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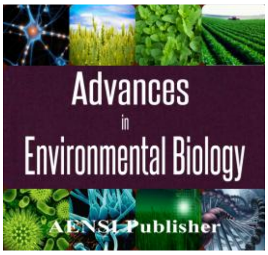

Hydraulic Characteristics of Rectangular Combined Sharp-Crest Weir-Gate

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ABSTRACT

Combined weir-gate is a relatively new-useful structure that measures flow discharge in irrigation canals. Various experimental studies illustrate that combined measurement structures could increase discharge coefficient and lead to increasing the discharge. In this research, numerical simulation of combined sharp crest weir-gate was done using FLUENT software to evaluate the hydraulic characteristics of combined weir-gate. Results show that approaching flow of the weir-gate is divided two sections: upper flow and under flow, which upper flow passing over the weir and under flow passing the gate. The combined weir-gate could increase the discharge coefficient effectively that results in increasing the flow discharge passing the structure. Also, the relationship between discharge coefficient and (Ht is total water depth upstream of weir-gate and w is the height of the weir) was approximately linear. It was concluded that discharge coefficient of the structure reached to 0.66 in different conditions.

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INTRODUCTION

Weirs and gates are small over-under flow type structures commonly used to raise the level of a channel or stream and cause a large change of water level behind them. These are obstruction structures generally put normal to the direction of flow. Flow discharge can be determined simply by recording the water depth upstream of the structure. These measurement structures have often been used in irrigation systems, hydroelectric schemes. Many researchers have studied to find the relation between the water surface level and the discharge passing through the structure with a simple cross section shape, such as rectangular, triangular, trapezoidal, truncated triangular, and others. The combined weir-gate is a relatively new structure that there are only a limited number of studies made for simultaneous flow over and under the measuring structures in literature. The main advantage of the combined structure is the minimization of sedimentation and deposition at the upstream of the system. The relationships between the discharge and water depth for weirs and gates have been studied by many researchers. Rehbock [19] purposed the flowing equation based on experimental data for estimating discharge coefficient of the rectangular weir with wide equal to channel.

$$C_d = 0.611 + 0.08\left(\frac{H}{w}\right) \quad (1)$$

Where H is the water depth upstream of the structure, w is the height of the weir. In the equation, surface tension and viscosity force are neglect and it be only used in $\frac{H}{w} < 5$. Kindsvater and Carter [9] developed the well-known equation for flow over the weirs as:

$$Q_w = \frac{2}{3} C_{dw} \sqrt{2g}\ b_e\ H_e^{\frac{3}{2}} \quad (2)$$

Where b_e is the effective weir width, h_e is the effective head over the weir. Kindsvater and Carter [9] defined $b_e=b+K_b$ where K_b is a function of b/B and $h_e=h+K_h$ where K_h has a constant value of 0.001m and $C_{de}=k_1+k_2(\frac{H}{w})$. The results showed that head over the weir and the discharge coefficient are also effected by inside construction of water flow. Kandasami and Rouse [10] suggested discharge coefficient in $\frac{H}{w} > 15$ as following:

$$C_d = 1.06\left(1+\frac{H}{w}\right)^{1.5} \quad (3)$$

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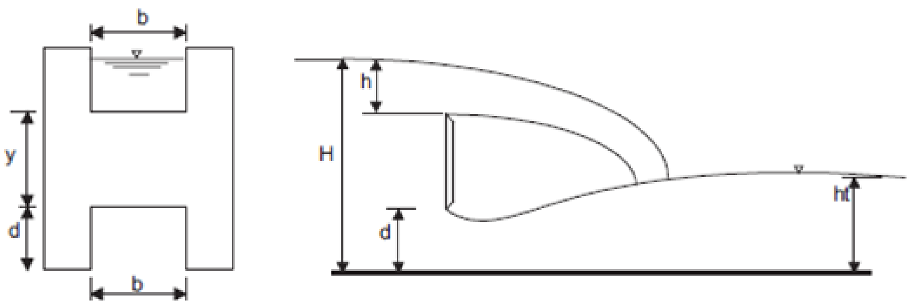
Bos [3] demonstrated that the minimum water depth upstream of the structure must be equal 20 mm to having completely the characteristics of sharp crest weir. This limitation reduces the effects of viscosity and surface detention, so that R_e and W_e is removed. Similarly, the discharge computations for gates have been given by Henry [6] as:

$$Q_g = C_{dg}\, bd\, \sqrt{2gH} \tag{4}$$

Where Q_g is the discharge passing through the gate, C_{dg} is the discharge coefficient, b is the width of the openings of the gate and d is the height of the opening of the gate. Swamee [21] and Montes [11] provided equations for calculating discharge passing under gate. Swamee [21] developed a discharge equation based on Henry's experimental data. Montes [11] described a numerical method to solve Laplace equation of discharge flow of gate.

