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EXPERIMENTAL VERIFICATION AND REVIEW PERFORMANCE OF THE MODIFIED TRIANGULAR PLAN FORM WEIR

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ABSTRACT

Weirs are discharge measurement structures have different geometrical shapes. The performances of the modified triangular plan form weirs were studied under free-flow condition. Three groups of weirs were tested experimentally. The first group has a flat top; the second has one slope and the third has two slopes. Each group has three vertex angles (60^o, 90^o and 120^o) with constant height. The hydraulic performances of weirs are based on the ability to pass the discharge for certain head flow and on the value of the coefficient of discharge. The values of discharge and the coefficient were compared with earlier studies being carried on conventional normal weir, broad crest, triangular plan-form and different labyrinth weirs. All the groups show better performance than conventional shaped and broad weir. The magnification of the actual discharge to the discharge of broad crested weir is more than one and the best one is the first in the third group, while the vertex angle is (60^o) for the second and third group and (120^o) for the first. The performance of the third group is better than rectangular labyrinth weirs, and it is compatible with the triangular labyrinth. The discharge coefficient decreases with the increase of relative value of the head to the height of weir except for the first group. Equations for predicting coefficient of discharge are proposed within the limitations of this test.

KEYWORDS: Discharge coefficient; Flow efficiency; Free-flow condition; Semi-piano weir; Triangular plan-form weir.

1. INTRODUCTION

During the nineteenth century, engineers concentrated on gauging stream based on weir structures (George Rafter (1900)). From that time a very wide range of investigations has been done on finding empirical formulas predicting the discharge in streams. Studies and practices headed on the performance of weirs related to its geometry. Geometric modifications are concentrated on height, length, edge, crest length, openings, grooves and vanes to increase weir efficiency. Based on result of eighteen earlier studies for predicting discharge coefficient for finite broad crested weir, Azimi and Rajaratnam (2009) were able to re-correlate these results using the critical state flow of parallel streamlines to introduce a new correlation curves for discharge coefficient (Cd). The eighteen used studies for re-correlation were as early as Bazin to Johnson (2000). The new correlation confirms the weir lengths into four classes. The proposed correlation for narrow weir was compared with the present study for

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the first model of a flat surface triangle weir. Ehsan Goodarzi et. al (2012) improved the flow over rectangular broad crested weirs by adding a sloping ramp in the upstream with different slopes from (90º) to (10º). The sloping face affects the surface flow profile, decreasing the separation zone and increasing discharge coefficient values by 18%. Jamidar Farid et. al (2015) compared stage-discharge relation of three labyrinth weirs triangular, trapezoidal and curved plan-form shapes and the best performance has the curved weir. A crested edge weir has different upstream face slopes has been studied experimentally by Jalil and Sarhan (2017), which show that the addition of slope to the upstream face of sharp crested weir increase the efficiency 20%. Bijankhan and Kouchakzadeh (2017) experimentally and theoretically studied of the triangular plan labyrinth weir for both free and submerged flow conditions. They proposed discharge coefficient equation, which can be used for both free and submerged flow conditions continuously and within the transition zone. Sayedeh Zahra et.al. (2018) improved the performance of sharp-crested rectangular plan form weirs by installing four guide vanes which they cause an increment the discharge coefficient up to 18%. Sayedeh Zahra et.al also detailed the efficiency of the triangular plan-form concentrated on installation guide vanes in the triangular duckbill weir, the results show its effectiveness when the vertex angle is (45^o). Simulation study on trapezoidal labyrinth of sidewall angle (15^o), the study indicated that there are no reasonable differences in adapting Renormalization Group turbulence model (RNG) or Large eddy simulation (LES) turbulence models, and there is an agreement within 3% to 7% with the physical modeling Crookston et. al. (2012). Al-dabbagh numerically investigated triangular broad-crested weirs under different flow conditions. Angles of triangular changed four times as: 90^o, 100^o, 110^o and 120^o. Comparison between the rectangular broad crested weirs and the effect of opening angle of weirs is investigated. The analysis of simulation showed that the upstream water level of the weir is inversely proportional to the opening angle, where an increment of (10^o) in the opening angle leads to a drop in water level about 1.5 cm. In addition, applying a discharge of 0.012 m^3s^{-1}, an uncovered region with water is created for the downstream triangular broad-crested weirs, while the bed downstream of the rectangular broad-crested weir is covered with a thin layer of water at the same flow discharge.

