Discharge Coefficient of a Two-Rectangle Compound Weir combined with a Semicircular Gate beneath it under Various Hydraulic and Geometric Conditions

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ABSTRACT

Two-component composite hydraulic structures are commonly employed in irrigation systems. The first component, responsible for managing the overflow, is represented by a weir consisting of two rectangles. The second component, responsible for regulating the underflow, is represented by a semicircular gate. Both components are essential for measuring, directing, and controlling the flow. In this study, we experimentally investigated the flow through a combined two-rectangle sharp-crested weir with a semicircular gate placed across the channel as a control structure. The upper rectangle of the weir has a width of 20 cm, while the lower rectangle has varying widths (W_2) of 5, 7, and 9 cm and depths (z) of 6, 9, and 11 cm. Additionally, three different values were considered for the gate diameter (d), namely 8, 12, and 15 cm. These dimensions were tested interchangeably, including a weir without a gate (d = 0), under different water head conditions. The results indicate that the discharge passing through the combined structure of the two rectangles and the gate is significantly affected by the weir and gate dimensions. After analyzing the data, empirical formulas were developed to predict the discharge coefficient (C_d) of the combined structure. It is important to note that the analysis and results presented in this study are limited to the range of data that were tested.

Keywords-combound weir; semicircular gates; discharge coefficient; combined structure; open channels; discharge measurement

I. INTRODUCTION

Hydraulic structures such as gates and weirs play a crucial role in regulating the open channels flow. One advantage of using gates on their own is their ability to retain floating materials. However, this potential issue can be avoided by combining gates with weirs. Conversely, when weirs are used exclusively, sedimentation problems may arise, but these can also be addressed by combining weirs and gates [1-4]. The hydraulic behavior of these combined weir and gate structures differs from that of individual weirs or gates. They effectively resolve all the issues that may emerge when weirs and gates operate independently. Numerous studies have been conducted to accurately estimate the discharge coefficient (C_d) in cases of simultaneous flow over the weir and under the gate. Furthermore, authors in [5, 6] investigated the geometrical properties of combined structures under various hydraulic conditions, including weir width (W_2), gate diameter (d), upstream water head, combined structure width, and height.

Authors in [7] presented a governing equation for calculating the discharge over a triangular, sharp-crested weir. Additionally, several empirical equations were formulated to estimate discharge over various types of weirs [8-10]. Authors in [11] estimated the discharge of the inverted V-shaped gate in a combined system composed of a rectangular weir and a triangular gate using the discharge equation derived in [12]. Their findings indicated that the triangular gate significantly influences the combined discharge. Authors in [13] experimented with rectangular compound sharp-crested side weirs [13]. It was observed that there is no significant correlation between the upstream Froude number and the discharge coefficient. Authors in [14] conducted a comparison between the numerical results obtained from the Flow 3D software and experimental tests to investigate the flow characteristics of a compound system comprising a vertical sharp-crested weir and gate. Authors in [15] examined the flow characteristics over a combined sharp-crowned rectangular-triangular weir. Authors in [16] employed a combined structure consisting of two triangular sections with different notch angles to measure flow rates for a range of discharges. Authors in [17] tested the free flow characteristics through a combination of a triangular weir and a rectangular sluice gate. They concluded that the weir angle exhibited an inverse relationship with the discharge coefficient, which, in turn, displayed a direct correlation with the vertical distance between the weir and the gate. Authors in [18] studied the flow over a rectangular sharp-crested weir and under an inverted rectangular sharp gate. Their findings revealed that both surface tension and viscosity had a significant impact on the combined discharge. Authors in [19] explored the flow features of a combination of a V-notch weir and a rectangular sluice gate. Authors in [20] conducted experimental runs to investigate the flow dynamics beneath a rectangular sluice gate and over a trapezoidal sharp-crested weir. Their findings indicated that enlarging the gap between the lower edge of the weir and the upper edge of the gate increased the discharge coefficient of the combined structure. Authors in [21] examined the discharge coefficient of a combined structure comprising a rectangular, sharp-crowned weir and a semicircular gate. Authors in [22] studied the combined flow over sharply crested weirs and beneath gates. Authors in [23] conducted experiments on a combined triangular weir and rectangular gate structure to determine its discharge coefficient. Authors in [24] carried out experimental runs on a compound weir consisting of two rectangles separated by sloping sides, along with a circular gate beneath it. Their objective was to develop empirical equations for calculating the combined weir discharge coefficient, considering various geometric and hydraulic properties.

The primary objective of this paper is to determine the discharge coefficient of the given combined structure. Unlike the conventional use of weirs and gates separately, the combined weir and gate structure is a relatively new system that has been proposed by several researchers. The main advantage of this combined system is the reduction of sedimentation and deposition upstream of the system, particularly when it comes to discharge measurement and control of the irrigation channel flow. Integrated weir and gate systems are cost-effective in terms of operation and maintenance, as they are self-cleaning discharge measurement devices. In this study, the hydraulic characteristics of a combined overflow weir and a semicircular gate below were experimentally investigated. Additionally, we explored various dimensions of the weir and gate, including the use of a weir without a gate. This exploration aimed to develop a more precise formula for calculating the discharge coefficient for this type of structure.