There have been limited studies made for the combined weir and gate structure. Some of the researches are experimental whereas others are numerical. Ferro [5] established experimentally a relation between stage and discharge for simultaneous flow over and under a sluice or a broad-crested gate. The characteristics of the combined weir-gate with equal contractions (Figure 1) were discussed by Negm *et al*. [12-14]. They found that the flow parameters $(\frac{H}{d})$ and geometrical parameter $(\frac{y}{d})$ have major effects on the discharge while the other parameters are insignificant.



a) Cross section b) Longitudinal section

Fig. 1: Simultaneous flow over weir and under gate with equal contractions [14]

In the above figure, h is effective water head upstream of weir, H is total water depth upstream of weir-gate, b is the width of the openings of the weir and gate, d is the height of the opening of the gate and y is the vertical distance between the bottom of the weir and top of the gate and h_t is water depth downstream of weir-gate.

Razavian and Heydarpour [17] studied on the combined flow characteristics over rectangular weir - gate with unequal contractions. Hayawi *et al*. [7] investigated the coefficient of discharge for a combined rectangular weir and semi-circular gate. The analysis of results show that the values of C_d range from 0.522 to 0.853 with an average value 0.695. Altan-Sakarya and Kokpinar [1] predicted discharge through H-weirs using optimization method and the method developed by Ferro [5]. Jalil and Sarhan [8] studied flow over a sharp crested weir and under gate. Different relationship models with acceptable significance are suggested. Also, values of C_d range from 0.623 to 0.403 with Standard Error 0.0047. Obead and Hamad [16] investigated the hydraulic characteristics of the combined flow over curved weirs and below rectangular gate. The results of this research show that the weir angle has a significant effect on the combined discharge through the weir-gate system. Overall, it has been concluded that mainly the gate section is passing water in lower flow. But in the higher flow, the combined weir - gate together are passing the flow and therefore water discharge can be increased. The main idea of this study is to depict numerically the discharge flowing through defined combined structure, where water flows simultaneously over and below the measuring structure.

There are limited numbers of numerical studies made for simultaneous flow over and below the combined weir-gate in literature. But Computational Fluid dynamic (CFD) simulation especially modeling with *FLUENT* software has been used in simulation of various hydraulic structures. These simulations show sufficient results with compared to experimental data. Some examples are such as modeling of flow pattern over cylindrical weir [4], simulation of water hammer [15] and numerical modeling of velocity and pressure distribution over broad crest weir [20]. Rostami and Namaii's study [20] shows that simulation results with *FLUENT* software have good agreement with experimental data. *K-ε* Realizable turbulence model has less error than the other turbulence models.

Aim of the all investigations about flow measurement structures is the increasing of discharge coefficient of the structures. Also, numerical simulations (CFD) compared with experimental researches are so useful to understand the hydraulic characteristics especially flow pattern around the structures. So, in this research a

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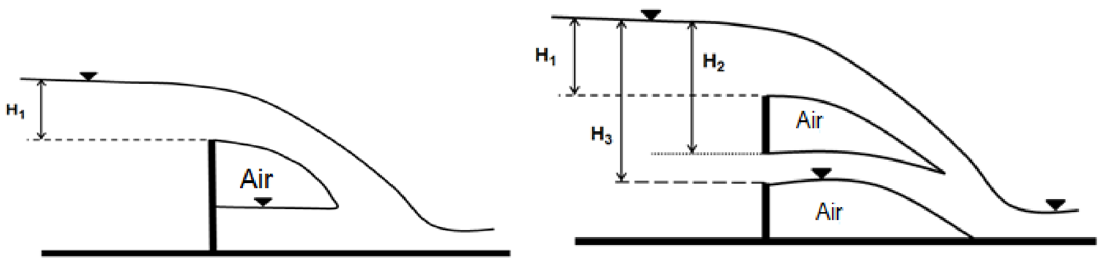
different form of combined weir-gate was introduced to increasing the discharge coefficient of structures and was simulated using the CFD models.