All weir types are important structures for the measuring discharge, so that a very wide range of geometric modification has been investigated. However, in the present study, an experimental work on three modified geometrically types of triangular plan form weirs are compared to some of those weirs which have been described in the literature.

2. BACKGROUND EXPERIMENTAL WORK

The empirical formulas for estimating discharge over different weir shapes are based on the theory of mass and energy conservation. Many of basic and fundamental literatures such as Rouse, Chow, Handerson, Bosand Subrahmanya stated the derivation of the flow equation over weir for the weir crest length equal to the channel width (B) as formulated in Eq. (1).

$$Q_{th} = \frac{2}{3}\sqrt{2g}BH_T{}^{3/2} \qquad (1)$$

Where: Q_{th} = the theoretical discharge (L^3T^{-1}), B= width of the channel (L), H_T= total head, $H_T = h + V^2/2g$ (L), h = head of water above the weir crest (L), V= velocity of the flow upstream (LT^{-1}) and g= gravitational acceleration (LT^{-2}). The actual discharge value depends on many factors which are presented in discharge coefficient. The discharge coefficient can be

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expressed as (Cd_B) when the weir crest length is equal to channel width, and expressed as (Cd_L) when the crest is longer than the channel width, such as in a labyrinth and oblique weir, as formulated in Eqs. (2) and (3).

$$Q_{act} = Cd_B \frac{2}{3}\sqrt{2g}BH_T^{\frac{3}{2}} \qquad (2)$$

$$Q_{act} = Cd_L \frac{2}{3}\sqrt{2g}L_T H_T^{\frac{3}{2}} \qquad (3)$$

Where: Q_{act} = the actual discharge (L^3T^{-1}), L_T= the total crest length. For practical purposes the measured depth of the water over the weir crest (h) can be used instead of the total head (H_T) and that will be reflected on the value of the discharge coefficient. The definition sketch of the figure (1) shows the depth of flow and dimensions of the modified weir.

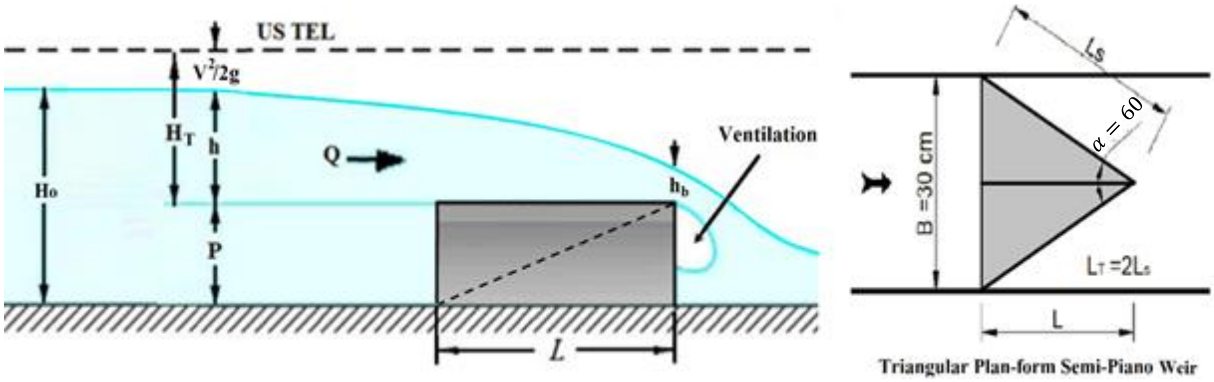

Fig. (1): Definition sketch

The modified weirs mixed with different shapes well-known conventional weirs. The major parameters affecting on the discharge coefficient of broad crested weir are the head (h), weir height (P) and the length in the direction of flow in the middle (L) (Ramamurthy et al. (1988)). The vertex angle (α), the brink depth (h_b) and the total flow depth upstream (H_o = P + h) are other additional parameters that affect the flow in labyrinth weirs (Bijankhan and Kouchakzadeh (2017), Crookston et. al. (2012) and Azza (2010)). The functional relationship of the coefficient discharge is presented in Eq. (4).