II. THEORY

Figure 1 displays the composite structure's perspectives, along with a sketch depicting the concurrent flow over weirs and beneath gates. The subsequent list enumerates the independent variables that can be employed to ascertain the combined discharge, both over weirs and beneath gates:

$$C_d = f(h_1, h_2, h_3, W_1, W_2, d, W, H, Z, \rho, g, \mu, \sigma) \quad (1)$$

where C_d is the discharge coefficient, h_1 is the water head on the upper weir rectangle sill, h_2 is the water head on the lower weir rectangle sill, h_3 is the water head on the semicircular gate upstream of the combined structure, W_1 and W_2 are the upper and lower weir rectangle widths, respectively, Z is depth of the lower rectangle, d is the semicircular gate diameter, H and W are the total height and width of the combined structure, ρ is the water density, g is the gravitational acceleration, μ is the water dynamic viscosity, and σ is the water surface tension.

Applying Buckingham's π theory and its associated characteristics to (1), we can derive dimensionless groups that influence the concurrent discharge coefficient for the flow over a compound weir with a semicircular gate beneath it.

$$C_d = f\left(\frac{h_1}{H}, \frac{h_2}{H}, \frac{h_3}{H}, \frac{W_1}{W}, \frac{W_2}{W}, \frac{Z}{H}, \frac{d}{H}, R_e, W_e\right) \quad (2)$$

where R_e and W_e represent the Reynolds and Weber numbers, respectively. It is assumed that these numbers have a negligible impact on the combined structure unless the head becomes exceptionally low. It should be noted that the aforementioned nondimensional groups can be combined to generate various dimensionless numbers. Several researchers have explored in literature the relationships between discharge and water depth for gates and weirs. Authors in [25] developed the renowned equation for flow over weirs, which was reformulated using superposition as follows:

$$Q_w = \frac{2}{3}\sqrt{2g}(W_1 - W_2)h_1^{3/2} + \frac{2}{3}\sqrt{2g}\,W_2 h_2^{3/2} \quad (3)$$

where Q_w is the theoretical discharge passing through the weir.

Also, the discharge through gates was given in [26] as:

$$Q_g = \frac{\pi}{8} d^2 \sqrt{2gh_3} \quad (4)$$

where Q_g is the gate theoretical discharge.

$$Q_{th} = Q_w + Q_g \quad (5)$$

$$Q_{act} = C_d\, Q_{th} \quad (6)$$

$$Q_{act} = C_d\left(\frac{2}{3}\sqrt{2g}(W_1 - W_2)h_1^{3/2} + \frac{2}{3}\sqrt{2g}\,W_2 h_2^{3/2} + \frac{\pi}{8} d^2 \sqrt{2gh_3}\right) \quad (7)$$

where C_d is the discharge coefficient of the combined structure.

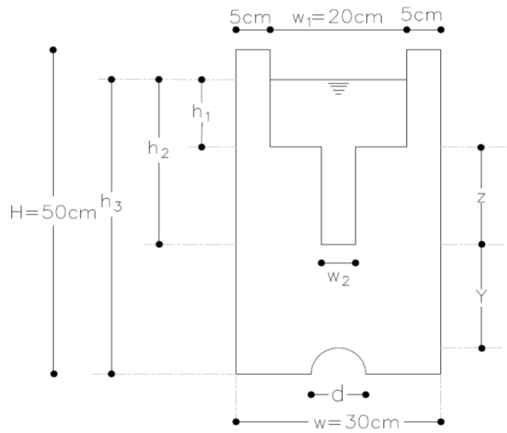

Fig. 1. Sketch of the compound weir with the semicircular gate positioned below.

III. EXPERIMENTAL SETUP

Experimental runs were carried out to achieve the purpose of this paper using a rectangular flume with dimensions of 4.0

m in length, 0.30 m in width, and 0.50 m in height. The closed water cycle is utilized by the self-contained experimental setup. A three-horsepower pump powers the flume's water-circulating system efficiently. The glassy sheets that make up the flume's side walls accommodate the experimental run observation. Baffle vertical plates were positioned at the entrance of the channel to prevent vortex motion and regulate the flow to control the damp fluctuations at the flume's entry. The exit water from the combined structure was collected into a hydraulic bench F13 type, and the volume of the collected water in the hydraulic bench was divided by the corresponding time to calculate the actual discharge (Figure 2).

Fig. 2. The flume and hydraulic bench layout.

For every experimental run, the actual discharge was determined as the average of three recorded discharge values. A vernier-type gauge with a 1 mm accuracy was used to measure the weir heads, h_1 and h_2, as well as the semicircular gate head, h_3. Calibration was performed before every experimental run to avoid instrument errors. The depth rod was precisely adjusted to the water's surface in order to guarantee that the channel's flow remained steady and constant. Throughout each experimental run, the discharge maintained constant. Rectangular sharp compound weir with a lower semicircular gate was made of acrylic glass with different lower rectangle widths and depths W_2 and Z, respectively, used for the experimental investigations. Three weir lower rectangle widths W_2 of 5, 7, and 9 cm and depths Z of 6, 9, and 11 cm were engaged. The semicircular gate below also had three diameters of 8, 12, and 15 cm. In addition, the case of employing the compound weir without the semicircular gate was considered. The mentioned dimensions were used interchangeably.

The accuracy of the discharge measurement is verified by measuring the water levels on the upstream side of the weir after completing the calibration procedure. Water levels were measured using a point gauge with a vernier scale, providing an accuracy of 1 mm. The point gauge was positioned at a location four times the maximum head over the weir upstream, in accordance with [7]. Discharge is determined by measuring the head over the weir within the weir section, as the bottom boundary effect dictates that the flow through the weir section should be in free flow.