In this study, hydraulic characteristics of the combined rectangular weir-gate are simulated with *FLUENT* software. Approaching flow pattern of the combined weir-gate were studied and variations of flow discharge and discharge coefficients are compared for both single weir and combined weir-gate.

MATERIAL AND METHODS

In this research, the flow discharge in the combined weir-gate was 2D simulated using *FLUENT* software and compared with experimental data. Discharge coefficient was experimentally and numerically investigated in the two type structures including single sharp crest weir and combined weir-gate. In figure 2, the Sketch of single weir and the combined structure used in simulation is shown.



a) Single sharp-crested weir b) Combined sharp-crested weir-gate

Fig. 2: Longitudinal section of single weir and the combined structure.

Experiments data used in performing the CFD model have been performed in a rectangular flume with Plexiglas side wall was 10 m long and 0.25 m width. Also, the bed slope was 0.0022 and 0.5 deep. In the experiments, a rectangular sharp-crested weir with 0.25 height was put normal to the direction of flow. Water depth over weir (H_1) was varied between 2.9 – 12.7 cm and flow discharge was measured in all experiments. Overall, the limits of the whole experiments are $0.116 \leq \frac{H_1}{w} \leq 0.508$, $0.601 \leq C_d \leq 0.635$ and $0.0023 \leq Q \leq 0.0124$ (m^3/s). It is mentioned that length of weir and width of gate is equal to width of channel.

FLUENT is one of the CFD models solving complex flow ranging from incompressible to highly compressible flows. Providing multiple choices of solver option, combined with a convergence-enhancing multi-grid method, *FLUENT* delivers optimum solution efficiency and accuracy for a wide range of speed regimes. *FLUENT* solves the governing 2D or 3D equations sequentially using the control volume method.

At first, 2D geometry model of the combined structure was created in Gambit software and proper grid of model was produced. It is important to establish a grid structure that grid-independent results be obtained. Also, the grid structure must be fine enough. It was found that results are independent of grid size, if at least 3000 nodes are used in 2D simulating. Figure 3 represents the grid structure of the simulated combined structure. Then, appropriate boundary conditions are specified at the domain in *FLUENT* software. Finally, the model is run by using the control volume method and selecting the turbulence model (K-ε) and other specifications.

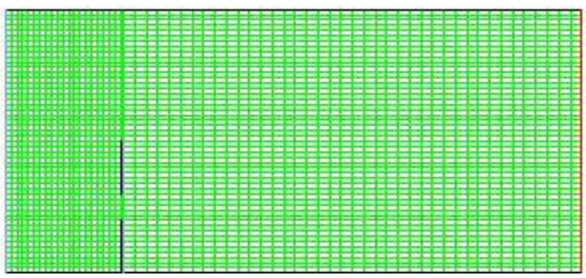


Fig. 3: Generated grid of combined weir-gate.

Geometry characteristics of three simulated models are given in table 1. Gate opening is equal 5%, 10% and 20 % of head over the weir. Design of the combined weir-gate has special condition that height structure over and under gate is equal; other hand gate location was in middle of the structure.

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Table 1: Geometry characteristics of studied models

Description	Height structure over and under gate (cm)	Gate opening (cm)	Height of weir (cm)	Type of structure	Models.
-	-	-	25	Rectangular weir	1
Gate opening is equal 5% of weir height	11.875	1.25	25	Weir-gate	2
Gate opening is equal 10% of weir height	11.25	2.5	25	Weir-gate	3
Gate opening is equal 20% of weir height	10	5	25	Weir-gate	4

To compute the discharge of the combined weir-gate, the following equation may be obtained by adding the discharge over the weir and gate as:

$$Q_t = C_d[\, Q_w + Q_G \,] \quad (5)$$

Where Q_t is total actual discharge, Q_w is discharge over the weir, Q_G is discharge under the gate, C_d is coefficient of discharge. The discharge over the sharp crest weir (Q_w) can be calculated using the following equation [2]:

$$Q_w = \frac{2}{3}\, C_{dw}\, \sqrt{2g}\;\; b\;\; H_1^{\frac{3}{2}} \quad (6)$$

Where Q discharge over the weir, H_1 is the water head on the weir, C_{dw} is the discharge coefficient of the weir, b is the width of weir and g is the gravitational acceleration. The discharge under the gate is calculated using the following equation adopted by Rajaratnam and Subramanya [18]:

$$Q_G = \frac{2}{3}\, C_{dG}\, \sqrt{2g}\; b\, (\, H_3^{\frac{3}{2}} - H_2^{\frac{3}{2}} \,) \quad (7)$$