$$Cd = f\left(\alpha, \frac{h}{P}, \frac{h_b}{h}, \frac{h_b}{H_o}\right) \qquad (4)$$

All experiments were carried out in a rectangular horizontal flume having a length 5m, width 0.3m with a regular cross section and a depth of 0.45m in the hydraulic laboratory of the College of Engineering at the University of Duhok. Three plastic modified geometry weir groups with constant height (15cm) were tested during the testing program. Each group included three models with different vertex angles (60°, 90°, and 120°). All the models were triangular plan-form weir, but each group has a different top surface, where the first has a flat top surface, the second has one slope as a piano weir, and the third one has two slopes as a semi-piano, as shown in figure (2) and table (1). Water surface profiles were measured along the center line via point gauge with accuracy 0.1 mm.

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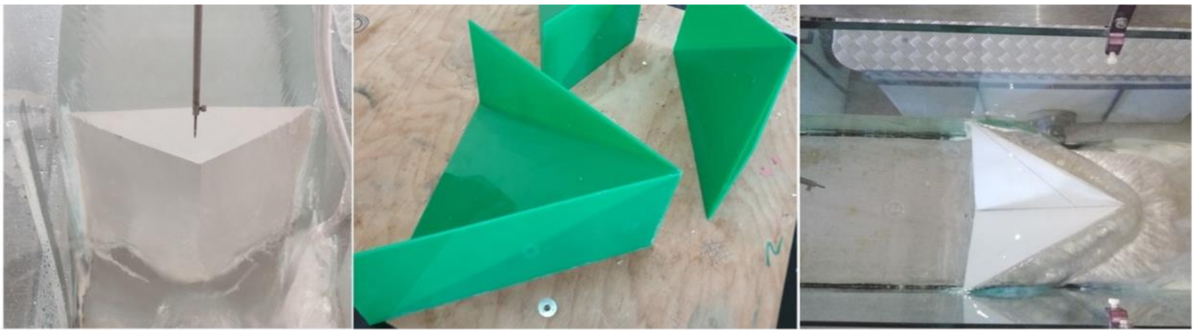

(a) Triangular plan form flat top weir **(b)** Triangular plan form piano weir **(c)**Triangular plan form semi piano weir

Fig. (2): Three groups of triangular plan form weir

Table (1): Models description

Mole	name	Height (P) cm	Vertex angle (α)	Top surface description
1	Triangular plan form flat top weir	15	60^o, 90^o, 120^o	Flat leveled
2	Triangular plan form pianoweir			One slope towards vertex angle
3	Triangular plan form semi-piano weir			Two side slopes towards vertex angle

3. RESULTS AND DISCUSSION

Geometric modification on broad crested improves its performance, such as the improvement via rounding upstream weir nose, Ramamurthy et al. (1988) show that the effectiveness of the rounding appears when the ratio of upstream top corner radius (R) to the weir height (P) is more than 0.094, causing an increase in the value of the coefficient of discharge. The rounded upstream top corner is also showing that the flow is not controlled by separation, and the pressure remain in hydrostatic distribution when (H_o/L) is <0.5 (Castro and Ayuso (2010)). The experimental data collected for the modified weir geometry in the present study are presented in figure 3 (a and b), showing that all three modified weirs perform better than the conventional broad crested weir of Subramanya (2009), also it can be noted that the triangular plan form semi-piano weir performs better than the two other weirs. This related to the two slopes operating to direct the flow to fall freely from weir edge.