IV. EXPERIMENTAL PROCEDURE

A total of 36 combined structure models were fabricated from acrylic glass sheets with different weir rectangles, W_2 and Z and semicircular gate diameter, d. Table I shows the form for each model, where W_2 and Z are the lower weir width and depth, respectively, and H is the height of the combined structure plate. Three weir lower rectangular widths W_2 of 5, 7, and 9 cm and depths Z of 6, 9, and 11 cm were used interchangeably with the diameter d of the semicircular gate having values of 8, 12, and 15 cm. Six experimental runs with different water heads for each setup were applied, which means that 216 experimental runs were carried out. The experimental programs are indicated in Table I.

TABLE I. EXPERIMENTAL DIMENSIONS

Semicircular gate diameter, d (cm)	Lower weir width, W_2 (cm)	Lower weir depth, Z (cm)
0 (Weir only)	5	6, 9, and 11
	7	6, 9, and 11
	9	6, 9, and 11
8 cm	5	6, 9, and 11
	7	6, 9, and 11
	9	6, 9, and 11
12 cm	5	6, 9, and 11
	7	6, 9, and 11
	9	6, 9, and 11
15 cm	5	6, 9, and 11
	7	6, 9, and 11
	9	6, 9, and 11

The following procedure was consistently adopted for each experimental run. Firstly, the model was securely fixed at the end of the flume. Next, water was incrementally introduced into the flume until the desired head over the weir was achieved. To ensure the attainment of a steady state condition, the experiment was carried out with a consistent flow rate both over the weir and beneath the gate. Using the hydraulic bench, the actual discharge for each experimental run was determined by dividing the collected water volume by the corresponding time. The conclusion of each experimental run involved turning off the pump. This same procedure should be followed for the subsequent combined structure model.

V. RESULTS AND DISCUSSION

The main aim of this paper is to demonstrate the influence of a sharp compound weir comprising two rectangular components and a semicircular gate situated below as a hydraulic control device, on the combined structure discharge coefficient (C_d). Various dimensions, including the width (W_2) and depth (Z) of the lower weir rectangle, as well as the diameter (d) of the semicircular gate, were systematically varied in the conducted experimental runs. Upon analyzing the results obtained from these experiments, a comprehensive combined structure discharge coefficient equation was ultimately formulated through regression analysis.

A. *Discharge Coefficient using the Compound Weir only (d=0)*

The effect of the gate head ratio, h_2/H, on the compound weir discharge coefficient C_d for the flow passing through with different lower rectangle width and depth values in the absence of the semicircular gate is shown in Figures 3-5. The compound weir discharge coefficient C_d increases as the head ratio h_2/H increases for lower rectangle width W_2 of 5, 7, and 9 cm and depth Z of 6, 9, and 11 cm. For W_2 of 7 cm and Z of 9 cm, increasing the head h_2 from 10.5 cm to 16.5 cm (57.14%) results in increasing the compound weir discharge coefficient C_d from 0.612 to 0.875 (42.97%). Also, C_d increases as the W_2 increases, as shown in Figure 6. For example, for h_2 = 16.1 cm, increasing W_2 by 80% (from 5 to 9 cm) leads to 4.47% (0.819 to 0.856) increase in C_d. This happens because increasing h_2 or W_2 results in an increase in the theoretical discharge, Q_{th}, with a rate less than that of the actual discharge, Q_{act}, which in turn results in an increase in the C_d value. The compound weir discharge coefficient decreases as the Z increases (Figure 7). For h_2 = 16.1 cm and W_2 = 7 cm, increasing Z from 6 to 11 cm results in a decrease in C_d from 0.88 to 0.83, which means that 83.33% increasing in Z results in 6.02% decrease in C_d.

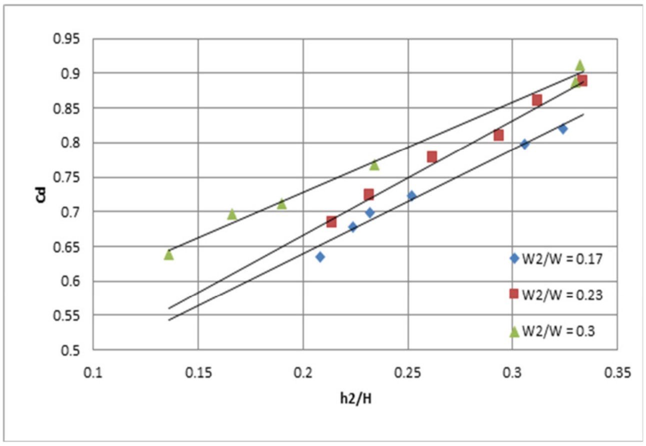

Fig. 3. Compound weir discharge coefficient C_d variation with h_2/H for Z/H = 0.22 and d/H = 0.