Where Q_G is discharge under the gate, C_{dG} is the discharge coefficient of the gate, b is the width of gate, H_3 is the upstream water depth from bottom the gate and H_2 is the depth of water just top of the gate. Discharge equation of the combined weir-gate could be determined by replacing equations 6 and 7 in equation 5 as:

$$Q = \frac{2}{3}\, C_{dw}\, \sqrt{2g}\;\; b\;\; H_1^{\frac{3}{2}} + \frac{2}{3}\, C_{dG}\, \sqrt{2g}\; b\, (\, H_3^{\frac{3}{2}} - H_2^{\frac{3}{2}} \,) \quad (8)$$

Above equation could be simplified as:

$$Q = C_d\, \frac{2}{3} \sqrt{2g}\;\; b\, [\, H_1^{\frac{3}{2}} + H_3^{\frac{3}{2}} - H_2^{\frac{3}{2}} \,] \quad (9)$$

In this research, equation 9 is used to calculate discharge coefficient of the combined structure.

RESULTS AND DISCUSSIONS

By using experimental data (single sharp crest weir), discharge coefficients were determined for Rehbock and Kindsvater–Carter's equations and compared with equation 6. Based on the results, Variation of discharge coefficient values (C_d) versus $\frac{H_1}{w}$ is shown in figure 4. As shown in this figure, the mentioned equations have approximately same result and error values are negligible. On the other hand, variation of discharge coefficient (C_d) versus $\frac{H_1}{w}$ is almost linear and it has good agreement with Rehbock and Kindsvater–Carter's equations

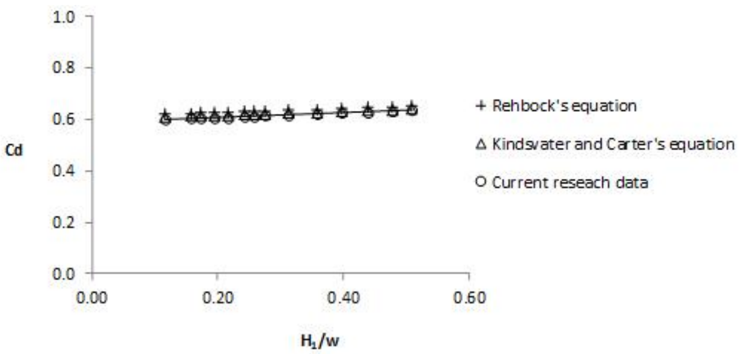

Fig. 4: Variation of Discharge coefficient values versus $\frac{H_1}{w}$ for single weir.

Figure 5 shows pattern of the simulated flow passing through the combined weir-gate. Approaching flow of the weir-gate is divided two sections: upper flow and under flow, which upper flow passing over the weir and under flow passing the gate. Also, approaching flow near the bed (Under flow) is gradually deflected to upper depths and compacted through approaching to the gate and then passes the gate. As shown in the figure, flow streamlines passing through the weir and gate joined together in downstream of the structure. On the other hand, vortexes zone of downstream the structure is divided two sections: upper section and under section, which under vortex zone is stronger than upper vortex zone. It means that the structure could increase the flow passing through the combined weir-gate.

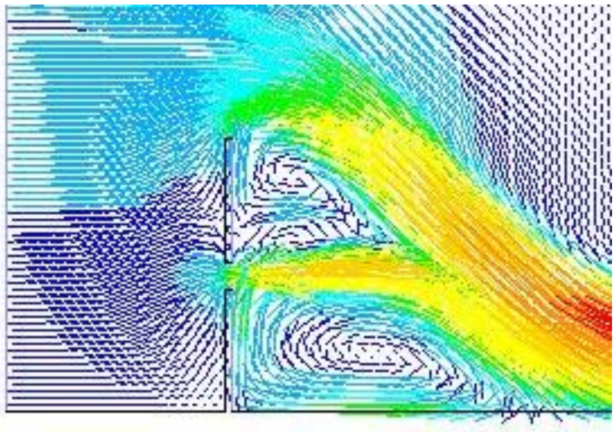

Fig. 5: Simulated flow pattern passing over and under the combined weir-gate.

Variation of flow discharge versus H_t at different conditions is shown in figure 6. The results show that the flow discharge increased in the combined structure and the relationship between flow discharges and H_t is approximately power law. Otherwise, the combined weir-gate could increase effectively discharge coefficient because of dividing the vortexes zone of downstream the structure into two sections that results in passing easily flow through the combined weir-gate.

