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HYDRAULIC PERSPECTIVE FOR FLOW OVER PARABOLIC WEIR AND UNDER PARABOLIC GATE

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ABSTRACT

The weir-gate structure is a very important discharge structure. Thus, understanding the hydraulic features of this structure is necessary. The water flow over the weir and under the gate was investigated experimentally. Both the weir and gate have a parabolic shape; therefore, this paper aims to understand the appropriateness of using a non-regular shape in the hydraulic features of the discharge structure. The following variables and parameters are adopted in this study: actual discharge, water depth above the weir crest, vertical distance between the weir and gate, cross-sectional area of flow that crosses the weir and gate, downstream water depth, discharge coefficient, Froude number, and Reynolds number. It is found that all these hydraulic variables and parameters depend mainly on the water flow velocity, water flow depth, and flow area that cross the weir and gate, respectively. As well, the variation in the results trend will be attributed to overlapping between weir flow velocity and gate flow velocity. The use of a weir and gate with a parabolic shape produces a slight alteration in some hydraulic features, and this can be considered one benefit of using a non-regular shape for the discharge structure. The conflict between water flow velocity and water flow depth will be reflected directly in the Froude number and Reynolds number.

I. INTRODUCTION

A weir-gate structure is referred to as a hydraulic irrigation structure that operates in order to achieve many functions, such as flow measurement, diverting the flow direction, controlling the flow depth, removing floating material by weir, and removing deposit material by gate. Therefore, this structure faces many challenges during its serviceability life, so it is very important to realize the hydraulic characteristics and geometrical dimensions of this structure in order to avoid any variation in the supply flow rate and water depth in any irrigation system during the operational period. Several papers dealt with this subject, so we selected some of these papers to give a simple review of this irrigation structure. [1] experimentally assessed the impact of oblique angles and cylinder diameter on the composite cylindrical weir-gate structure. To achieve this objective, sixteen models of composite discharge structures are tested in the flume. Four oblique angles are adopted in this study; for any angle, four diameters are used. From the results they found, the ratio of diameter to height and the ratio of length to height are inversely proportional to the flow rate; also, the flow rate will increase with increases in the diameter and decrease with decreases in the oblique angle. [2] conducted many experiments in order to build an equation to predict the real discharge, which is passed through the composite weir-gate structure. In this work, uniform and non-uniform shapes for gates and weirs are used to achieve the experiments. [3] employed the artificial neural network (ANN) in order to calculate the discharge coefficient of a composite weir-gate structure, which is composed of a trapezoidal weir and a rectangular gate. To achieve this objective, experiments are performed, and the collected data is analyzed. Also, dimensional analysis is adopted to show the variables that have an impact on the discharge structure. [4] studied numerically and experimentally water flow through a combined structure that has a weir with a trapezoidal shape and three different shapes of gate; the first has a rectangular shape, while the other two have a trapezoidal shape. Also, the study adopted a weir with a trapezoidal shape in the achieved test. The selection of these samples (models) relies on eight different flow rates that pass through them. As well, ANSYS CFX is used to perform the numerical simulation of water flow through hydraulic structures. They found that the trapezoidal gate allowed a large flow rate to pass through it as compared with the rectangular gate. [5], [6], [7], [8], performed many experiments to give a good image of the hydraulic features and geometrical features impact on the response of weir-gate structure, considering regular and non-regular shapes for weir and gate. [9] estimated the discharge coefficient of combined orifice-weir flow based on experiments and theoretical analysis. The variables that have an impact on the discharge coefficient have been determined. [10] examined experimentally the scour hole dimensions that occur downstream of the weir-gate structure. Different shapes of gates have been used, like rectangular, triangular, and semi-circular, while the weir is composed of two geometric shapes. The study dealt with the alteration of weir and gate geometry, flume flow rate, and particle size of bed material on the scour hole dimensions. [11] investigated experimentally the free flow case through a weir-gate structure, where both gate and weir have a rectangular shape. The study focused on estimating the flow rate based on reading the water depth upstream of the weir-gate structure.

The aim of this paper is to concentrate on understanding the hydraulic characteristics for the hydraulic field on both sides of the weir-gate structure and also to realize how the dominant hydraulic and geometrical variables of the weir-gate structure manage the hydraulic variables like actual discharge, flow area, which cross both weir and gate, respectively, discharge coefficient of the composite structure, and the downstream water depth. Furthermore, this study utilizes a weir-gate structure with a non-uniform shape, like a parabolic shape, to introduce and produce an excellent vision about using this shape regardless of the difficulty in the construction of this structure.

