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Hydraulics of combined triangular sharp crested weir with inverted V-shaped gate

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KEYWORDS

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Discharge coefficient;
Hydraulic jump

Abstract The current research investigates experimentally the flow passing through combined hydraulic structure consists of V-notch sharp crested weir and inverted V-shaped sharp gate installed in straight channel as a control structure. Nine structure models were used considering three different vertex angles simultaneously used for the weir and the gate (θ = 60°, 90° and 120°). Eighty-one experimental runs were executed to explore the influence of the combined structure geometry, the upstream head, and the tailwater depth on the conveyed flow, the discharge coefficient and the downstream flow pattern with special emphasize on the hydraulic jump characteristics. The outcomes were analyzed and graphically presented. The results proved that the simultaneous flow through the combined structure regardless the vertex angles conveyed more discharge with less downstream water disturbance on account the classical V-notch weir and the inverted V-shaped gate. The flow discharge increased up to 10 times, and the discharge coefficient increased by around 26% for combined structure of 120° vertex angle under similar hydraulic conditions. The conveyed discharge was influenced by the gate angle than the weir angle. The downstream flow characteristics were more sensitive to the weir angle than the gate angle under similar hydraulic conditions. The measured hydraulic jump lengths were compared to other formulas and showed good agreement. Also, the weir and gate vertex angles effectively influenced the hydraulic jump characteristics. The outcomes were used to develop empirical equations for predicting the discharge coefficient and dimensionless jump length associated to the combined structure. The results and analysis in this research are limited to tested data range.

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Notations

B	The flume width [m]	Q_w	Theoretical discharge of the weir [L/s]
b_1	Bottom width of the inverted V-notch angle [m]	y_{tail}	The tailwater depth [m]
C_d	Discharge coefficient of the combined device [–]	y	The distance between the weir and gate vertices [m]
d	The height of the inverted V-notch gate [m]	y_1	The initial water depth of the hydraulic jump [m]
g	Gravity acceleration [m/s^2]	y_2	The sequent water depth of the hydraulic jump [m]
H	The upstream flow depth [m]	θ_w	The angle of the V-notch weir [degree]
h	The head over the weir vertex [m]	θ_g	The angle of the inverted V-shaped gate [degree]
L_j	Hydraulic jump length [m]	ρ	Fluid density [kg/m^3]
Q_{CA}	Actual combined discharge [L/s]	μ	Dynamic viscosity of fluid [kg/m.s]
Q_{CT}	Theoretical combined discharge [L/s]	σ	Surface tension [N/m]
Q_g	Theoretical discharge of the gate [L/s]		

1. Introduction

Heading-up structures are mainly used to control the water level and to measure the flow discharge in waterways. Hydraulic engineers use heading-up structures individually or in combination, according to the required purpose. Despite they are considered the classical devices used, weirs and sluice gates are widely used for flow measurement, flow diversion and flow regulation in open channels. Weirs are used for measuring discharge in open channels by using the principle of rapidly varied flow. They are classified into two major categories, broad-crested weirs and sharp-crested weirs. Sharp crested weirs, also are known as thin plate weirs or notches which are of cut neck on their top and are named based on the form of that cut. The most common shapes are (trapezoidal, rectangular and triangular (V-notch)).

The simultaneous utilization of both weirs and gates is extensively applicable in laboratories, industries, irrigation processes and may be implemented as dam instrumentation devices. Using sharp crested weirs or sluice gate individually, usually associated with disadvantages from morphological point of view in terms of scour and sedimentation. Also, trapping the floating materials is considered one of major passives of sluice gates. Consequently, leads to decrease the structure performance in heading-up and decrease the discharge measurement accuracy. Moreover, the local scouring process may endanger the overall structure instability. Thence, combining both weir and sluice gate in one hydraulic structure, is considered a practical solution to maximize the merits of weir and sluice gate installation in straight open channels. The combined structure conveys more discharge compared to the individual usage of the classical weir and gate, however, the downward opening helps to reduce the trapping of sediment carried by the flow. Consequently, many researches are developed recently to estimate accurately the discharge and discharge coefficient due to the simultaneous flow over the weir and underneath the gate. In addition, exploring the geometrical characteristics of the combined structures under different hydraulic conditions (e.g. angle of weir, angle of gate, upstream water head, tailwater depth, width and height of the combined structure); [1] and [2].

Bos [3] expressed a governing equation to estimate the discharge over a triangular sharp crested weir. Different empirical equations have been developed for discharge estimation over different types of weirs [4–6]. Alhamid et al. [7] used the discharge equation obtained by [8] as a basic to estimate the discharge for the inverted V-shaped gate of the combined system consisted of rectangular weir and triangular gate. They concluded that the triangular gate has a significant effect on the combined discharge.

Zahiri et al. [9] proved that the discharge coefficient has insignificant relation with upstream Froude number by conducting experimental runs on rectangular compound sharp crested side weirs. Sarhan and Jalil [10] compared the results numerically obtained by the Flow 3D software and the experimental tests carried out to study the flow of compound system consisted of vertical sharp crested weir and gate. Muhammad and Abdullahi [11] investigated the flow characteristics over combined sharp crested rectangular triangular weir. Piratheepan et al. [12] measured the flow rates for wide range of discharges by using combined structure consisted of two triangular parts with different notch angles. Hayawi et al. [13] explored the characteristics of free flow through combined triangular weir and rectangular sluice gate. They concluded that the discharge coefficient was inversely proportional to the weir angle, and directly proportional to the vertical distance between the weir and the gate. Negm et al. [14] studied the flow over rectangular sharp crested weir and below inverted rectangular sharp gate. The results confirmed that the viscosity and surface tension effectively influenced the combined discharge. Alhamid et al. [15] investigated the flow characteristics downstream combination of V-notch weir and rectangular sluice gate. The results concluded that the conveyed discharge was increased by the increase of weir vertex angle. Also, they developed semi empirical equation for estimating the combined discharge coefficient for this compound system. Khassaf and Habeeb [16] conducted experimental tests to study the flow over trapezoidal sharp crested weir and below rectangular sluice gate. They concluded that by increasing the distance between the lower edge of the weir and the upper edge of the gate led to increase the discharge coefficient of the combined structure. Alniami et al. [17] studied the discharge coefficient of combined structure consisted of rectangular sharp crested weir and semicircular gate. Samani and Mazaheri [18] studied the combined flow over sharp crested weirs and below gates. Balouchi and Rakhshandehroo [19] conducted experiments on combined triangular weir and rectangular gate structure to evaluate the discharge coefficient. AL-Saadi [20] investigated the hydraulic characteristics of weirs and combined weirs in cases of (rectangular, V-notch, semicircular weir, rectangular combined weir with a rectangular gate, V-notch combined weir with a rectangular gate, semi-circular combined weir with a rectangular gate and semicircular combined weir with a semi-circular gate). The study explored that the combined structure geometry significantly affects the downstream flow characteristics. Furthermore, emphasizing the estimation of hydraulic jump length as focal parameter involved in designing the stilling basin, many researchers have concluded different empirical equations based on experimental data to estimate the hydraulic jump length as [21–31]. These equations are tabulated in Table 1.

Very few data are accessible for the combination of V-notch sharp crested weir and the inverted V-notch gate. Therefore, the research motivation is to explore the flow pattern and hydraulic characteristics downstream this new shape. Different parameters are studied to formulate a clear understanding about the new combined structure.

Moreover, Weirs and sluice gates are installed in open channels according to specific requirements that affect choosing their type, shape, direction and geometry. The new combined structure gives technical support to the decision makers and hydraulics specialists in the selection of the required water control structure. The effect of the proposed combined structure on the downstream flow characteristics is investigated and compared to the classic V-notch weir to fill the missing gap in the knowledge about this new proposed shape.