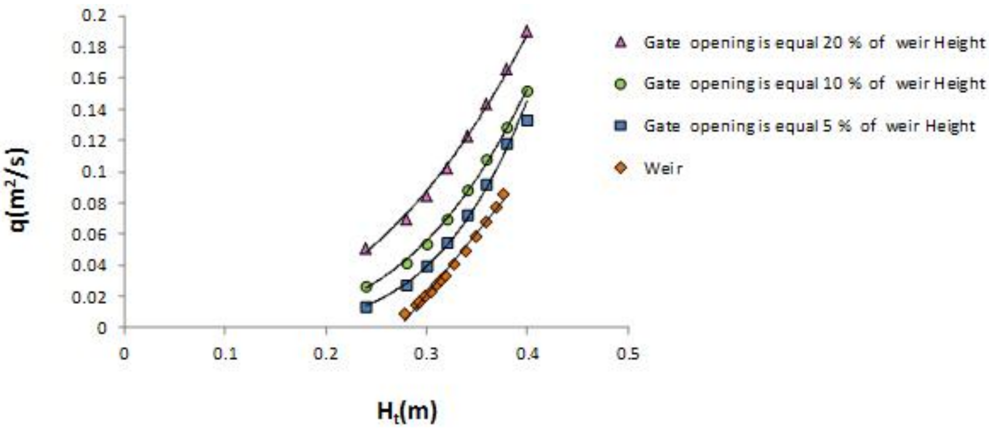

Fig. 6: Variation of discharge versus H_t in studied models

In figure 7, variation of discharge coefficient versus $\frac{H_t}{w}$ for three simulated combined weir-gate and single weir is shown. Discharge coefficient increased efficiently by using the combined structure. It was shown that the relationship between discharge coefficient and $\frac{H_t}{w}$ is approximately linear. Rehbock [19] also purposed a linear equation (Equation 1) between discharge coefficient and $\frac{H_t}{w}$. Discharge coefficient of the combined weir-gate with 5 % gate opening is more than other models. Also with increasing $\frac{H_t}{w}$, discharge coefficient value is reached to 0.66 in different conditions. It means that discharge coefficient reduces gradually by increasing of H_t or decreasing of w.

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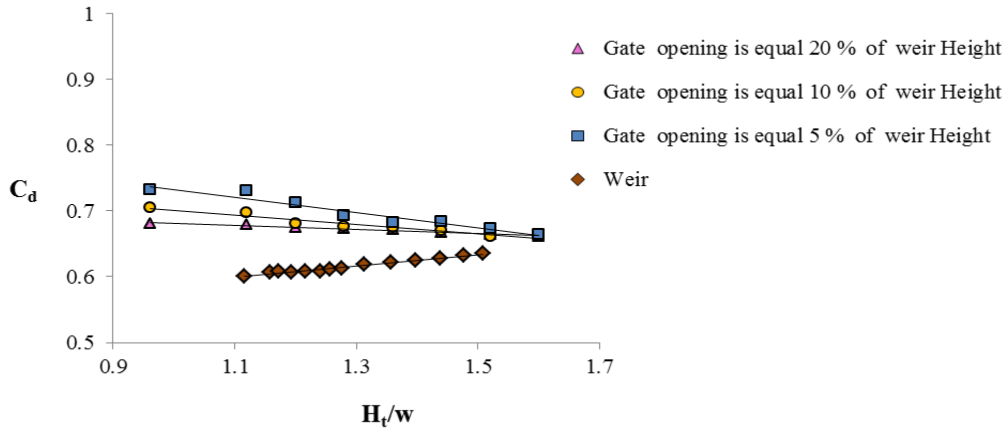

Fig. 7: Variation of discharge coefficient versus $\frac{H_t}{w}$ in studied models.

Conclusions:

In this research, hydraulics characteristics of the combined weir-gate were studied numerically. Results of simulated flow pattern showed that approaching flow near the weir-gate is divided two sections: upper flow and under flow, which upper flow passing over the weir and under flow passing the gate. It was shown that relationship between flow discharge and H_t was approximately power law. Discharge coefficient increased efficiently by using the combined structure, so the relationship between discharge coefficient and $\frac{H_t}{w}$ was approximately linear. By increasing of H_t or decreasing of w, discharge coefficient reduced gradually and reached to constant value of 0.66. It was concluded that the combined structure could increase the flow discharge.

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