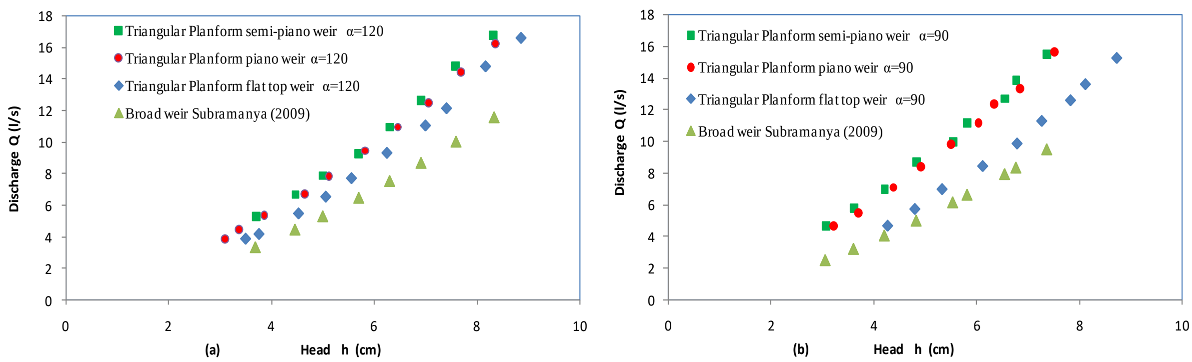

Fig. (3): Comparison between modified weirs and conventional broad weir

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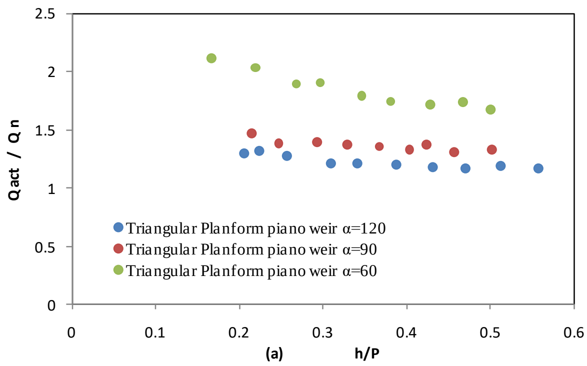
This related to the two slopes operating to direct the flow to fall freely from weir edge.

The efficiency of weirs was examined by the ratio of discharges (Q_{act}/Q_n), the actual discharge of proposed weirs to discharge of normal weir of the same head (h) and height (P). Figure (4a) shows the value of (Q_{act}/Q_n) decreases with increase of (h/P) which related to the interference of the jets. The efficiency is more than one for all models. The best vertex angle is (60^o) for the triangular plan form piano weir and triangular plan form semi piano weirs models. The comparison is carried out with the results of Kumar et.al. (2011),who studied the efficiency of the sharp-crested triangular plan form weirs. The discharge efficiency of the weir decreases with the increase of the vertex angle and also with the increase of (h/p), and this agrees with the two models having a sharp breath crest as presented in figure (4b). The predicted value of (Cd_L) from Kumar is higher than the values of the two models by 18% to 13%, while a comparison with Noori and Aaref (2017) show that an advantage of the rounded crested triangular plan form weirs is between 5% to 3%. The sharp crested curved plan form weirs were tested also by Kumar et al. (2013) showing higher values for (Cd), while Gupta et.al. (2013) studies of the triangular plan from weirs and the proposed empirical equations for the predicting discharge coefficient, showed a little bit lower value than what have been reached in this present study as shown in figure (4b).



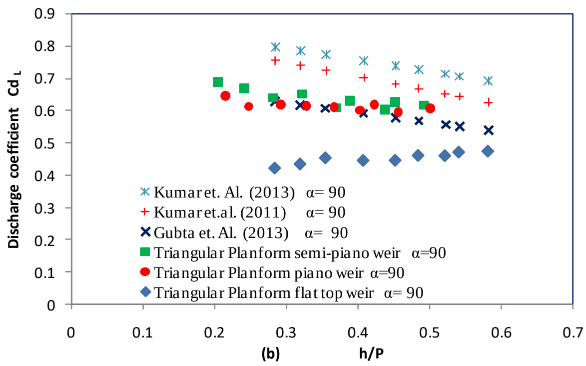


Fig. (4): Variation of efficiency (Q_{act}/Q_n) and (Cd_B)with (h/P)

Azza (2010) investigated two types of triangular end lip broad crested weirs, and the study proposed empirical discharge equations based on the normal and the brink depths of flow on the weirs. He introduced a curve representing the relation between the ratio of the brink depth to the critical depth (h_b/Y_c) and discharge coefficient (Cd_B). Comparison was made with the results of Azza of brink depth at the center line of the weirs which presented in figure (5a). It can be noted that the ratio of the brink depth to the critical depth is higher for the piano and semi-piano weirs than noted by Azza for broad crested weir; it is believed that the differences are related to the long flat top surface with end lip.

