively. This indicates that notch angle θ has a negligible effect on the discharge coefficient. Hence, in the present study, the average experimental value of the discharge coefficient, C_d which is 0.455 can be used to give a weir coefficient equals 1.075. Hence,

$$Q = 1.075 \left(\tan \frac{\theta}{2}\right) H^{2.5}. \tag{28}$$

Noting that, for ideal flow for which $C_v = 1.0$ discharge coefficient C_d equals to 0.53666. Hence, the discharge equation for ideal flow is,

$$Q = 1.26778 \left(\tan \frac{\theta}{2}\right) H_o^{2.5}.$$

On the other hand, the average value of y_c/H is equal to 0.75. Using this value, an empirical formula for the weir discharge may be expressed as,

$$Q = 1.079 \left(\tan \frac{\theta}{2}\right) H^{2.5}. \tag{29}$$

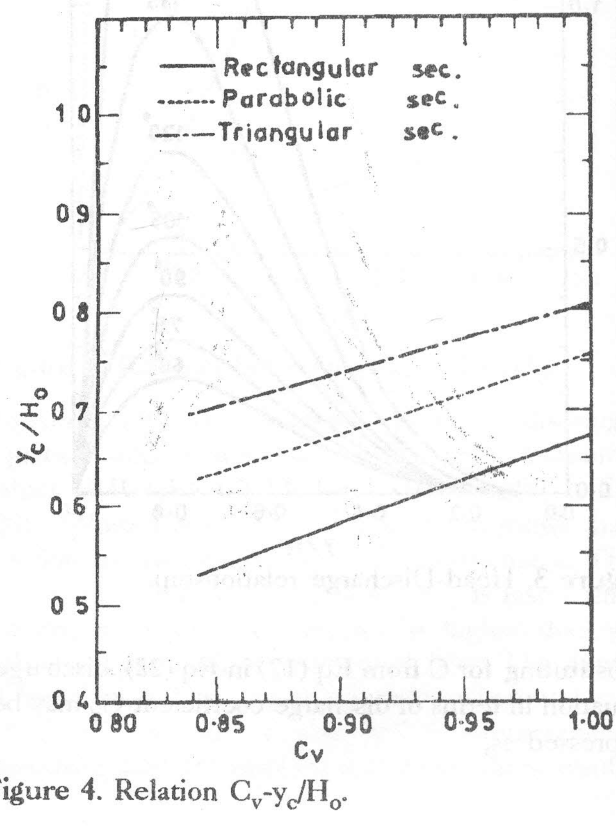

Figure 4. Relation C_v-y_c/H_o.

Table 1. Experimental measurements and verification of the theoretical equations for, y, C_v, y_b, and Q.