II. FLOW CALCULATION

In a free flow situation, the theoretical discharge through a composite device represents the sum of both weir discharge and gate discharge.

$$Q_{theo} = Q_W + Q_g \tag{1}$$

For parabolic weir [12].

$$Q_w = \frac{\pi}{2} \sqrt{f\, g} hu^2 \tag{2}$$

For parabolic gate, the continuity equation can be used to estimate the discharge

$$Q_g = V\, A = \sqrt{2\, g\, H}\;\; Ag \tag{3}$$

Then, the discharge coefficient can be estimated

$$Q_{act} = c_d\; Q_{theo} \tag{4}$$

$$Q_{act} = c_d \left[\frac{\pi}{2} \sqrt{f\, g} hu^2 + \sqrt{2\, g\, H}\;\; Ag\right] \tag{5}$$

Where:

H: upstream water depth (H= d + y + hu)
hu: water head above sharp crest weir
y: vertical distance between weir and gate
d: water depth of gate opening
Ag: cross sectional area of the gate (cross sectional area of the flow through the gate)
V: water velocity at gate
f: focal distance
g: acceleration due to gravity
Q_g: gate discharge
Q_{theor}: theoretical discharge
Q_{act}: actual discharge
c_d: discharge coefficient

Figure (1) reviews the definition of composite flow over parabolic weirs and under parabolic gates that has been adopted in the current paper.

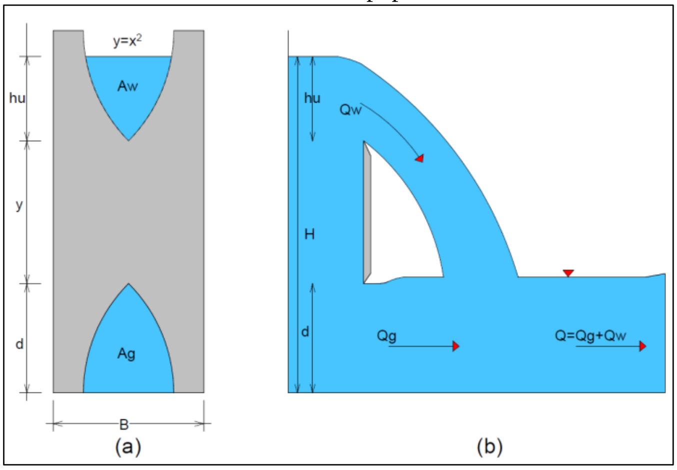

Figure 1: Definition Sketch for Composite Free Flow over parabolic Weir and below parabolic Gate (a) Cross Section (b) Longitudinal Flow and Geometry Section.
Source: Authors, (2024).

III. EXPERIMENTAL INVISTIGATION

All the experiments have been done in a flume with a rectangular section with glass sides. The dimensions of the flume are 2000 mm in length, 150 mm in depth, and 75 mm in width. The actual flow rate (actual discharge) has been measured by the volume method, and the water depth has been measured by the scale fixed in the wall of the flume. The model dimensions that have been fabricated from wood material are shown in Table (1) as well Table (2) gives all the experimental data that has been obtained in the laboratory.

The following steps are taken when conducting laboratory tests.

1- Initially, the flume is always horizontal.
2- At a distance of 80 cm from the flume's start, the models were fastened into the flume.
3- The tailgate was taken off to fulfill the free flow requirement.

For each model, the aforementioned process was repeated.

Table 1: The Tested Model Dimensions and Details of Parabolic weir and Gate

Model No.	h cm	hd cm	d cm	y cm	H cm	Ag cm^2	Aw cm^2	Vd cm/sec	Vu cm/sec
1	1	1.25	2	6	9	3.63	1.15	43.01	5.97
2	1	1.85	3	4	8	6.44	1.15	43.65	10.09
3	2	2.20	3	4	9	6.44	3.63	37.67	9.21
4	1	2.30	4	2	7	9.76	1.15	44.75	14.70
5	2	2.50	4	2	8	9.76	3.63	41.96	13.11
6	1	2.00	4	4	9	9.76	1.15	54.10	12.02
7	1	0.70	2	4	7	3.63	1.15	53.35	5.34
8	2	1.60	2	4	8	3.63	3.63	34.95	6.99
9	3	1.75	2	4	9	3.63	6.44	34.83	6.77
10	1	1.75	3	5	9	6.44	1.15	45.08	8.77
11	1	1.50	2	5	8	3.63	1.15	32.84	6.16
12	2	1.60	2	5	9	3.63	3.63	40.21	7.15
13	1	2.30	4	3	8	9.76	1.15	44.48	12.79
14	1	1.70	3	3	7	6.44	1.15	37.71	9.16
15	2	1.80	3	3	8	6.44	3.63	45.95	10.34
16	3	2.50	3	3	9	6.44	6.44	43.48	12.08

Source: Authors, (2024).