Data was therefore investigated experimentally for the proposed V-notch weir combined with inverted V-gate structure in order to study the efficiency of this structure to convey more discharge and to develop empirical equations for predicting the combined discharge coefficient and the hydraulic jump characteristics. The new combined structure is investigated under three different upstream water depths, three tailwater depths and three different notch angles for weir and gate individually. The results are used in comparison with the classic 120° V-notch weir, to demonstrate the novelty of this research paper. So, the obtained results are limited to the investigated data range.

Table 1 The hydraulic jump length formulas.

Reference	Formulas
Ludin [21]	$L_j = y_2(4.5 - \frac{V_1}{V_c})$
Safranez [22]	$L_j = 5.2y_2$
Douma [23]	$L_j = 3y_2$
Kinney [24]	$L_j = 6.02(y_2 - y_1)$
Bakhmeteff & Matzke [25]	$L_j = 5(y_2 - y_1)$
Posey [26]	$L_j = 4.5 - 7(y_2 - y_1)$
Sulistiono & Makrup [27]	$L_j = C_j(y_2 - y_1)$ (a) $C_j = 6.3237 + 0.5974(\frac{y_1}{y_2})$ (b) $C_j = 3.827 + 3.088(\frac{y_1}{y_2})^{0.1}$
Karbasi [28]	$\frac{L_j}{y_1} = 2.84 - 12.6F_{r_1} + 14.9\frac{y_2}{y_1}$
Wu [29]	$L_j = C_j(y_2 - y_1)$ $C_j = 10(F_{r_1})^{-0.16}$
Woyciki [30]	$L_j = C_j(y_2 - y_1)$ $C_j = 8 - (0.05\frac{y_2}{y_1})$
Ivanchenko [31]	$L_j = C_j(y_2 - y_1)$ $C_j = 10.6({F_{r_1}}^2)^{-0.185}$

2. Theoretical approaches

2.1. Discharge equations

The combined flow over V-notch sharp crested weir and underneath inverted V-notch gate is sketched in Fig. 1. In order to determine the interaction between the flow passing through the combined system, Eqs. (1) and (2) presented by [3] and [7] respectively, are used. To compute the discharge over V-notch sharp crested weir individually, Eq. (1) is used, however the flow passing through the inverted V-notch sharp gate individually in case of submerged flow condition is similar to the case of the normal sluice gate and governed by Eq. (2):

$$Q_w = \frac{8}{15}\sqrt{2g}\tan\left(\frac{\theta_w}{2}\right)(h)^{2.5} \tag{1}$$

$$Q_g = \frac{1}{2}b_1 d\sqrt{2g}\sqrt{d + y + h - y_{tail}} \tag{2}$$

Presenting the discharge coefficient; C_d, to illustrate the differences between the simplified theory and experimental ones; the actual discharge in the experiments, Q_{CA}, may be presented as a function in the theatrical discharge; Q_{CT} and written as deduced by [20]:

$$Q_{CA} = C_d Q_{CT} \tag{3}$$

$$Q_{CA} = C_d(Q_w + Q_g) \tag{4}$$

In the case of simultaneous flow condition (i.e. over the weir and under the gate), the Q_{CA} can be written as:

$$Q_{CA} = C_d\left(\frac{8}{15}\sqrt{2g}\tan\left(\frac{\theta_w}{2}\right)(h)^{2.5} + \frac{1}{2}b_1 d\sqrt{2g} \times \sqrt{d + y + h - y_{tail}}\right) \tag{5}$$

Then, from Eq. (5), the value of C_d can be experimentally estimated.

2.2. Dimensional analysis

Dimensional analysis is applied to develop physical relation between the tested parameters to explore their influence on the discharge coefficient. For flow through V-notch weir and inverted V-shaped gate as combined structure, the actual discharge Q_{CA} can be expressed by the following functional relationship:

$$Q_{CA} = f(d, y, h, y_{tail}, b_1, g, B, \theta_w, \theta_g, S_0, L_{ap}, \mu, \rho) \tag{6}$$

In which, d = water depth under gate, h = water depth over weir, y_{tail} = tailwater depth, b_1 = bottom width of the inverted V-notch angle, g = gravitational acceleration, B = flume width, θ_w = the vertex angle of V-notch sharp weir, θ_g = the vertex angle of the inverted triangular gate, S_0 = water slop, L_{ap} = apron length, ρ = fluid density, μ = dynamic viscosity of fluid.

The combined discharge coefficient C_d, may be expressed as follow:

$$C_d = f(d, y, h, y_{tail}, b_1, g, B, \theta_w, \theta_g, S_0, L_{ap}, \mu, \rho) \tag{7}$$

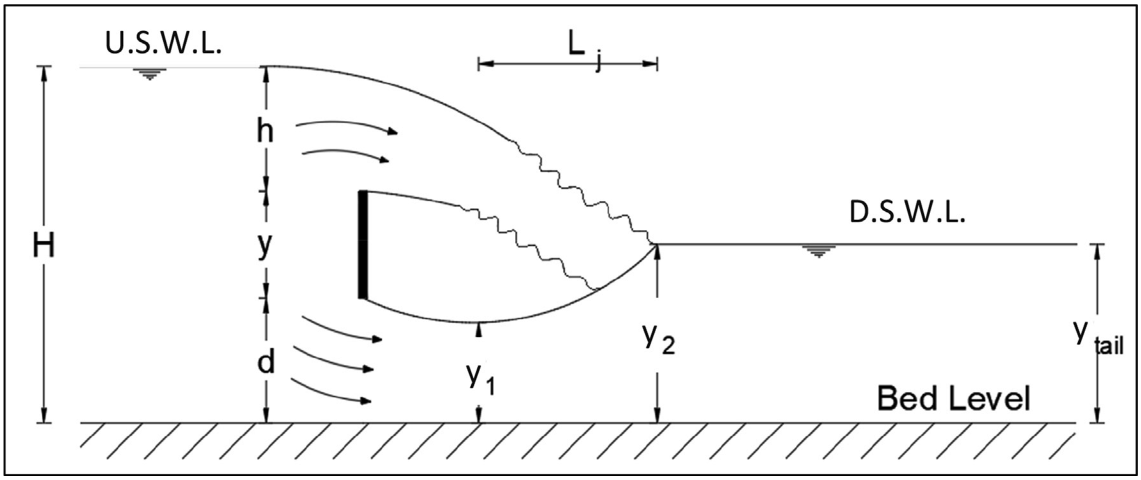


Fig. 1 Sketch for the longitudinal flow passing the combined system.