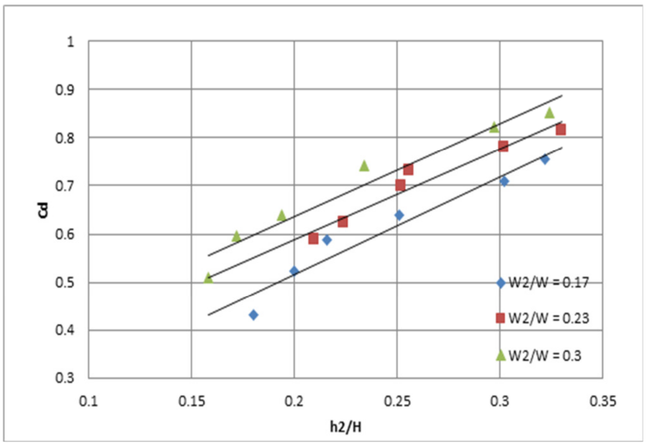

Fig. 4. Compound weir discharge coefficient C_d variation with h_2/H for Z/H = 0.18 and d/H = 0.

A general equation was developed to determine the discharge coefficient for the compound weir flow in the absence of the semicircular gate by analyzing the results and applying regression analysis.

$$C_d = 0.3517\, ln\left(\frac{h_2}{H}\right) + \left(5.638\frac{W_2}{W} - 1.67\right)\frac{Z}{H} + 1.3164 \quad (8)$$

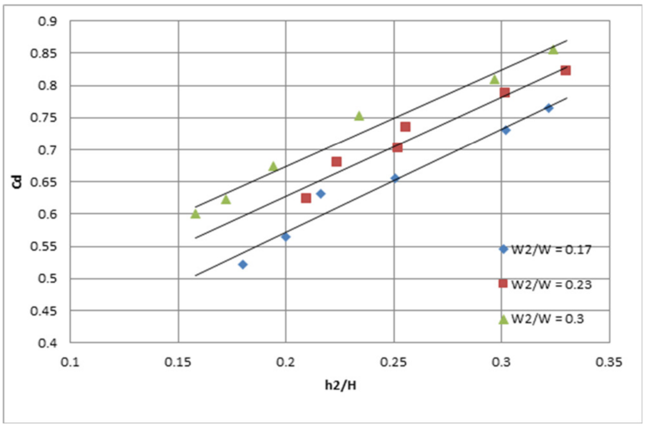

Fig. 5. Compound weir discharge coefficient C_d variation with h_2/H for Z/H = 0.12 and d/H = 0.

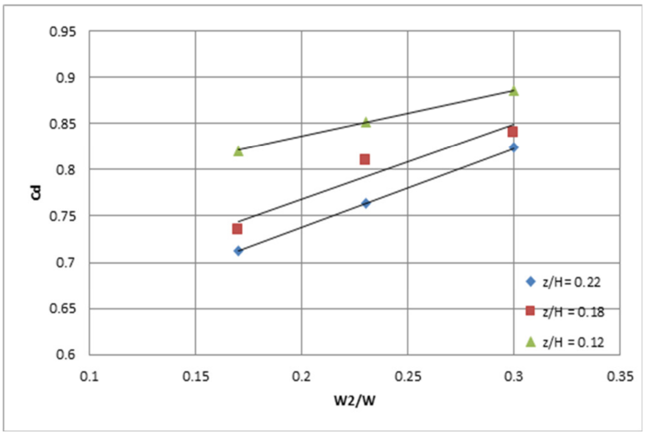

Fig. 6. Variation of C_d with W_2/W, for h_2/H = 0.32 and d/H = 0.

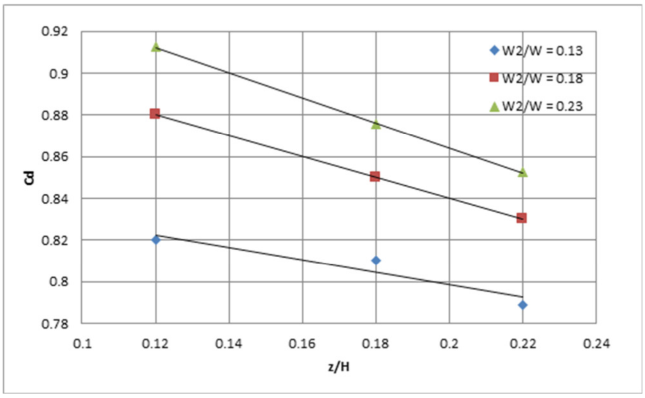

Fig. 7. Variation of C_d with z/H, for h_2/H = 0.32, and d/H = 0.

The compound discharge coefficient was computed using (8), which was determined to be a valid formula when applied to compound weir flow only, particularly when compared to the findings from earlier studies. Figure 8 illustrates the consistency between the calculated discharge coefficient, the measured discharge coefficient, and previous research results.

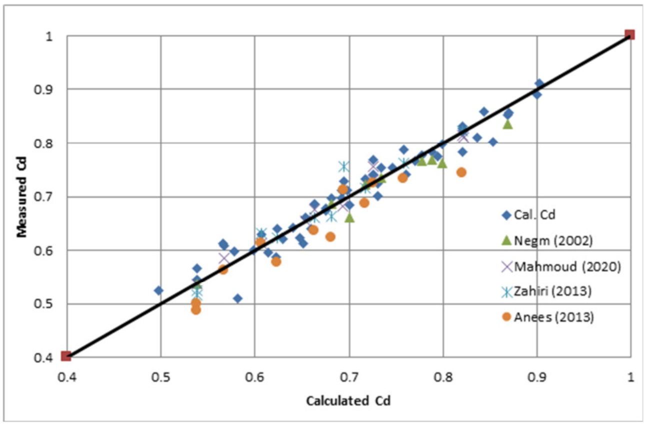

Fig. 8. Measured and calculated C_d for compound weir flow only*(d/H=* 0).