No	Q,meas ℓ/sec.	H, cm	values of C_v			values of y, cm.			values of y_b, cm.			values of Q, l/sec.	
			Exp.	theo. Eq. (16)	% dev.	meas.	Cal., Eq (18)	% dev.	meas	Cal. Eq (26)	% dev.	Q_{cal} Eq (20)	% dev.
1	2	3	4	5	6	7	8	9	10	11	12	13	14
θ= 60°, and L = 60 cm													
1	2.04	10.31	0.893	0.903	1.1	7.0	6.92	-1.1	6.04	6.33	4.8	2.08	2.0
2	4.04	13.53	0.892	0.905	1.5	9.25	9.11	-1.5	7.95	8.33	4.8	4.16	3.0
3	6.06	15.85	0.896	0.908	1.3	10.68	10.71	-1.4	9.33	9.77	4.7	6.20	2.3
4	8.01	17.73	0.897	0.907	1.1	12.12	11.98	-1.2	10.45	10.93	4.5	8.17	2.0
5	10.03	19.38	0.895	0.908	1.5	13.31	13.11	-1.5	11.48	11.96	4.2	10.29	2.6
6	12.13	20.80	0.904	0.914	1.1	14.34	14.18	-1.1	12.35	12.87	4.2	12.36	1.9
7	14.02	22.05	0.903	0.913	1.1	15.19	15.01	-1.2	13.06	13.64	4.4	14.28	1.9
8	16.08	23.25	0.905	0.915	1.1	16.05	15.87	-1.1	13.80	14.4	4.3	16.04	-0.3
9	18.11	24.35	0.911	0.916	0.8	16.74	16.65	-0.5	14.48	15.10	4.3	18.06	-0.3
10	20.07	25.3	0.911	0.918	0.8	17.51	17.36	-0.9	15.0	15.71	4.7	20.31	1.2
11	22.0	26.26	0.910	0.917	0.7	18.15	18.0	-0.8	15.70	16.31	3.9	22.24	1.1
12	24.1	27.19	0.913	0.919	0.0	18.80	18.68	-1.0	16.30	16.90	3.7	24.28	0.8
13	26.10	28.07	0.918	0.918	0.3	19.26	19.27	0.0	16.76	17.45	4.1	25.93	-0.7
14	28.06	28.68	0.916	0.919	0.0	19.91	19.85	-0.3	17.22	17.96	4.3	28.07	0.0
15	30.10	29.72	0.917	0.917	0.0	20.41	20.41	0.0	17.76	18.48	4.4	29.93	-0.6
16	32.12	30.47	0.918	0.918		20.95	20.95	0.0	18.20	18.97	4.2	31.93	-0.6
θ= 190°, and L = 60 cm													
1	2.02	8.23	0.912	0.906	-0.7	5.5	5.54	0.7	4.83	5.06	4.8	1.99	-1.5
2	4.04	10.88	0.917	0.903	-1.5	7.2	7.31	1.5	6.40	6.69	4.5	3.92	-3.0
3	6.06	12.73	0.922	0.907	-1.6	8.47	8.60	1.5	7.53	7.85	4.2	5.87	-3.0
4	8.01	14.27	0.917	0.904	-1.4	9.47	9.61	1.5	8.40	8.79	4.6	7.77	-3.0
5	10.03	15.55	0.921	0.907	-1.5	10.38	10.53	1.5	9.15	9.61	5.0	9.74	-3.0
6	12.03	16.65	0.923	0.912	-1.2	11.2	11.34	1.3	9.90	10.31	4.1	11.73	-2.5
7	14.02	17.70	0.917	0.91	-0.8	11.96	12.05	0.8	10.49	10.97	4.6	13.79	-1.6
8	16.08	18.66	0.913	0.912	-1.1	12.71	12.73	0.2	11.08	11.57	4.4	15.98	-0.6
9	18.06	19.51	0.912	0.913	1.1	13.37	13.34	-0.2	11.62	12.12	4.3	18.06	0.0
10	20.04	20.29	0.907	0.915	0.9	14.06	13.92	-1.0	12.11	12.62	4.2	20.32	1.4
θ = 120°, and L = 40 cm													
1	0.50	3.85	0.877	0.884	0.8	2.55	2.35	-0.8	2.22	2.34	5.5	0.507	1.4
2	1.00	5.03	0.891	0.898	0.8	3.38	3.36	-0.6	2.94	3.8	4.8	1.02	2.0
3	2.02	6.61	0.902	0.904	0.2	4.46	4.45	-0.2	3.87	4.06	4.9	2.03	0.57
4	3.04	7.77	0.904	0.906	0.2	5.25	5.24	-0.2	4.54	7.79	5.5	3.05	0.3
5	4.04	8.69	0.903	0.907	0.4	5.90	5.87	-0.5	5.13	5.36	4.5	4.07	0.7
6	5.05	9.50	0.901	0.907	0.7	6.46	6.42	-0.6	5.58	5.86	5.0	5.10	1.0
7	6.06	10.17	0.910	0.912	0.2	6.94	6.92	-0.3	6.03	6.29	4.3	6.09	0.5
8	7.03	10.77	0.909	0.913	0.4	7.38	7.34	0.5	6.40	6.67	4.2	7.08	0.7
9	8.01	11.34	0.908	0.913	0.6	7.79	7.74	-0.6	6.73	7.03	4.5	8.09	1.0
10	9.00	11.83	0.913	0.918	0.6	8.15	8.11	-0.5	7.05	7.34	4.1	9.04	0.4

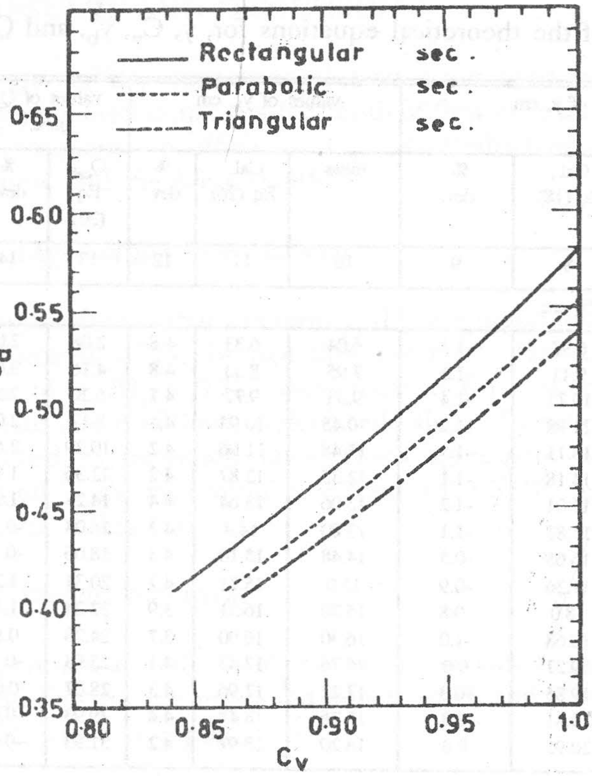

Figure 5. Relation C_v-C_d.

where, in Eqs. (28), and (29), Q is in m^3/sec and H is in meters.