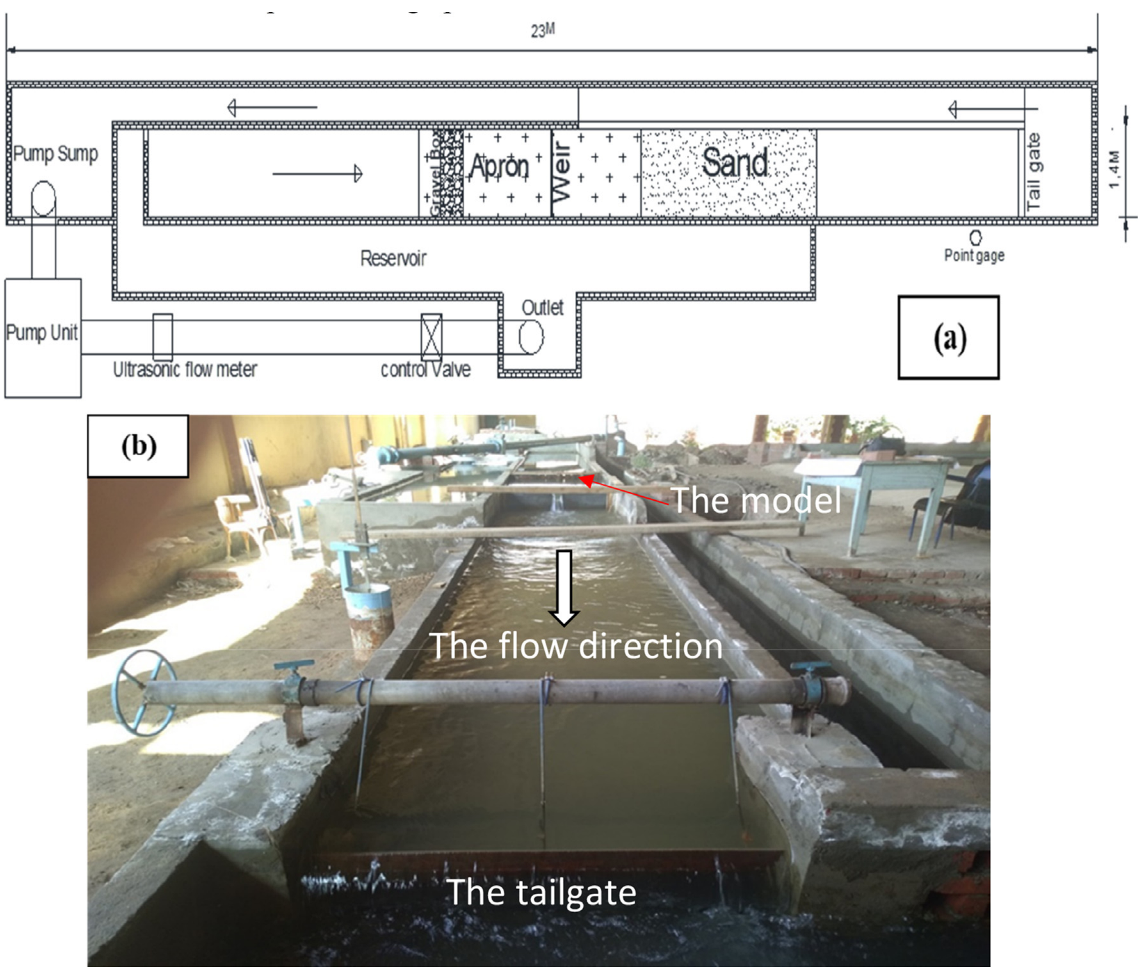


Fig. 2 Experimental flume; (a) flume layout (plan view), (b) flume during operation.

In this research B,L_{ap}, d, ρ, μ and y are kept constants, consequently they are removed from the equation. So, by using dimensional analysis (Buckingham π-theorem), the combined discharge coefficient can be written as in eq. (8):

$$C_d = f\left(\frac{h}{b_1}, \frac{h}{d}, \frac{\theta_w}{\theta_g}, \frac{y_{tail}}{d}, \frac{Q_{CA}}{\sqrt{2g}d^{2.5}}\right) \tag{8}$$

3. Experimental work

The experimental work was executed in the Hydraulics Research Institute, the National Water Research Center, Egypt. A recirculating flume was used, the flume channel is 23 m long, 1.4 m wide, 0.6 m deep. The side walls along the flume length are made of brick and covered with mortar to prevent water leakage. The model bed was constructed using leveling instrument, the combined model was fixed on a rigid apron made of mortar, started 3 m upstream the structure and extended 2 m downstream. A sand bed soil with d_{50} = 0.432 mm covered the 4 m next to the apron and leveled to it. A wire box filled with aggregate gravel was placed 2 m downstream the flume inlet to scatter any flow disturbance. The water level downstream the combined structure was controlled by tilted downstream steel gate fixed at the flume end. A centrifugal pump driven by induction motor was used for water supply to the flume. A control valve was installed on the main pipeline to control the delivered water. The flow discharge was measured using ultrasonic flowmeter 1% accuracy. The water level in the model was measured using point gage of accuracy ±0.1 mm. Fig. 2 shows schematic diagram for the used flume from plan view in addition to photo during operation.

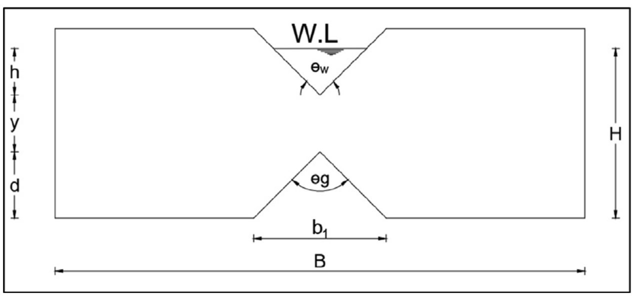


Fig. 3 Definition sketch of the tested model.

Emphasizing the tested hydraulic model, all models were made of steel with 2 mm thickness, 0.5 m height and 1.4 m width. The models were cut from top and bottom according to the vertex angle of the V-notch weir and gate. The vertical distance between weir and gate vertices were kept constant (y = 0.15 m and d = 0.175 m), as shown in Fig. 3. Eighty-one experimental tests with total number of nine different weir models were tested, in addition to the classical V-notch weir that was used for comparison processes. The tested models are illustrated in Fig. 4.

The test program is designed to explore the effect of selected independent variables: flow depth over weir vertex, h; tailwater depth, y_{tail}; the angle of V-notch sharp weir, θ_w; and the angle of the inverted triangular gate, θ_g continuously and alternatively. For each tested model 9 tests were carried out as illustrated in Table 2. The nine tests are formulated to include three weir angles and three inverted gate angles. For

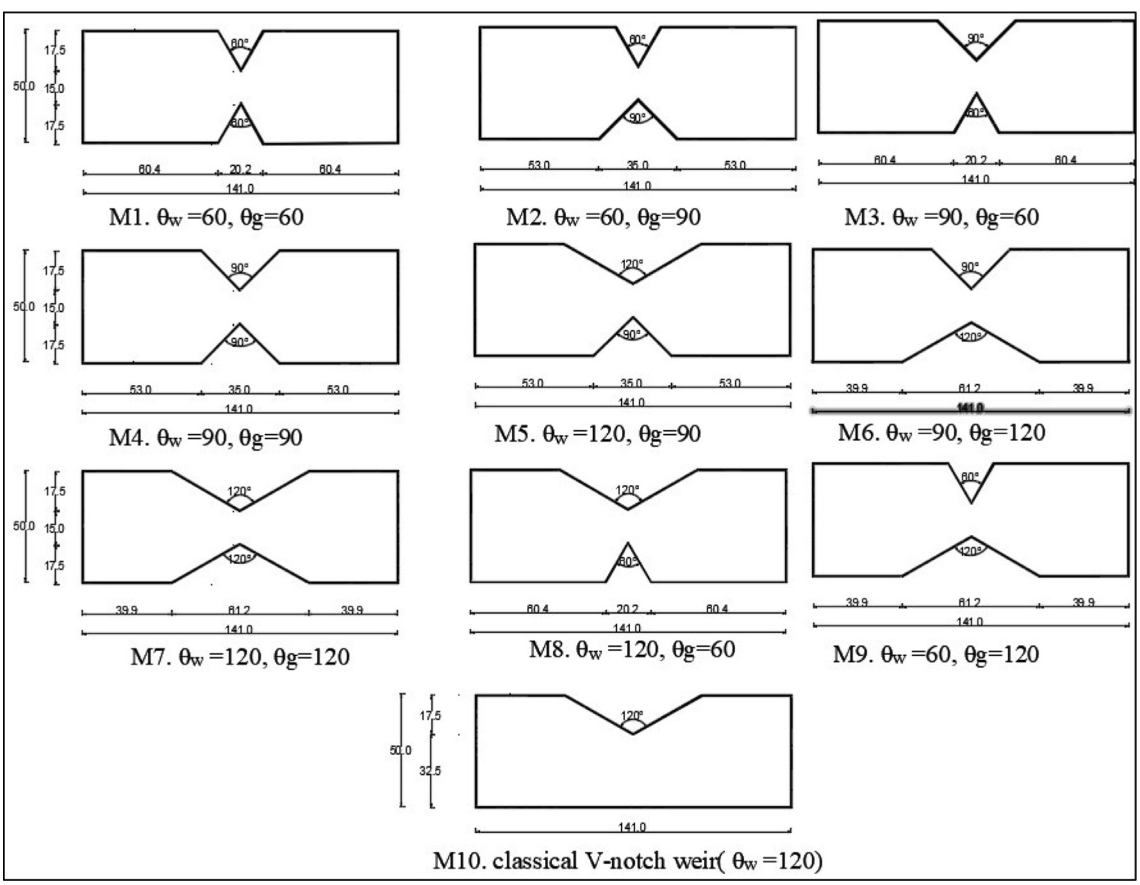


Fig. 4 Details of tested models.