B. *Discharge Coefficient using the Combined Structure (d = 8, 12, and 15 cm)*

In this section, the discharge coefficient of the combined structure, which consists of the compound weir with the semicircular gate under it with diameters of 8, 12, and 15 cm, was calculated. For each semicircular diameter value, three values for the weir lower rectangle width of 5, 7, and 9 cm and depth of 6, 9, and 11 cm were used. Through the analysis of the obtained results, the discharge coefficient C_d for the compound weir with the semicircular gate under it increases as the water head h_2 increases (Figures 9–17).

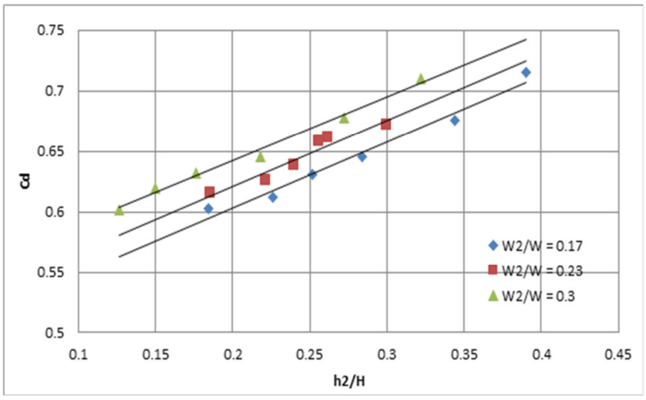

Fig. 9. Variation of C_d with h_2/H for Z/H of 0.22 and d/H of 0.16.

For example, for a W_2 = 7 cm, d = 8 cm and Z = 9 cm, it was found that changing W_2 from 11.2 to 15.2 cm changes C_d from 0.663 to 0.73. Also, it was discovered that C_d has a direct proportional relationship with W_2 (Figures 18–20).

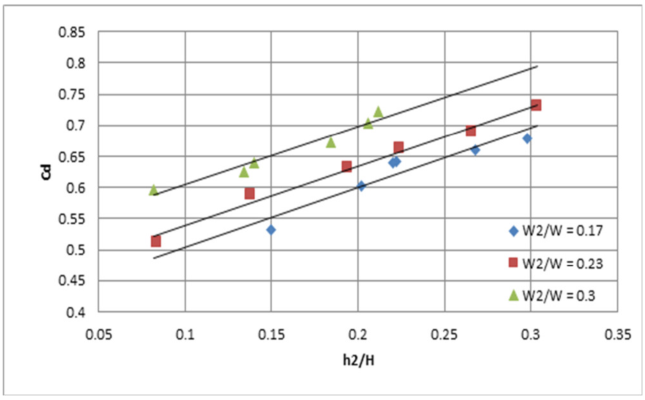

Fig. 10. Variation of C_d with h_2/H for Z/H of 0.18 and d/H of 0.16.

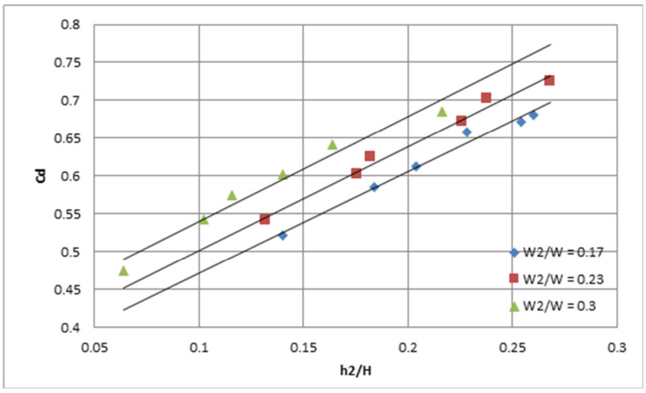

Fig. 11. Variation of C_d with h_2/H for Z/H of 0.12 and d/H of 0.16.

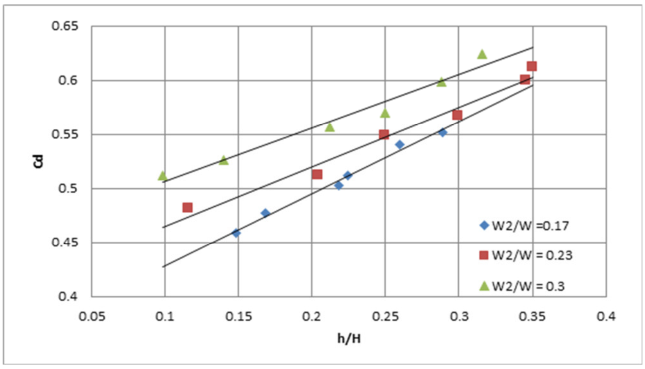

Fig. 12. Variation of C_d with h_2/H for Z/H of 0.22 and d/H of 0.24.