Table 2: Results of the Experimental Models

Model No.	Ag/B.H	Aw/B.H	y/H	Q_{theo} (l/sec.)	$Q_{act.}$ (l/sec.)	Cd
1	0.054	0.017	0.667	0.507	0.403	0.795
2	0.107	0.019	0.500	0.832	0.606	0.728
3	0.095	0.054	0.444	0.954	0.622	0.651
4	0.186	0.022	0.286	1.169	0.772	0.661
5	0.163	0.061	0.250	1.321	0.787	0.595
6	0.145	0.017	0.444	1.322	0.812	0.614
7	0.069	0.022	0.571	0.450	0.280	0.622
8	0.061	0.061	0.500	0.553	0.419	0.758
9	0.054	0.095	0.444	0.704	0.457	0.649
10	0.095	0.017	0.556	0.881	0.592	0.672
11	0.061	0.019	0.625	0.479	0.369	0.771
12	0.054	0.054	0.556	0.581	0.483	0.831
13	0.163	0.019	0.375	1.247	0.767	0.615
14	0.123	0.022	0.429	0.780	0.481	0.617
15	0.107	0.061	0.375	0.905	0.620	0.685
16	0.095	0.095	0.333	1.077	0.815	0.757

Source: Authors, (2024).

The following limits are applied to the testing of sixteen models: $0.222 \leq y/H \leq 0.667$, $0.054 \leq Ag/B.H \leq 0.186$, $1.366 \leq V/(gB)^{(1/2)} \leq 1.713$, $0.017 \leq Aw/B.H \leq 0.095$, $0.25 \leq hu/d \leq 1.5$. The variable B represents the total width of the channel and equal to 7.5cm. Models are manufactured of (and attached to flume using supports made of plexiglass). Based on the available lab resources, the flume and model materials were chosen. Each test involves measuring the combined flow rate (Qact), head over the weir (hu), upstream flow depth (H), and downstream flow depth, all while the flow is free.

IV. RESULTS AND DISCUSSIONS

Figure (2) illustrates the relation between the discharge coefficient and Froude number for both upstream and downstream of the combined structure, respectively. It is obvious from the figure that as the upstream Froude number increases, the discharge coefficient decreases gradually, while with a slight change in the downstream Froude number, the discharge coefficient values rise dramatically. For more visibility, the upstream and downstream Froude numbers rely on water velocity and water depth in the upstream and downstream regions of the combined structure, respectively, but the discharge coefficient mainly relies on overflow velocity from the weir and underflow velocity from the gate. Therefore, there is no direct interaction between the Froude number and the discharge coefficient. In addition, we mention here that all the values of the Froude number refer to subcritical flow.

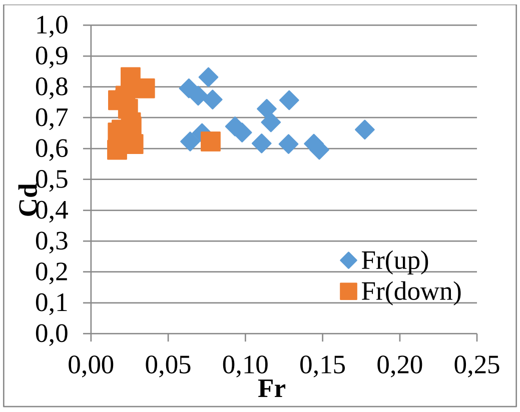

Figure 2: relation between discharge coefficient and Froude number.
Source: Authors, (2024).

Figure (3) presents the alteration of the discharge coefficient and Reynolds number downstream of the combined structure. With an increase in the Reynolds number, the values of the discharge coefficient will fluctuate slightly, so there is no noticeable change in the relationship between the two parameters in the downstream region. For more illustration, the Reynolds number relies on water velocity and water depth, while the discharge coefficient mainly relies on overflow velocity from the weir and underflow velocity from the gate. Therefore, there is no direct interaction between the Reynolds number and the discharge coefficient. All the values of the Reynolds number refer to turbulent flow.