Table 2 The test program.

Model Number	$\theta°_w$	$\theta°_g$	$\theta°_w/\theta°_g$	H (m)	y_{tail} (m)
(1)	60	60	1.0	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(2)	60	90	0.6	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(3)	90	60	1.5	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(4)	90	90	1.0	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(5)	120	90	1.3	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(6)	90	120	0.75	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(7)	120	120	1.0	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(8)	120	60	2.0	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(9)	60	120	0.5	0.10, 0.13, 0.16	0.20, 0.225, 0.25
(10)	120	–	–	0.10, 0.13, 0.16	0.20, 0.225, 0.25

each model three water depth over weir were examined (h = 0.10, 0.13, 0.16 m). The tests were executed under three tailwater depths (y_{tail} = 0.20, 0.225, 0.25 m).

For each test run, the following steps were done. The model was fixed in the desired place in the flume. The flume was filled with water slowly and simultaneously from upstream and downstream the structure until each of head over V- notch weir and tailwater depth reached the designed value. The tailgate was adjusted by screwing until the desired tailwater depth was achieved. Then the test runs for at least 4 hrs to confirm constant flow rate over the weir and under the gate and ensure reaching the steady state. During the run of each test, the discharge was measured using an ultrasonic flowmeter with an accuracy of $\pm 1\%$. The hydraulic jump length, initial and sequent depths were measured for at least four times within the last one hour to ensure the measurements accuracy and the average values were recorded. At the end of each test, the pump was switched-off and the flume was drained gradually.

4. Results and discussions

This research is focused on demonstrating the effects of hydraulic controlling device consisted of V-notch weir and inverted V-sluice gate with different vertices angles installed in straight channel on hydraulic flow parameters in terms of water surface profile and hydraulic jump characteristics. This is achieved through the results analysis of the tested runs. The combined discharge coefficient equation for this structure is finally developed using regression analysis. The result analysis shows the same pattern and trend with the different tailgate water depth, consequently the presented figures are in the case of y_{tail} = 0.20 m.

4.1. Impact of weir/gate angle ratio on water surface profile

The water levels measurements along the flume are used to investigate the surface water profile and displayed in Fig. 5 that discusses the effect of (weir angle/gate angle) under different operation scenarios. The figure shows insignificant differences in the upstream water levels. However, a noticeable decrease in the downstream water levels for the different tested models are found higher than the classic V-notch weir. This is resulted due to the more conveyed discharge from inverted V-gate of the tested combined device. Investigating the cases of$\theta_w/\theta_g > 1$, Fig. 5 (a) shows that the case of $\theta_w/\theta_g = 1.3$ has more stable water surface profile with less fluctuations compared with other ratios. These findings are due to the smaller V-notch weir angle limits the conveyed discharge. Fig. 5 (b), presents the cases of $\theta_{w/}\theta_g < 1$ to explore the effect of smaller weir angles. The figure illustrates that the case of$\theta_w/\theta_g = 0.75$ shows more stable water surface profile where the higher weir vertex angle allows more discharge to pass that scatters the water turbulence due to the flow from the gate. Emphasizing the models with$\theta_w/\theta_g = 1$; Fig. 5 (c) is plotted. It is clear that there are unnoticeable differences in water levels and the same water profile is displayed. Finally, in comparison with the base case of 120° classic V-notch weir, it is concluded that the combined structure of V-notch weir and inverted V-shaped gate effectively maintained less disturbance in water surface profile. That is owned to the interaction between the water passing underneath the inverted V-gate and over the V-notch weir.

4.2. Impact of weir/gate angle ratio on initial water depth

Considering the constant vertical distance between the V-notch weir and inverted V-shaped gate, the impact of the proposed combined structure with different θ_w/θ_g ratios on the initial water depth is presented in Fig. 6. The figure is plotted in terms of the dimensionless initial water depth (y_1/y_{tail}) and the ratio of (h/y_{tail}).

The figure shows inversely proportion trend for the different weir models; where under fixed y_{tail} by the increase of upstream water head over the weir vertex which in turn led to decrease in the y_1. Fig. 6 (a) shows that the initial water depth is decreasing with increasing the V-shaped weir angle, on contrary Fig. 6 (b) shows adverse trend with the V-notch gate angle. Combining the outcomes of Fig. 6 (a) and (b), it's demonstrated that the y_1/y_{tail} is more sensitive to the θ_w more than θ_g. Fig. 6 (c) illustrates the effect of combined device with equal angles, it shows that higher initial water depth is reported for angle of 120°, and this is due to higher discharge conveyed for that case.

4.3. Impact of weir/gate angle ratio on the combined discharge

Fig. 7 is plotted to explore the effect of θ_w/θ_g on the conveyed discharge. The figure illustrates that the combined device con-