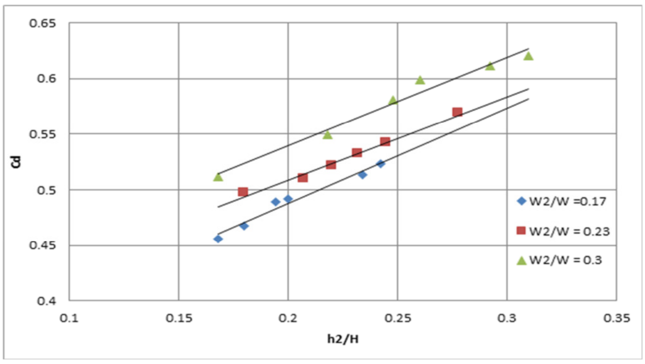

Fig. 13. Variation of C_d with h_2/H for Z/H of 0.18 and d/H of 0.24.

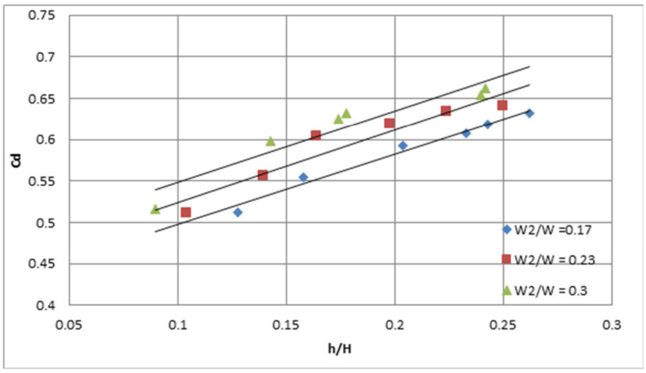

Fig. 14. Variation of C_d with h_2/H for Z/H of 0.12 and d/H of 0.24.

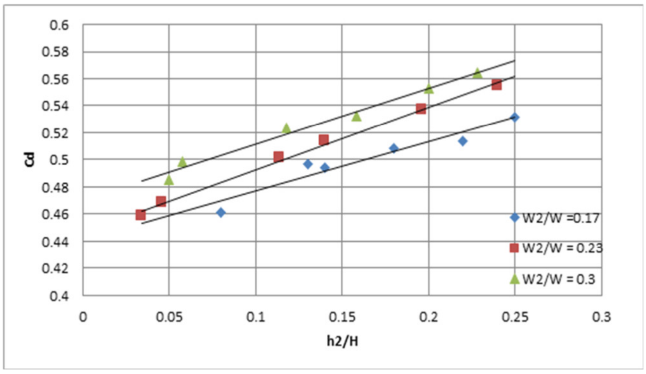

Fig. 15. Variation of C_d with h_2/H for Z/H of 0.22 and d/H of 0.30.

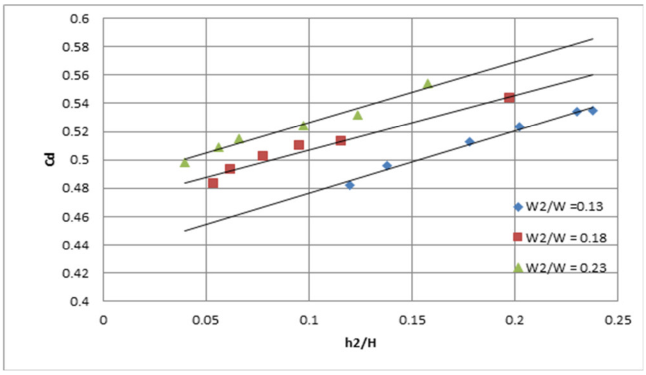

Fig. 16. Variation of C_d with h_2/H for Z/H of 0.18 and d/H of 0.30.

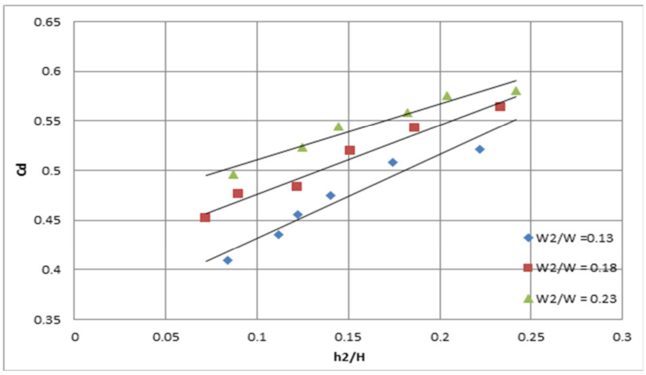

Fig. 17. Variation of C_d with h_2/H for Z/H of 0.12 and d/H of 0.30.

For instance, when W_2 changes from 5 to 9 cm for d = 8 cm, Z = 9 cm, and h_2 = 15 cm, it results in a change of C_d from 0.67 to 0.69. But the C_d of the combined structure has inversely proportional relationship with Z. It was found that for d = 8 cm, h_2 = 15 cm, and W_2 = 7 cm, increasing Z from 6 to 11 cm decreases C_d from 0.71 to 0.655, i.e., increasing Z by 83.33% leads to a decrease of 8.39% in C_d (Figures 21–23).