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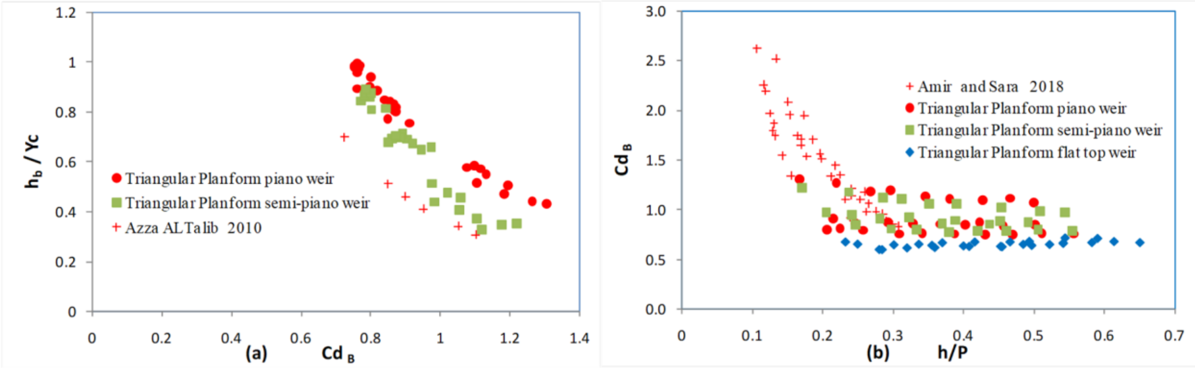

Fig. (5): Variation of discharge coefficient with (h_b/Y_c) and (h/P) for three vertex angles

Amir and Sara (2018) investigated the performance and the flow properties over rectangular labyrinth weirs of one circle, and the study included free and submerged conditions. The discharge coefficients of weir found declining with the increase of the discharge and the relative length ratio (L_T/B), furthermore, Amir and Sara suggested two empirical equations to predict the value of the discharge; one based on the channel width (Cd_B), and the second based on the crest length (Cd_L). It could be seen that within the range of (h/P > 0.2) there is a reasonable matching as show in figure (5b), and even there is a performance advantage for the triangular plan form piano and the triangular plan form semi-piano weirs.

The coefficient of discharge based on crest length (Cd_L) is compared with the study of Shaghaghian and Sharifi (2015), which simulated the flow over a triangular plane sharp weir of vertex angle (90°). The study concentrated on the relation between the cell size and the discharge error percentage, and it suggested an equation for predicting the value of (Cd_L) also a drawing of variation with (h/P). Plotting the calculated (Cd_L) values of the present study on the figure (6a) showed that the triangular plan labyrinth weir has higher average values of the (Cd_L) and compared with the modification in the geometry of the triangular plan form semi-piano and the triangular plan form piano weirs by 9% and 14% respectively.

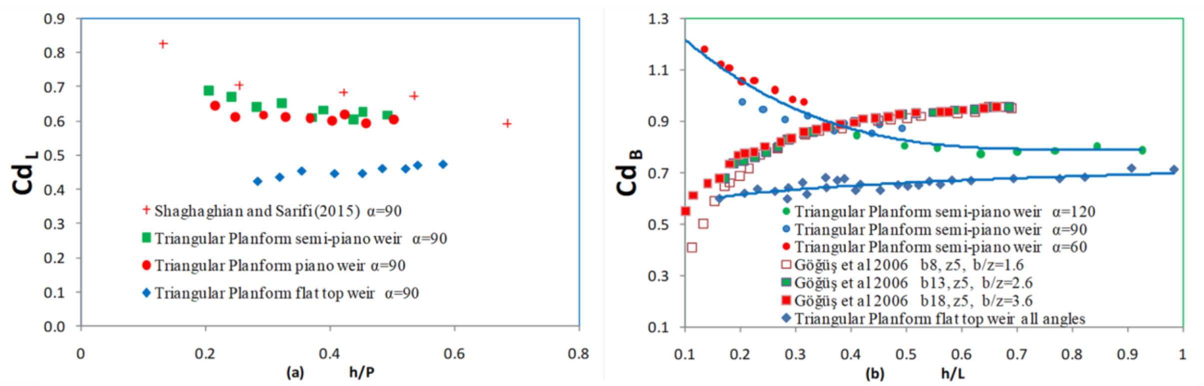

Fig. (6): Variation between (Cd_L) and (Cd_B) with (h/P) and (h/L)