4.4. Brink depth

As for the brink depth, Eq. (26) is verified. The values of C_v are calculated using Eq. (16) and substituted in Eq. (26) to calculate the brink depth, y_b. Calculated values are compared to measured values. As shown in Table (1), good agreement exists with deviation of 5.5%. The average experimental value for the brink depth ratio y_b/y_c, is found to be 0.7954 which is in complete agreement with value obtained by Rajaratnam, and Muralidhar [13].

Figure (6) depicts values of brink depth ratio, calculated using the momentum [12,13] and energy equations, for rectangular, parabolic, and triangular shapes of a broad crested weir. Neglecting energy loss in the energy equation, i.e, C_v = 1.0, the ratio y_b /y_c equals 0.8, which is very close to both experimental value (0.7954), and theoretical value obtained by Replogle (0.7943). Figure (6) indicates the discrepancy in values of y_b /y_c obtained by Replogle (12) and Rajaratnam (13) for values of k>0. This is referred to difference in assumptions made by each one through applying the momentum equation.

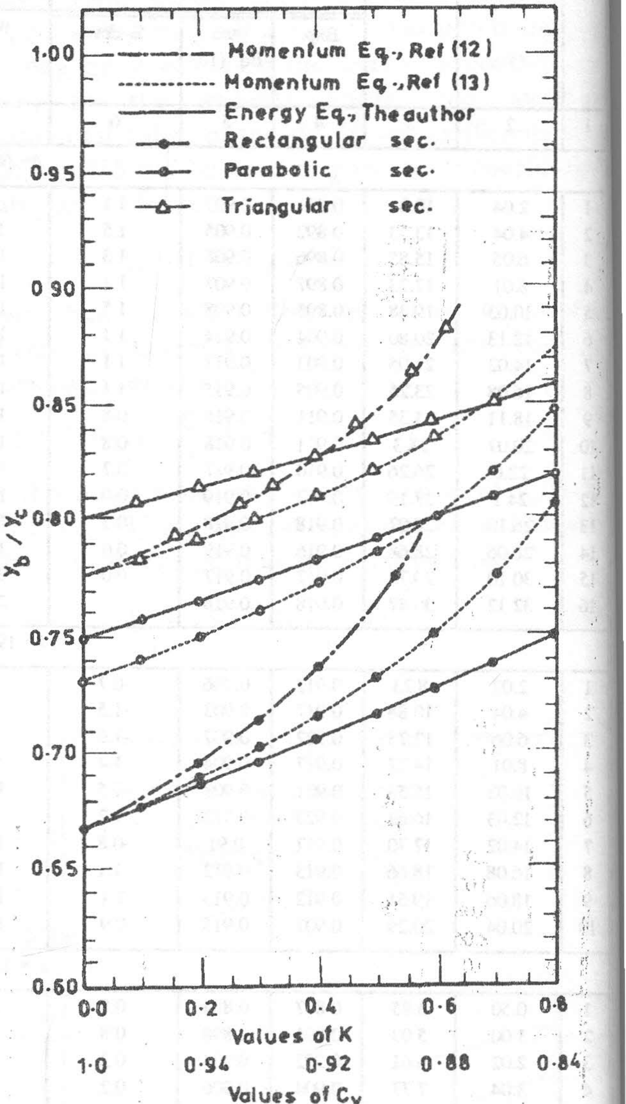

Figure 6. Comparison between the energy and momentum equations for evaluating y_b/y_c.

Table (2) shows a comparison between the theoretical values of the brink depth ratio, y_b, y_c, obtained using momentum (k = 0), free vortex, and energy (C_v=1.0) equations. In case of parabolic, and triangular cross sections, it is clear that the values of y_b/y_c, obtained by the energy equation, are very close to y_b/y_c values using the free vortex theory.

Table 2. Comparison between theoretical values of the brink depth ratio, y_b/y_c, obtained using momentum, free vortex, and energy equations.

Weir Cross section	Momentum Eq. (k=o) Rf. (10, 12,13)	Free vortex Theory Rf. (14)	Energy Eq. (C_v =1), The author
Rectangular	0.667	0.673	0.667
Parabolic	0.731	0.747	0.750
Triangular	0.775	0.798	0.800

5 - CONCLUSION

As a result of the present study, theoretical equations and charts are developed to be applied in the following aspects:

1. Evaluation of velocity coefficient, C_v, in terms of critical depth and total head on weir, Eq. (16).
2. Evaluation of discharge coefficients, C_d, as a function of velocity coefficient, Eq. (17).
3. Evaluation of flow depth over the weir, Eq (18), or chart in Figure (2).
4. Estimation of weir discharge in terms of head on the weir, and flow depth at the control section, Eq (20), or chart in Figure (3)
5. Evaluation of the brink depth ratio, Eq (26).

According to the analysis of the experimental data, the following could be concluded:

1. The measured brink depth ratio has an average value equals 0.7954.
2. The notch angle θ has a negligible effect on the discharge coefficients C_d.
3. The discharge coefficient C_d has an average experimental value equals 0.455.
4. Eq. (29) is recommended for discharges measurement.

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