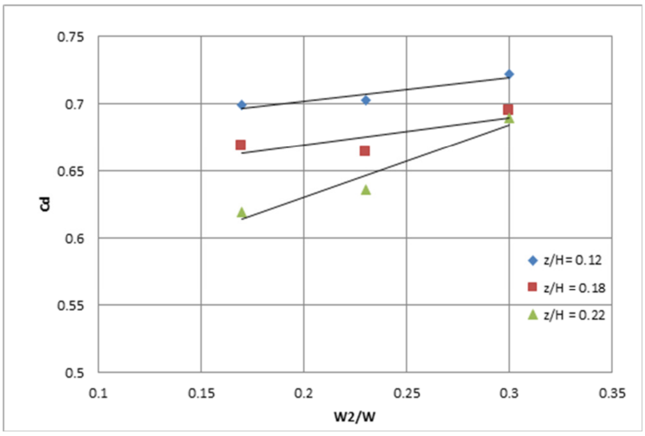

Fig. 18. Variation of Cd with W_2/W, for h_2/H = 0.3, d/H = 0.16.

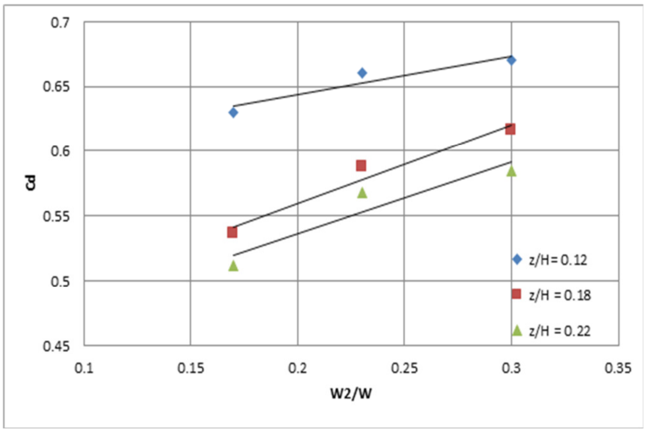

Fig. 19. Variation of C_d with W_2/W, for h_2/H = 0.3, d/H = 0.24.

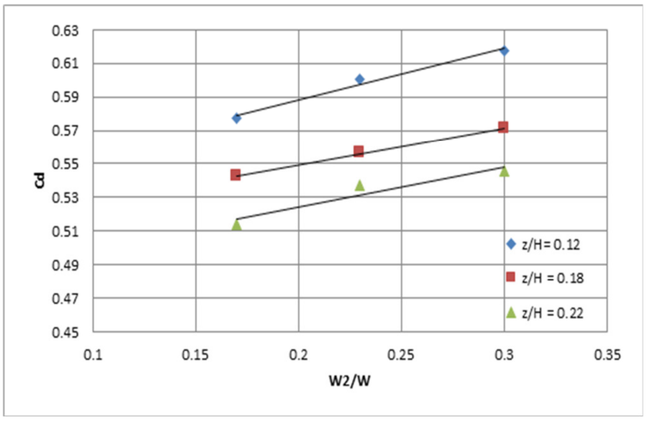

Fig. 20. Variation of C_d with W_2/W, for h_2/H = 0.3, d/H = 0.3.

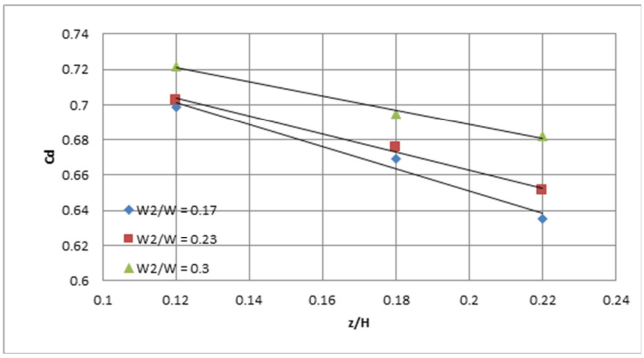

Fig. 21. Variation of C_d with z/H, for $h_2/H = 0.3$, $d/H = 0.16$.

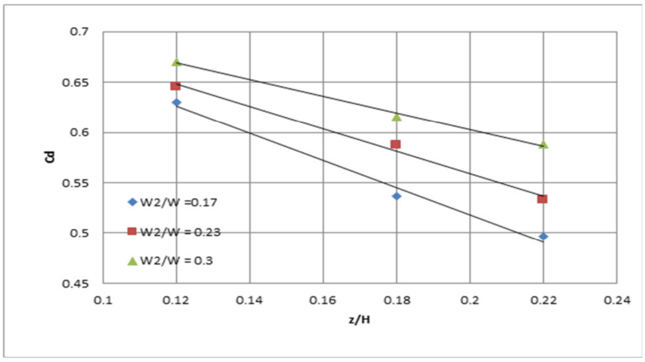

Fig. 22. Variation of C_d with z/H, for $h_2/H = 0.3$, $d/H = 0.24$.

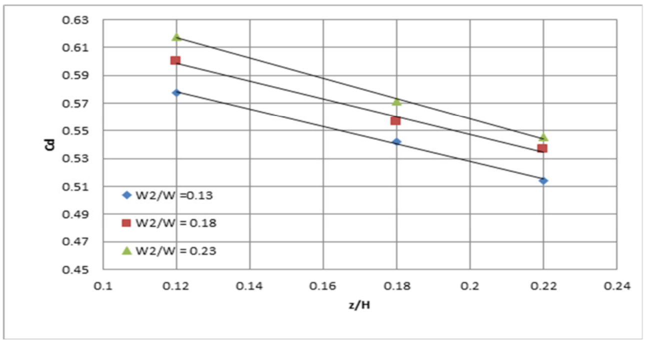

Fig. 23. Variation of C_d with z/H, for $h_2/H = 0.3$, $d/H = 0.3$.