The results also compared with the modified conventional broad weir, Göğüşet al. (2006) performed in a laboratory experiments to study a modified compound broad weir. The modification has done by lowering the weir crest step and changing the groove width and depth. The results of Göğüş et al. showed that the discharge coefficient increased as the groove weir

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crest width increases for low flow heads while there is no effect for the step height on the value of (Cd_B). Figure (6b) views the comparison which shows the increasing value of (Cd_B) for the triangular plan form flat top weir as the head length ratio increases and so for the groove weir of Göğüş, and the advantage is for the groove weir of Göğüş in the case, while the triangular plan form semi-piano weir performs in the opposite way, the value of (Cd_B) decreases with the increase of the head length ratio, and it has an advantage over the groove for the values (h/L< 0.35).

A study for evaluating coefficient of discharge for flat topped and sharp-crested weirs were based on experimental data and on the conventional weir discharge equation has been carried on by Michael Johnson (2000). The study summarized the effect of crest length into two curves includes all the examined models. The first curve presents flat top weir, while the second curve for the sharp-crested weir. A comparison has carried out and presented in the figure (7a) which indicates the triangular plan form flat top weir of this presented study. The performance of this modified weir is a little bit better than finite flat top weir by 28%, 16% and 12% depending on the vertex angle for (H_t/L<1.5). The comparison of the other two models with shape-crested also shows a higher performance as in figure (7b).

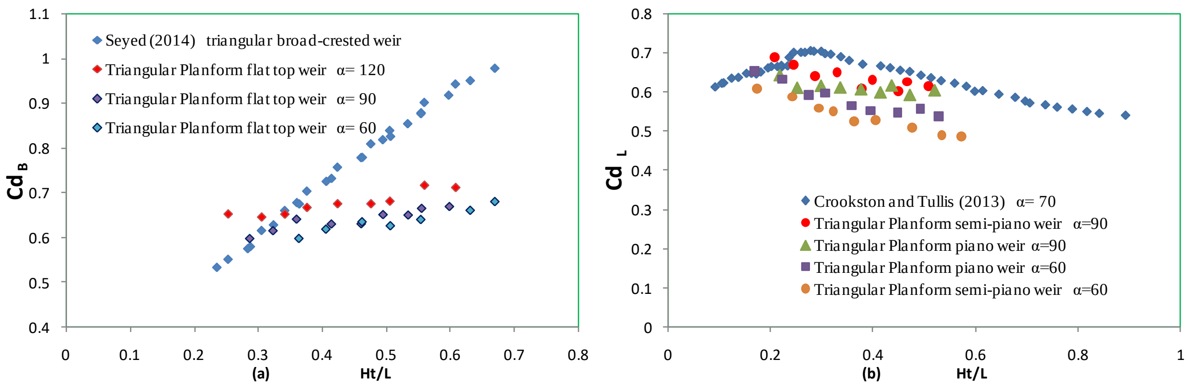

Fig. (7): Variation of discharge coefficient (Cd_B) with (Ht/L) and (Ht/P)

Seyed Hoseini (2014) tested the flow over triangular broad-crested experimentally and made a comparison with Bos (1976) results, in which it was found that dimensionless parameters of (H_t/L) and Froude's number are the two parameters effecting the coefficient of discharge. The study suggested empirical equation for predicting the value of (Cd_B). As this weir has a geometrical shape nearly as the broad weir, therefore a comparison can be experimented with the triangular planform flat top weir being of presented in this study. Figure (8a) shows that for the values of (H_t/L<0.35), and the triangular plan-form flat top weir in the presented study performs is a little bit better.