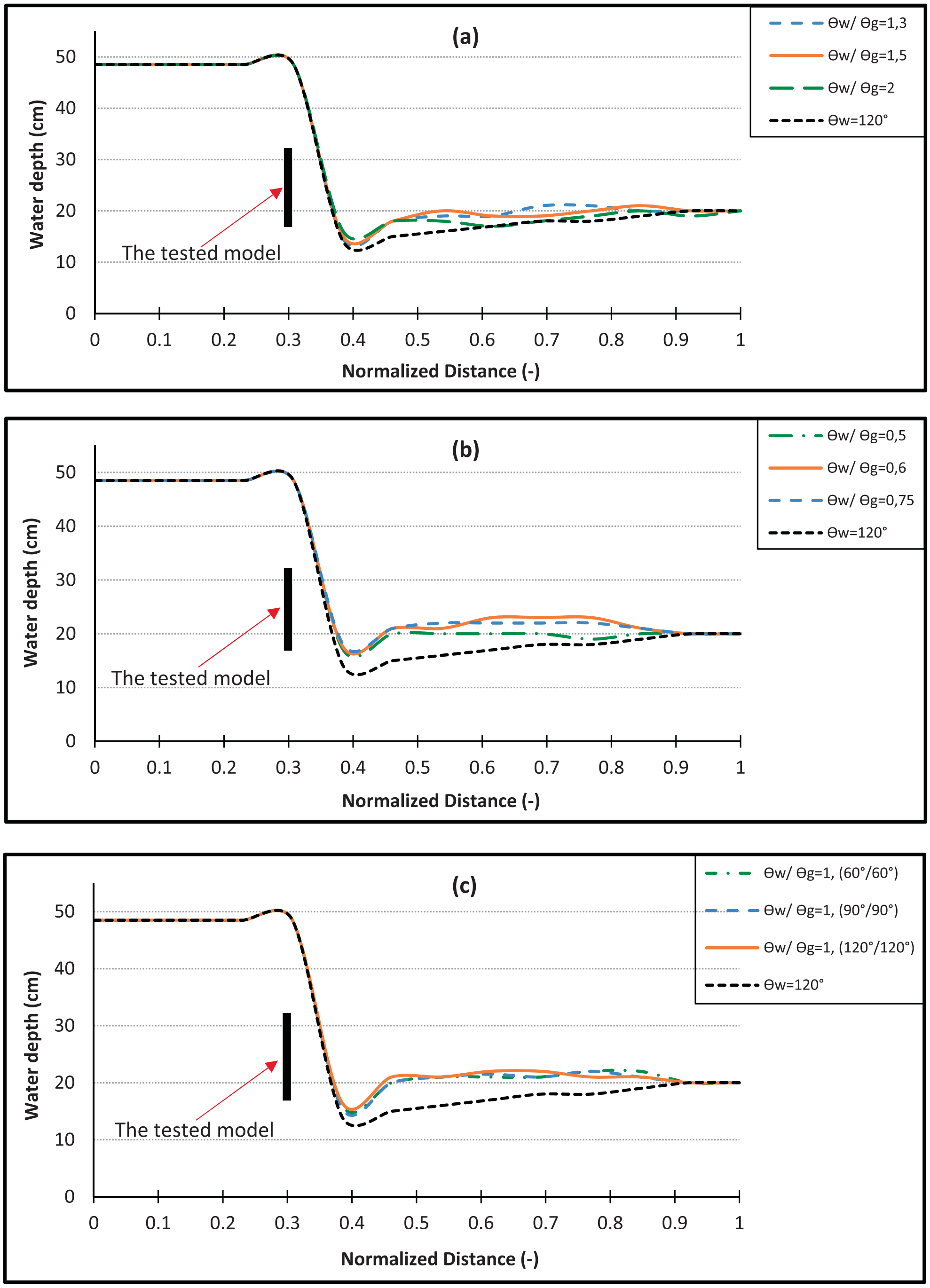


Fig. 5 Water surface profile; (a): $\theta_w/\theta_g > 1$; (b): $\theta_w/\theta_g < 1$; (c): $\theta_w/\theta_g = 1$.

veyed more discharge regardless the tested angles compared to the classic V-notch weir. The conveyed discharge is directly proportion to the head over the weir vertex, however it shows an inverse proportionality to θ_w/θ_g angle ratio. It is found that the discharge capacity for the proposed compound weir-gate model is higher than the case of 120° classic V-notch weir. From Fig. 7 (a), it is concluded that more discharge is conveyed with the decrease of θ_w/θ_g in other words, by increasing the V-notch gate angle. On the contrary, in the case of $\theta_w/\theta_g < 1$, the discharge increases with higher weir/gate angle ratio as illustrated in Fig. 7 (b). While Fig. 7 (c) for$\theta_w/\theta_g = 1$ illustrates that the discharge increases with the increase of weir and gate vertex angle.

It is obvious also that the discharge of combined weir-gate model is higher than the normal sharp crested weir which has good agreement with [5] and [13]. These results are due to the increase of the velocity head in the upstream outstanding to increasing water depth over weir. The results show that the combined weir model of 120°/120° (weir angle/gate angle) passes the highest discharge compared to the tested models, even when compared with the 120° V-notch classic weir. The reported findings are consistent with [7] and [15].

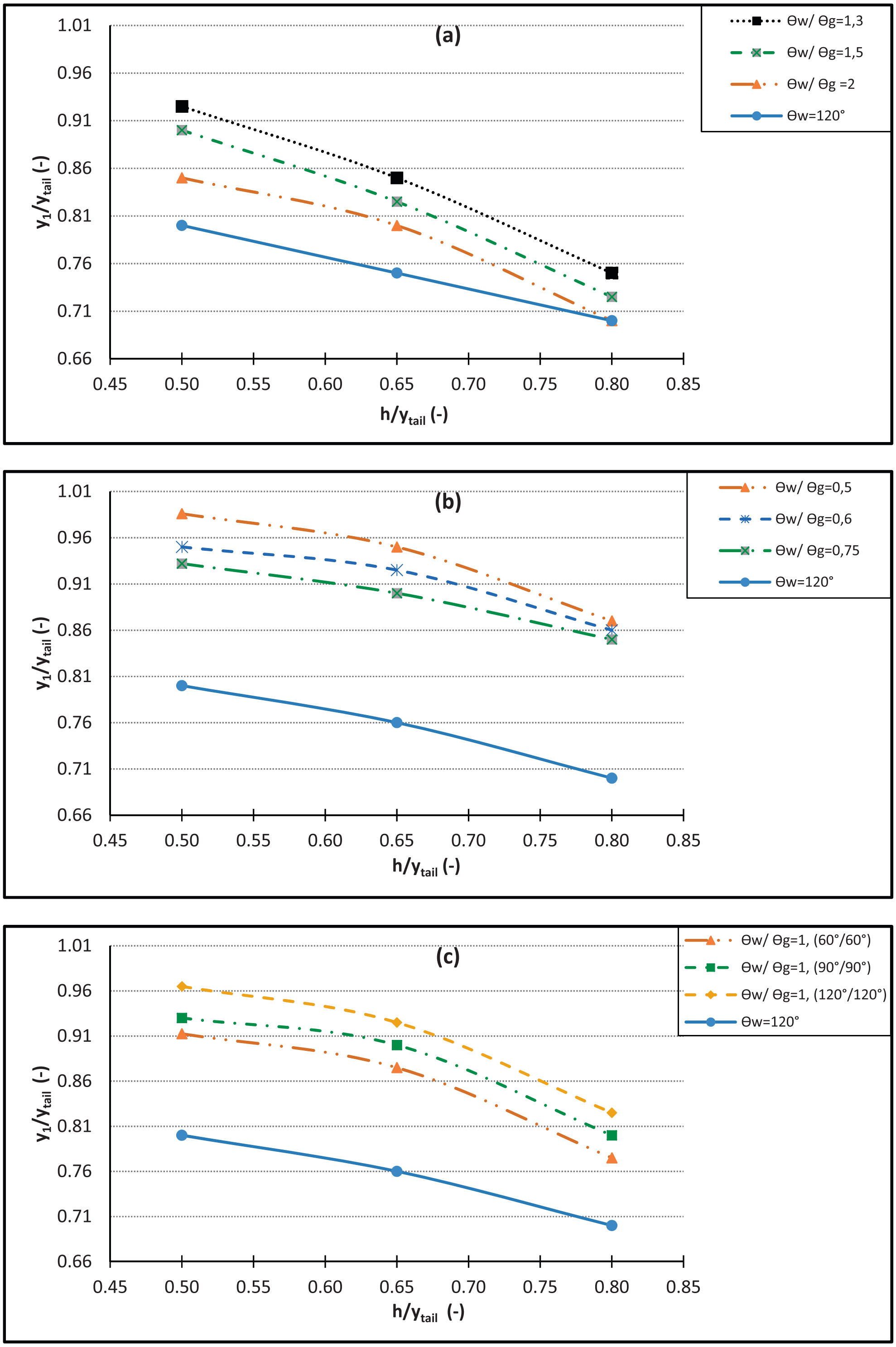


Fig. 6 Effect of weir/gate angle on initial water depth; (a) $\theta_w/\theta_g > 1$; (b) $\theta_w/\theta_g < 1$; (C) $\theta_w/\theta_g = 1$.

4.4. Impact of weir/gate angle ratio on the combined discharge coefficient (C_d)

Fig. 8 defines the relationship between the combined discharge coefficient and the effect of θ_w/θ_g ratio under constant conditions of head above the weir (h = 0.10, 0.13 and 0.16 m). Fig. 8 (a), displays the discharge coefficient for $\theta_w/\theta_g > 1$. The figure shows that the discharge coefficient decreases with higher θ_w/θ_g ratios, which agrees with [13]; where the study reported similar conclusions for the combined triangular weir and rectangular gate. While Fig. 8 (b) shows the adverse relation in the case of $\theta_w/\theta_g < 1$. Consequently, it's concluded that the discharge coefficient for the combined device has high sensitivity to the weir angle compared to the gate angle which