C. Developing General Mathematical Equations

The obtained experimental results were analyzed and utilized in the development of general empirical equations through the application of the dimensionless group regression method, which was taken into consideration when estimating the combined structure discharge coefficient. A correlation between the computed dimensionless groups and the dependent values of C_d was examined. The h_2/H, W_2/W, Z/H, and C_d dimensionless groups were found to have a significant correlation. The developed empirical equations are:

- For $d/H = 0.16$:

$$C_d = \left(-0.74\left(\frac{W_2}{W}\right) + 0.259\right) ln\left(\frac{h_2}{H}\right) - 0.579\frac{Z}{H} - 1.266\,\frac{W_2}{W} + 1.1685 \quad (9)$$

- For $d/H = 0.24$:

$$C_d = \left(0.179\left(\frac{W_2}{W}\right) + 0.111\right) ln\left(\frac{h_2}{H}\right) - 0.367\frac{Z}{H} + 0.47\,\frac{W_2}{W} + 0.803 \quad (10)$$

- For $d/H = 0.30$:

$$C_d = 0.054\, ln\left(\frac{h_2}{H}\right) + \left(5.878\frac{W_2}{W} - 1.512\right)\frac{Z}{H} - 0.77\,\frac{W_2}{W} + 0.846 \quad (11)$$

These equations were validated using the experimentally measured results versus the calculated values for the discharge coefficient of the combined structure (Figures 24–26). The results show a good agreement between the experimental and the predicted values.

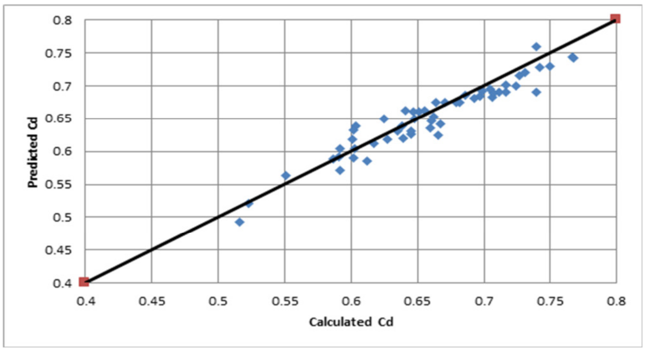

Fig. 24. Measured and calculated C_d for combined structure flow *(d/H=* 0.16).

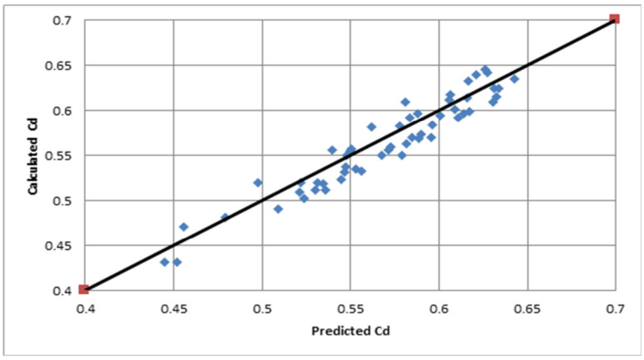

Fig. 25. Measured and calculated C_d for combined structure flow *(d/H=* 0.24).

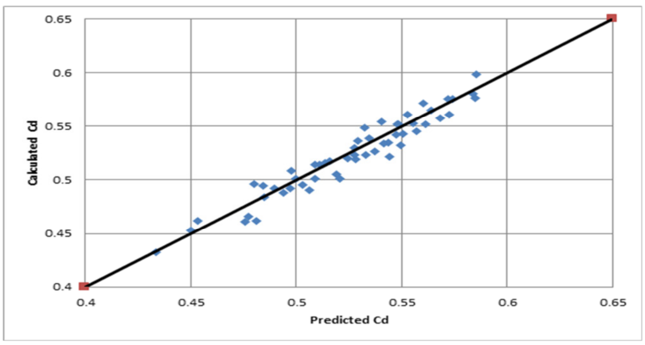

Fig. 26. Measured and calculated C_d for combined structure flow *(d/H=* 0.30).

VI. CONCLUSION

In this paper, experimental runs were conducted to explore the discharge coefficient of a combined hydraulic structure comprising a compound weir and a semicircular gate situated beneath it, under varying hydraulic and geometric conditions. The influence of parameters such as the water head over the weir lower rectangle sill (h_2), the water head over the below gate (h_3), the width of the weir lower rectangle (W_2), and its depth (Z), on the discharge coefficient were thoroughly investigated. The following conclusions were drawn:

- Based on the weir-gate width ratio, the combined structure conveyed greater discharge by approximately 2 to 10 times than the traditional rectangular notch weir, indicating that it is more effective than the traditional weir in terms of discharge capacity.
- The discharge coefficient values of the combined structure ranged from 0.46 to 0.89, with an average value of 0.675. The discharge coefficient increases when the head of water over the weir h_2/H increases for given W_2, Z, and gate diameter d.
- For a given weir lower rectangle depth Z, water head h_2, and gate diameter d, the discharge coefficient values of the combined structure increase by increasing the weir lower rectangle width ratio W_2/W.
- The developed general empirical equations can be used to calculate the discharge coefficient values of the combined structure for given h_2/H, W_2/W, and Z/H.

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