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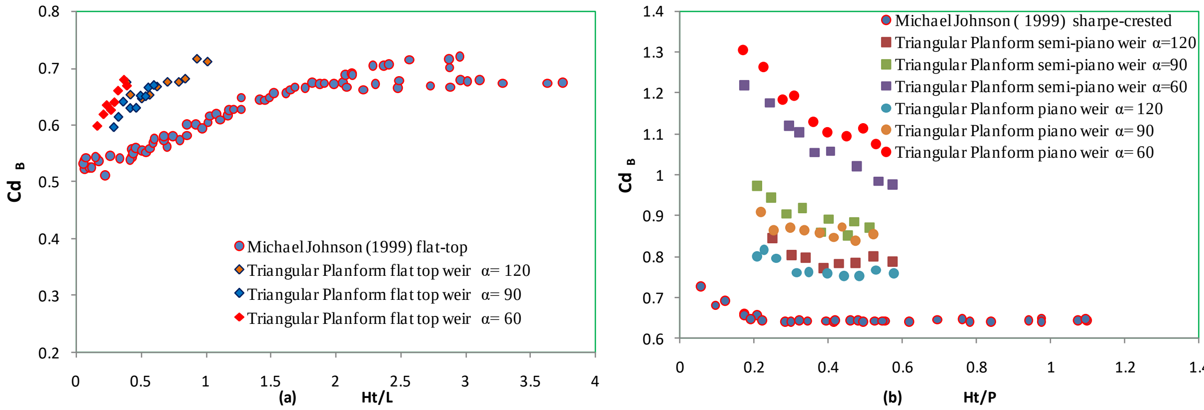

Fig. (8): Comparison (Cd_B) and (Cd_L)Values with Seyed (2014) and Crookston and Tullis (2013)

Crookston and Tullis (2013) investigated labyrinth weirs experimentally to find the discharge coefficient for quarter-round crest and half-round for different side wall angles. Also discussing the effect of geometric parameters and nappe effects on the weir performance; moreover, several curves for the value of (Cd_L) are presented for several side wall angles. One of these curves is adapted to compare the values of (Cd_L) with the present study values for the triangular plan form piano and the triangular plan form semi-piano weirs as shown in figure (8b). It can be noted that values of (Cd_L) for both geometric shapes are less than that the value of the labyrinth weirs by 8.6% and 6.1% for triangular plan form semi-piano weir and triangular plan form piano weir respectively.

Pearson correlation factor shows that the highest significant correlations at the 0.01 level (2-tailed) between (Cd_B) are variables (h/P) and vertex angle (α) in radians, with values (-0.957 and -0.841). The coefficient of discharge related to the total crest length (Cd_L) also shows high correlations with the same factors especially in each of the weir group. As the output of the linear regression is a simple mathematical model, therefore, it was adopted leading to acceptable relations listed in the equations (5) to (12), with their coefficient of determination. Eq. (5) is generated to relationship mode for (Cd_B), Eq. (6) (Cd_L) for all groups as shown below:

$$\mathrm{Cd_B} = 2.2.185 - 0.051\alpha_{\mathrm{rad}} - 0.100\frac{\mathrm{h}}{\mathrm{P}} - 1.220\frac{\mathrm{h}}{\mathrm{Y_c}} \ldots\ \mathrm{R^2} = 0.983 \qquad (5)$$

$$\mathrm{Cd_L} = 0.88 + 0.247\alpha_{\mathrm{rad}} - 0.057\frac{\mathrm{h}}{\mathrm{P}} - 0.573\frac{\mathrm{h}}{\mathrm{Y_c}} \ldots\ \mathrm{R^2} = 0.983 \qquad (6)$$

The regression of the utilized input data for triangular plan form flat top weir generated two equations for each type of the discharge coefficient as listed in Eqs. (7) and (8).

$$Cd_B = 0.601 + 0.053\alpha_{rad} + 0.853\frac{h}{P} - 0.022\frac{h_b}{h} - 1.322\frac{h_b}{Ho} \ldots\ R^2 = 0.909 \qquad (7)$$

$$Cd_L = -0.019 + 0.265\alpha_{rad} + 0.129\frac{h}{P} \ldots\ldots\ldots.\ldots\ R^2 = 0.994 \qquad (8)$$

The regression models for the triangular plan form piano weir is listed in Eqs. (9) and (10), with their coefficient of determination.