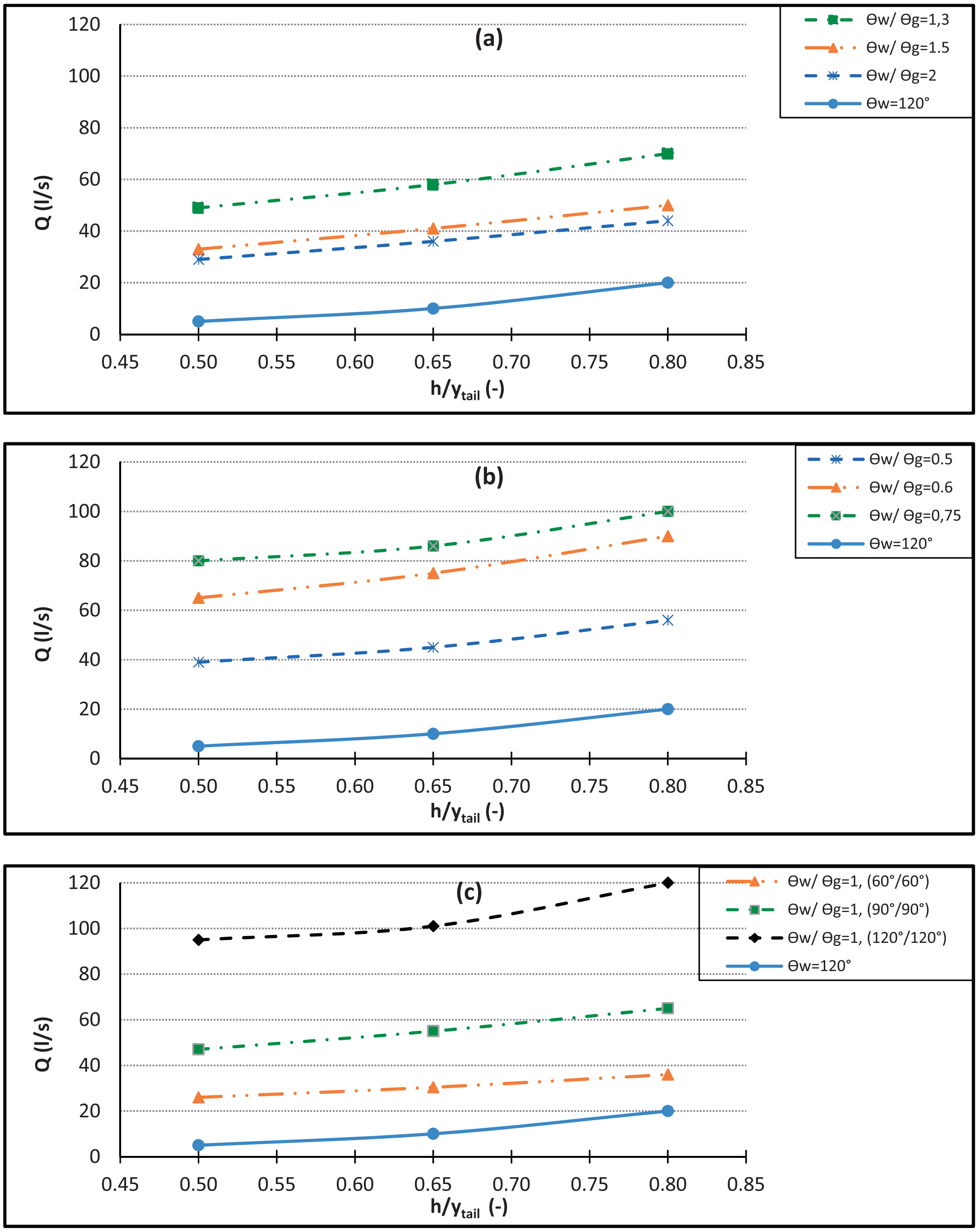


Fig. 7 Effect of weir/gate angle ratio on the combined discharge; (a) $\theta_w/\theta_g > 1$; (b): $\theta_w/\theta_g < 1$; (c): $\theta_w/\theta_g = 1$.

agrees with the findings reported in Section 4.3. Fig. 8 (c) displays the combined device influence on the C_d in the case of equal weir and gate vertex angle. The figure illustrates that the higher C_d is associated to the higher θ_w and θ_g. These results are because the greater vertex angle for weir and gate allows more discharge to pass through the control device. In other words, the combined discharge coefficient is directly proportional to the head over weir vertex, weir and gate angles which agrees with [13]. The showed results are compared to the classic V-notch weir of 120°. It is perceived that the combined discharge coefficient values ranged from 0.4 to 0.7 with an average value of 0.55, and shows about a 26% increase in values in comparison to the classic V-notch weir.

4.5. Impact of weir/gate angle ratio on the hydraulic jump

In stilling basin structure, the kinetic energy is dissipated by the resulted hydraulic jump. When the flow regime changes from the super-critical flow of high velocity to a sub-critical flow of higher flow depth and lower velocity, the hydraulic jump phenomenon happens. The resulted hydraulic jump just downstream the tested combined device is investigated and presented in Fig. 9. The figure presents the effect of V-notch weir and the inverted V-shaped gate vertex angles in addition to the head over weir vertex on the hydraulic jump length under the minimum fixed tailwater depth (y_{tail} = 0.20 m). Generally, the jump length is directly proportional to the water

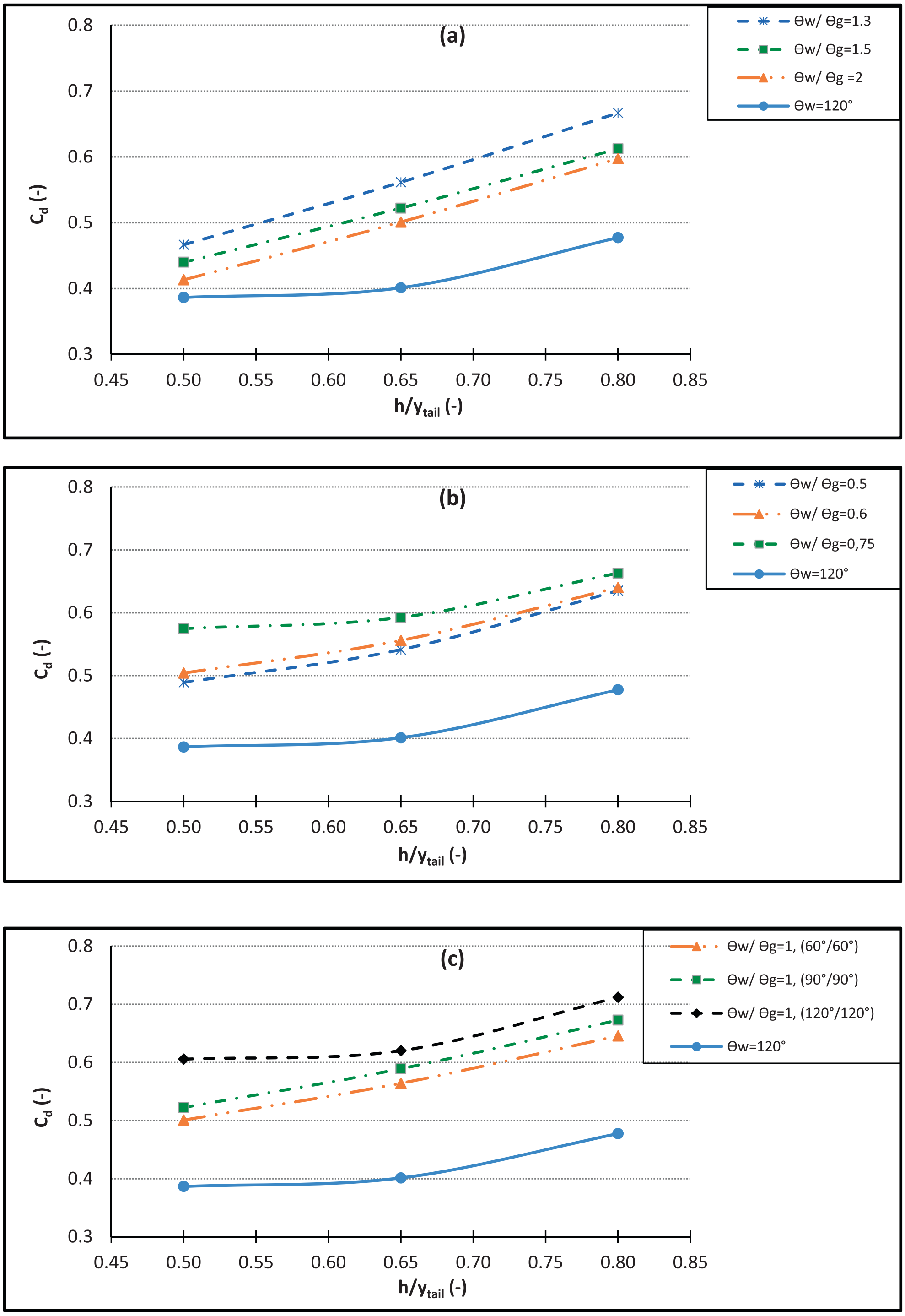


Fig. 8 Effect of weir/gate angle ratio on the discharge coefficient; (a) $\theta_w/\theta_g > 1$; (b): $\theta_w/\theta_g < 1$; (c): $\theta_w/\theta_g = 1$.