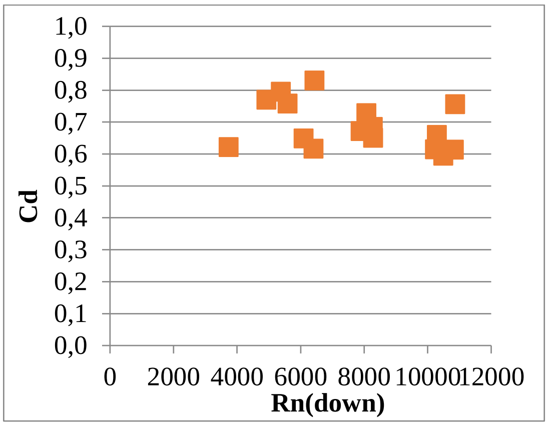

Figure 3: relation between discharge coefficient and Reynolds number.
Source: Authors, (2024).

Figure (4) presents the variation between the discharge coefficient and the ratio (h_u/H). It is evident that with an increase in the ratio (h_u/H), the slight variation in the discharge coefficient values is described, regardless of the inverse relationship between water depth above the weir crest (h_u) and discharge coefficient. Here, it is inferred that the use of non-regular weir shapes has a direct benefit on the values of the combined structure discharge coefficient.

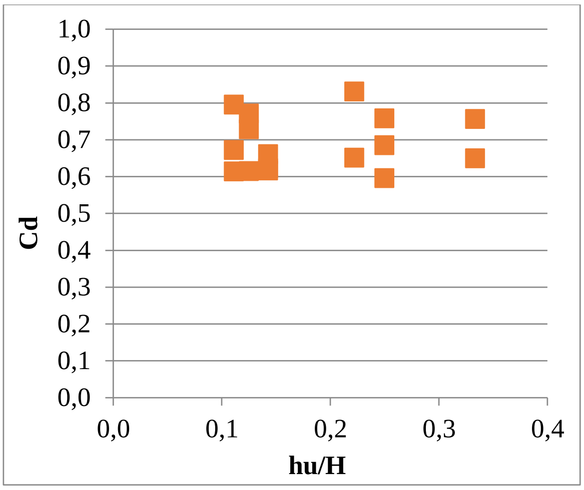

Figure 4: relation between discharge coefficient and (hu/H).
Source: Authors, (2024).

Figure (5) illustrates the relationship between the upstream Froude number and the upstream Reynolds. Figures reveal a direct relationship between the two parameters; both parameters depend on water velocity and water depth in the upstream region of the combined structure. Here, the flow velocity will dominate and be responsible for the hydraulic behavior of the regime upstream. As well, the flow velocity is directly proportional to the Reynolds number and the Froude number.

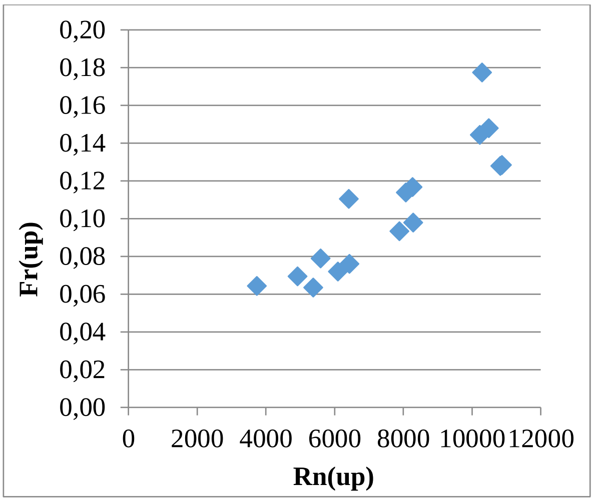

Figure 5: relation between upstream Froude number and Reynolds number.
Source: Authors, (2024).

Figure (6) illustrates the relation between the Froude number and Reynolds at the downstream region of the combined structure. Figures reveal an inverse relationship between the two parameters; both parameters depend on water velocity and water depth in the downstream region of the combined structure. The downstream water depth is considered small while the water velocity is considered high, and this conflict will be reflected mainly in the relationship trend.