$$Cd_B = 2.303 - 0.112\alpha_{rad} + 2.875\frac{h}{P} - 1.220\frac{h_b}{h} - 5.414\frac{h_b}{Ho} \ldots\ R^2 = 0.969 \qquad (9)$$

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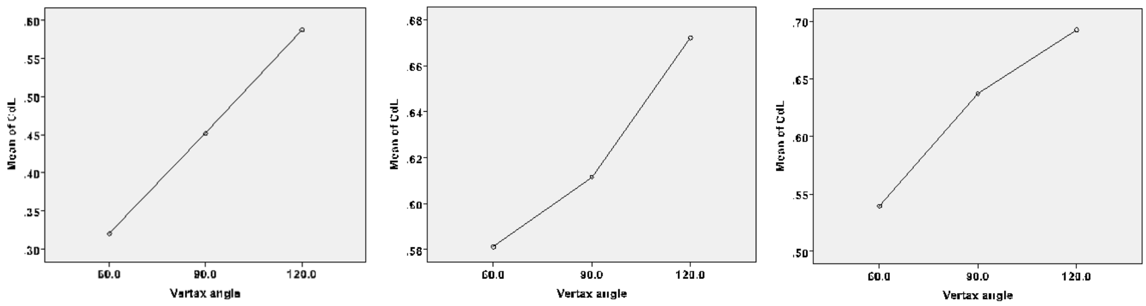
$$Cd_L = 0.545 + 0.092\alpha_{rad} - 0.190\frac{h}{P} \dots\dots\dots \quad R^2 = 0.903 \qquad (10)$$

Finally, the regression output of the experimental data of triangular plan form semi-piano weir data produced Eqs. (11) and (12) their coefficient of determination.

$$Cd_B = 1.822 - 0.098\alpha_{rad} + 2.177\frac{h}{P} - 5.481\frac{h_b}{h} - 4.639\frac{h_b}{Ho} \dots \quad R^2 = 0.966 \qquad (11)$$

$$Cd_L = 0.472 + 0.156\alpha_{rad} - 0.252\frac{h}{P} \dots\dots\dots \quad R^2 = 0.941 \qquad (12)$$

The impact of the parameters in the prediction models of (Cd_L) is studied by two-way sensitivity analysis, the most two important independent parameters are the vertex angle and the ratio of (h/P). The predicted values are affected by 87% and about 13% of input value of the vertex angle and the ratio of (h/P), respectively, when both of parameter changes between maximum and minimum value. The effect changes of the output values of the discharge coefficient (Cd_L) were found 17% and 14% for piano weir, and 30% and 17% for the semi-piano weir. The one-way ANOVA test between the dependent variable (Cd_L) and the vertex angle shows significant relations of homogeneity and equality of mean tests for all weir types, and the mean value plot for each weir shown in figure (9).



(a) Triangular plan form flat top weir **(b)** Triangular plan form piano weir **(c)** Triangular plan form semi piano weir

Fig. (9): Mean plots for discharge coefficient and vertex angle

4. CONCLUSION

The flow over triangular plan-form weirs of the three different groups where, flat top surface, one top slope and two top slopes are tested experimentally, with the limitation of these tests, a comparison with some other geometrical weir shapes can lead to forward the followings:

1- All the tested groups performed better than the conventional broad crested weir, and the efficiency (Q_{act}/Q_n) was more than one, and it reaches to (2) for the triangular plan form semi-piano weir.

2- The value of the discharge coefficient decreases with the increase of the (h/P) of the weirs having top surface slope, while it increases the trend of the flat top models.

3- The vertex angle of (60^o) is the most productive comparing the other two other angles for the both piano and semi-piano weirs, while there is no high influence of the angle on the flat top group weirs performance and the angle (120^o) can be operate a little bit better in this group.

4- The brink depth in the middle of the weir is higher than the one over the end edge of the

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conventional broad crested weir due to jet interference.

5- The triangular plan form semi-piano weir (two slopes) performs better than the rectangular labyrinth weirs, while it is compatible with the triangular labyrinth weirs especially for the low values of the (h/P).

6- Within the limitations of this test, discharge coefficient prediction equations are suggested.

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