head over the weir vertex angle regardless the tested combined device model. Exploring the effect of$\theta_w/\theta_g > 1$, Fig. 9 (a) demonstrated that the jump length is inversely proportion to the θ_w/θ_g under fixed h/y_{tail}. Taking into account the findings of Fig. 7 (a) and 8 (a) that reported the wider angles for weir and gate allows more discharge to be conveyed, consequently the outcomes of Fig. 9 (a) is illustrated, where more water turbulence is generated and in turn a longer jump length. Regarding the cases where$\theta_w/\theta_g < 1$, it is concluded that the hydraulic jump length is directly proportion to θ_w/θ_g due to the wider weir angle. Considering the cases of$\theta_w/\theta_g = 1$, the same findings of Section 4.3 and Fig. 7 (c) is repeated; where the jump length is found for the higher vertex angle due to the larger amount of flow and in turn the fluctuations in water levels are considered. Comparing the combined device outcomes with the classic 120° V-notch weir, it is found that the

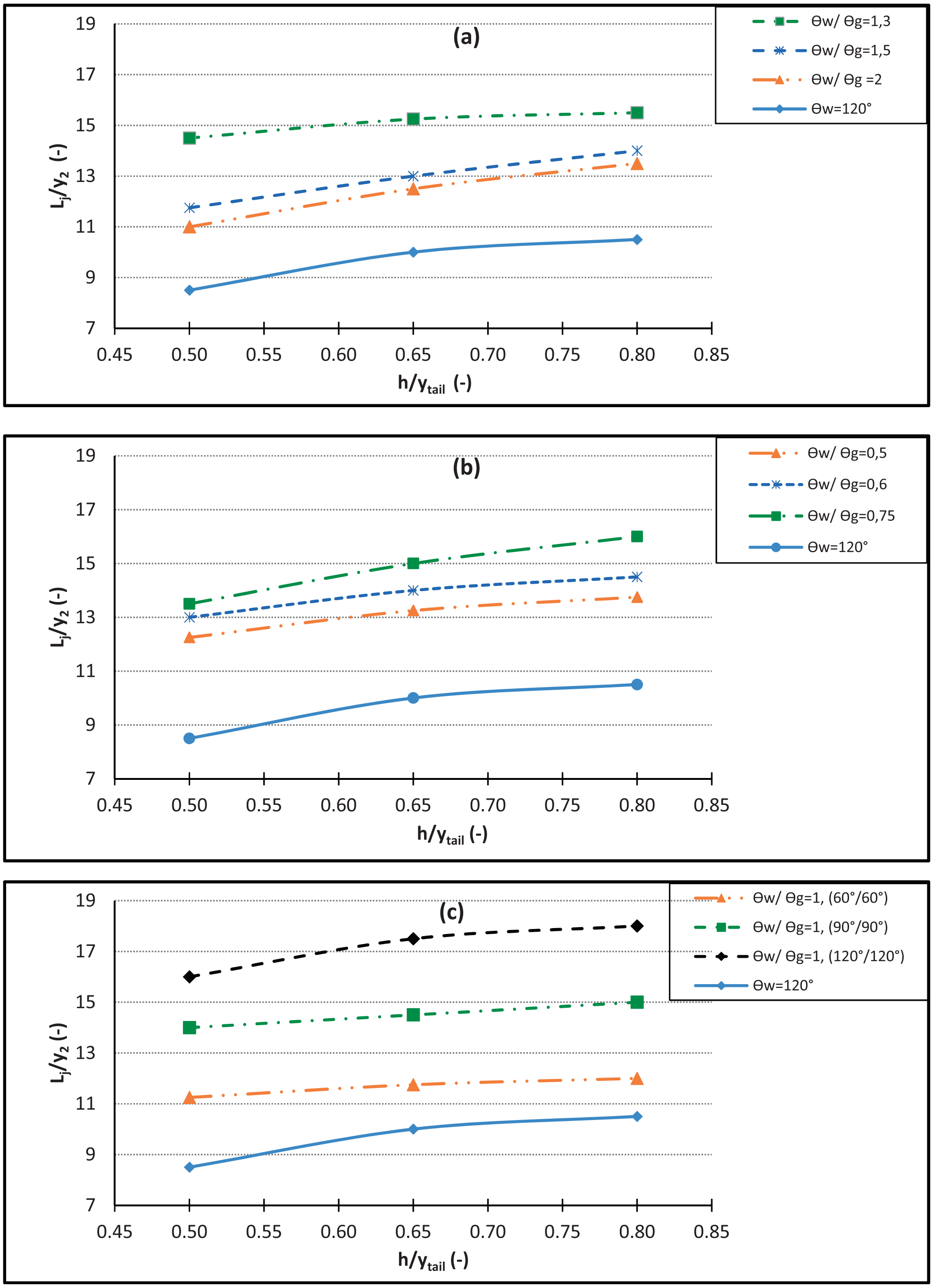


Fig. 9 Effect weir/gate angle ratio on hydraulic jump length; (a) $\theta_w/\theta_g > 1$; (b): $\theta_w/\theta_g < 1$; (c): $\theta_w/\theta_g = 1$.

hydraulic jump length in case of the tested compound structure is higher due to the simultaneous flow and the conveyed discharge.

4.6. Developing mathematical relations

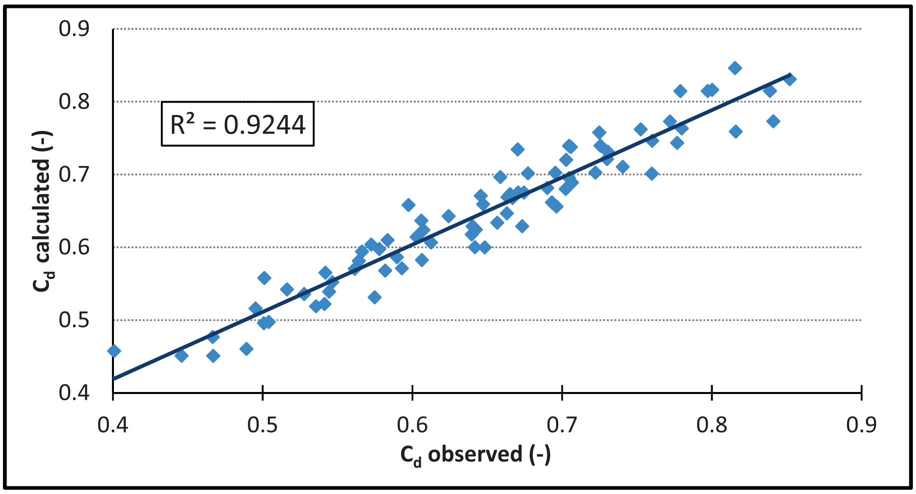
The experimental results are used for developing empirical equations, using regression analysis model including the various dimensionless variables considered in estimating the discharge coefficient and the relative length of the hydraulic jump downstream the combined device. The correlation between the depended value of C_d and L_j/y_1 with the calculated dimensionless parameter is studied. It is found that the (h/d, h/b_1, y_{tail}/d, θ_w/θ_g, and Q_{ca}) dimensionless parameter have significant correlation, the developed formulas can be written as follows with cofficients values as tabulated in Table 3:

$$C_d = C_1\frac{h}{d} + C_2\frac{h}{b_1} + C_3\frac{y_{tail}}{d} + C_4\frac{\theta_w}{\theta_g} + C_5\frac{Q_{CA}}{d^{2.5}\sqrt{2g}} + C_6 \quad (10)$$

$$\frac{L_j}{y_1} = C_1\frac{h}{d} + C_2\frac{h}{b_1} + C_3\frac{y_{tail}}{d} + C_4\frac{\theta_w}{\theta_g} + C_5\frac{Q_{CA}}{d^{2.5}\sqrt{2g}} + C_6 \quad (11)$$

Table 3 Coefficient values of the discharge coefficient and dimensionless Hydraulic jump length.