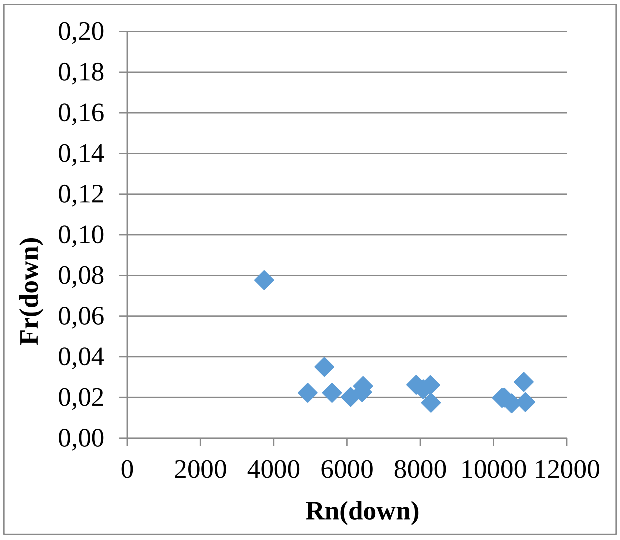

Figure 6: relation between downstream Froude number and Reynolds number.
Source: Authors, (2024).

Figure (7) presents the variation of actual discharge with the ratio(A_w/H) and$\left(A_g/H\right)$. It is shown that with an increase in both ratios, the discharge quantity increase too, owing to direct proportional relation between discharge flow and the cross-sectional area, which passes through the weir (Aw) and gate (Ag), respectively, according to continuity equation. It is visible from the figure that the gate opening shares more in increasing the discharge quantity as compared with weir. This is because the gate opening is always full of water while water depth above weir is considered changeable.

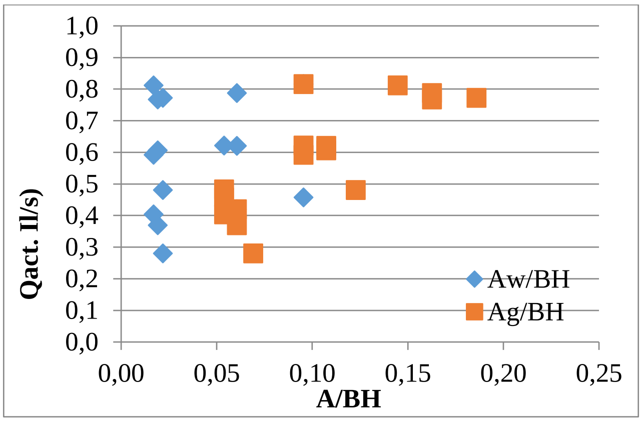

Figure 7: Relation between actual discharge and (A/BH).
Source: Authors, (2024).

The relation between the discharge coefficient and combined structure discharge is illustrated in figure (8). This figure shows a slight variation in relation to discharge coefficient and discharge quantity, regardless of the direct proportion between them. This will reflect the other benefit of using a non-regular shape for the weir and gate. Considering the purpose of discharge coefficient is to correct the total discharge quantities passing through the composite structure, it is found from the experimental study that this coefficient has moderate behavior with actual discharge passing through irregular composite structure. This is made clear from the slope of the relation between discharge coefficient and actual discharge, where it is approximately a constant slope and that signifies additional benefit to use irregular composite structure especially parabolic shape.

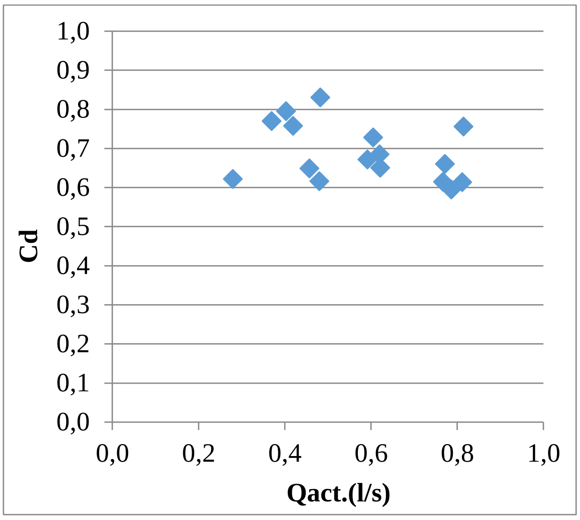

Figure 8: Relation between discharge coefficient and actual discharge.
Source: Authors, (2024).

Figure (9) presents the variation of actual discharge with the ratio(y/H) andh_u/H . It is inferred from the figure that with a decrease in ratio (yH), the discharge quantity will increase. Here, y is referred to as the vertical distance between the weir and gate, which confined some quantity of discharge behind the combined structure. So with a decrease in distance (y), this leads to an increase in discharge quantity. Also, the variation in discharge quantity with ratio (hu/H) is considered less important in spite of the water depth over weir (hu) share in the discharge quantity of the combined structure.

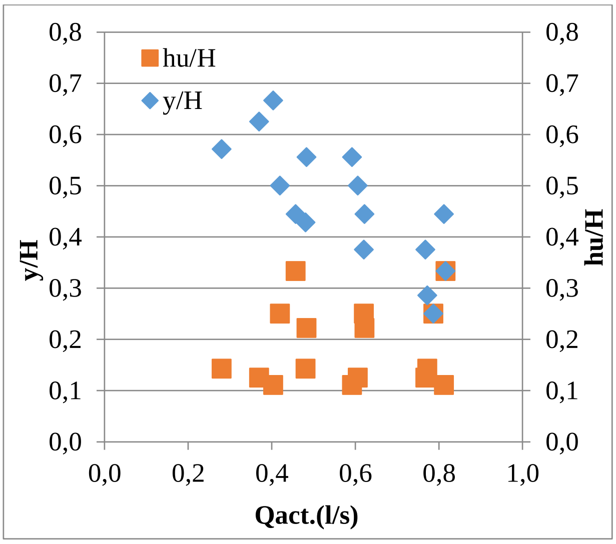

Figure 9: Relation between actual discharge with both (y/H) and (hu/H).
Source: Authors, (2024).

Figure (10) presents the variation of downstream water depth and the ratio(A_w/H) andA_g/H. Actually, any increase in the cross-sectional area of flow that crosses the weir and gate will be directly reflected in the increase in the downstream water depth, as shown clearly in figure (10). Also, it is very important to mention here that the gate opening shares more in the increase of downstream water depth as compared with the weir.

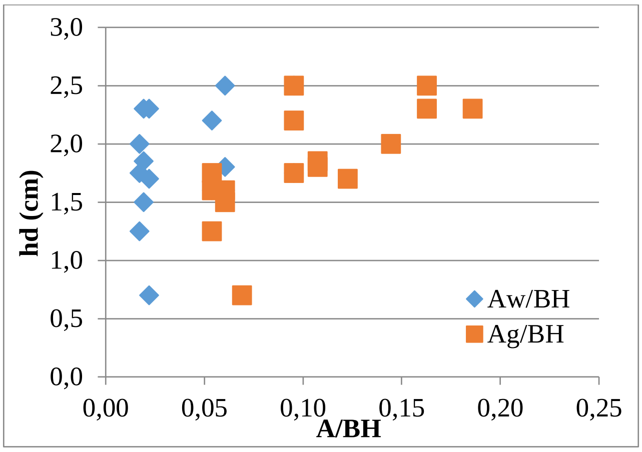

Figure 10: Relation between downstream water depth and (A/BH).
Source: Authors, (2024).

V. CONCLUSIONS

The current work deals with flow over and under combined discharge structures with non-regular shapes. From the results, we infer that the use of a weir and gate with a non-regular shape provides a reasonable hydraulic response, and this appears especially in the hydraulic relation between discharge coefficient and actual discharge, as well as discharge coefficient and ratio (hu/H). It is found that with an increase in cross-sectional area of flow that crosses the weir and gate, respectively, the actual discharge and downstream water depth increase simultaneously. There is a slight change in some hydraulic variables, and this clearly appears in the relation between discharge coefficient and actual discharge, as well as the discharge coefficient and ratio (hu/H). More than ever, it is obvious that both water velocity and water depth dominate the non-dimensional parameters such as Froude number and Reynolds number. Also, there is no theoretical equation or experimental equation connecting the combined structure discharge coefficient with Froude number and Reynolds number upstream or downstream of the combined structure, respectively. In spite of using a non-regular shape for the weir and gate, the vertical distance between the weir and gate plays a vital role in limiting some quantity of actual discharge behind the combined structure. Final, it is important to mention here in spite of the difficulty in the construction of a combined discharge structure with a weir and gate having a parabolic shape in the site, but it is recommended to use this shape due to the moderate hydraulic response or suitable values obtained for the hydraulic variables and parameters from the experimental investigation.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Methodology: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Investigation: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Discussion of results: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Writing – Original Draft: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Writing – Review and Editing: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Resources: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Supervision: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.
Approval of the final text: Ihsan A. Abdulhussein, Rafi M. Qasim, Ayad A. Yahya.

VII. ACKNOWLEDGMENTS

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