Coefficient No.	C_1	C_2	C_3	C_4	C_5	C_6	R^2	SEE
Eq. (10)	0.0171	0.4606	0.6389	−0.0576	0.1826	−0.498	0.9244	0.0288
Eq. (11)	7.5742	−6.0141	−14.29	2.555	2.4874	24.019	0.8115	1.2747



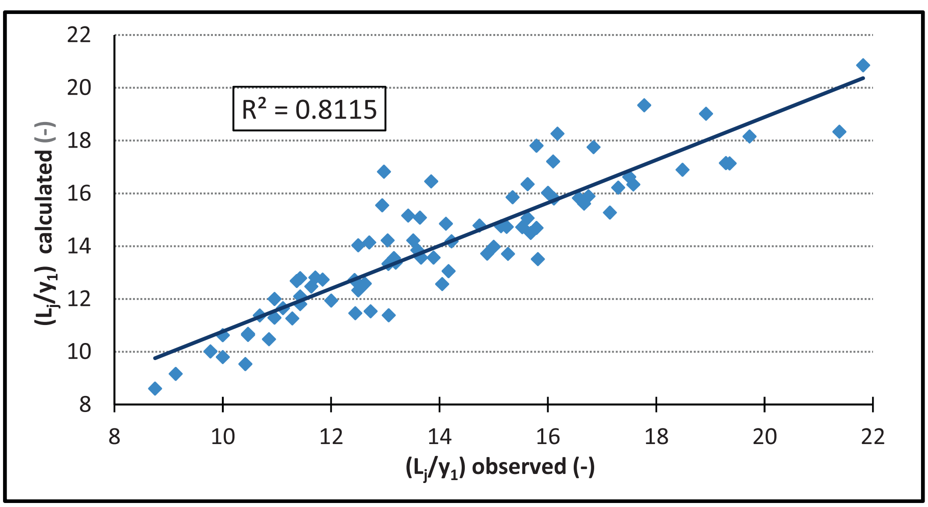


Fig. 10 Comparison between observed and calculated values of; (a) combined discharge coefficient; (b) dimensionless hydraulic jump length.

These equations are validated using the experimentally observed data versus the calculated values for the discharge coefficient and the dimensionless parameter L_j/y_1 as shown in Fig. 10. The results show a good agreement between the experimental and predicted values.

To investigate the accuracy of the measured hydraulic jump lengths and to validate the developed empirical equation, Eq. (11); the results are compared to the presented equations from previous studies which are tabulated in Table 1. The outcomes are plotted in Fig. 11. The figure shows good correlation and similar trend with previous studies, and the observed results are within the range of the calculated values.

5. Conclusions

Experimental study was carried out to investigate the flow characteristics downstream combined hydraulic structure consisted of V-notch weir and inverted V-shaped gate under different hydraulic conditions. The effect of water depth over weir vertex, combined device geometry in terms of weir and gate vertices, on the water surface profile, the discharge coefficient and dimensionless hydraulic jump length were investigated. Three vertices' angles for the V-shaped weir and gate 60°, 90° and 120°, under constant conditions of water head above

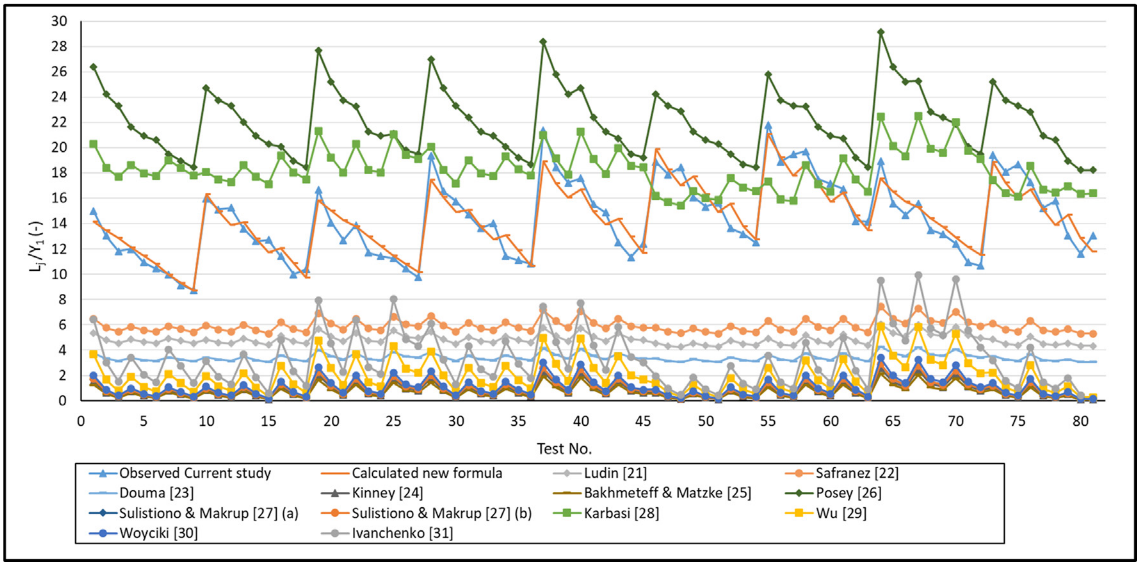


Fig. 11 Comparison between calculated L_j/y_1 of the current study and calculated using other formulas.

the weir vertex (h = 0.10, 0.13 and 0.16 m) were tested with three tailwater depths (0.20, 0.225, 0.25 m), which means that the research results are limited to this data range.

Based on the experimental results it is found that the combined structure is more efficient than the classic weir in terms of discharge capacity; where it conveyed more discharge by about 2 to 10 times than the classical V-notch weir based on the weir-gate angle ratio. The flow characteristics downstream the combined device is more sensitive to the weir angle than the gate angle. The maximum discharge is found to occur in the case of equal weir and gate angle of 120°. The discharge coefficient values of the combined structure ranged from 0.4 to 0.77 with an average value of 0.55, it increased by increasing the head of water over the weir vertex. The discharge coefficient for the combined device is higher than the classical V-notch weir by an average of 8% to 50% according to the weir-gate angles ratios. The maximum discharge coefficient is reported for constant 120° vertices angle for both weir and gate. The flow downstream the combined structure is more stable with less fluctuations and turbulence in the water surface profile compared to the classic V-notch weir. The turbulence of the water surface profile is found insignificant considering equal weir/gate angles. The combined device generates longer hydraulic jump length, it increases by about 88% in the case of weir and gate angle equals 120° compared to the classic V-notch weir. The hydraulic jump length is directly proportional with the head over weir and weir/gate angle ratio. The inverted V- shaped gate angle has a significant effect on the hydraulic jump length and found in direct proportional relation. The observed hydraulic jump length values showed a good agreement with the calculated in previous studies.

For further studies, it's recommended to test the simultaneous flow across combined weir-gate models with different geometrics (e.g. semi-circle with different radii, elliptical shape, and trapezoidal with different side slopes) to develop generic equations for the flow characteristics and discharge coefficients and generalize the applications of the new proposed combined weir-gate structure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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