

# Hydraulic Analysis of a Combined Rectangular Sharp-Crested Weir with a Below-Rectangular Gate

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## ABSTRACT

Irrigation systems often incorporate composite hydraulic structures, consisting of two key components: a weir, responsible for managing the overflow regime, and a gate, which regulates the underflow regime. Both components are crucial for flow control, measurement, and diversion, playing a vital role in governing the hydraulic behavior of open channels or rivers with precision and reliability. This study examined the flow dynamics through a combined rectangular sharp-crested weir with a below rectangular gate used as a control structure. The experiment tested three different weir sill breadths ( $B_n$ ) of 3, 5, and 7 cm, and three gate breadths ( $B_g$ ) of 3, 5, and 7 cm. These dimensions were used in various combinations, including scenarios where either the weir or the gate was absent ( $B_g = 0$  or  $B_n = 0$ ). The results revealed that the discharge through the combined weir and the below gate system was significantly influenced by the geometric characteristics of the weir and the below gate, i.e.  $B_g$  and  $B_n$ , and the hydraulic characteristics as their heads,  $h_g$  and  $h_n$ . Empirical equations were derived to calculate the combined structure coefficient of discharge ( $C_d$ ) for the given experimental data. The findings and analyses are limited to the specific range of parameters tested in this study.

**Keywords-**composite weir; coefficient of discharge; weir and gate combination; measurements; actual discharge

## I. INTRODUCTION

Weirs and gates are hydraulic structures used to control the open channel flow. One disadvantage of using gates solely is the possibility of retaining floating materials, which can be resolved by combining them with weirs. Also, when using weirs only, the problem of sedimentation occurs. This can be resolved by combining weirs with gates. The combined weirs and gates create a new hydraulic condition that differs from the one produced by using either a weir or a gate only. This combined structure, consisting of a weir with breadth ( $B_n$ ) and an underlying gate with breadth ( $B_g$ ), offers solutions to the issues that arise when these components function independently. For the simultaneous flow through the combined structure, both the weir and the underlying gate must be considered. Many studies have been conducted to calculate the discharge and discharge coefficient ( $C_d$ ) accurately. Combined structures' geometric dimensions, such as weir breadth ( $B_n$ ), length ( $L$ ), and gate breadth ( $B_g$ ), have also been investigated for different upstream water heads [1-2]. An equation has been provided to determine the discharge over a sharp-crested triangular weir [3]. Since then, numerous empirical formulas for calculating discharge over various weir types have been created [4-7]. Discharge estimation for the inverted triangular gate underneath a rectangular weir is based

on equations developed in [8-10]. The results demonstrated that the inverted triangle gate impacts significantly the total discharge. The coefficient of discharge does not show a significant relationship with the upstream Froude number in laboratory experiments carried out using rectangular compound weirs [11]. Experimental tests investigating the flow in a compound system that includes a gate and a vertical sharp-crested weir were compared with numerical results generated by Flow 3D software [12]. The flow parameters across a triangular and rectangular weir with sharp crested edges were examined in [13]. Additionally, flow rates over a combined construction consisting of two triangular sections with different triangular angles were measured for varying discharges [14].

The characteristics of free flow through a rectangular gate underneath a triangular weir were studied in [15]. It was concluded that the discharge coefficient is inversely proportional to the weir angle and directly proportional to the vertical distance between the weir and the gate. Authors in [16] investigated the flow over a rectangular weir with a below rectangular gate and found that the combined discharge was strongly influenced by viscosity and surface tension. Meanwhile, the flow variations over a triangular weir with a below rectangular gate were examined in [17]. The flow over a trapezoidal weir with a below rectangular gate was

experimentally investigated in [18]. It was found that the separating distance between the upper edge of the gate and the lower edge of the weir results in improving the discharge coefficient of the combined construction. A combined system of a rectangular weir with a below semicircular gate was used for discharge coefficient estimation [19]. In [20], the overall flow through gates and weirs was studied, while in [21], the discharge coefficient was evaluated through experiments performed on a rectangular gate construction and a triangular weir.

In contrast to the widespread use of individual weirs and gates, the present study focuses on examining the discharge coefficient of a combined weir and gate structure, which is a relatively novel technology. The primary benefit of the combined system is its capacity to decrease upstream sedimentation and deposition, which is especially advantageous for irrigation channel flow control and discharge measurement. These integrated systems function as low-maintenance, self-cleaning discharge metering tools. In order to establish more equations for calculating the coefficient of discharge for a rectangular weir with a below rectangular gate, the study experimentally examined the hydraulics of combined overflow weirs and below-flow gates utilizing a variety of weir and gate dimensions and configurations.

## II. THEORETICAL STUDY

Figure 1 illustrates the combined structure, showing a simultaneous flow over the weirs and through the gates. The factors that affect the cumulative discharge that flows over the weirs with the gates are:

$$C_d = f(h_g, h_n, B_n, B_g, L, B, \rho, g, \mu, \sigma) \quad (1)$$

where  $C_d$  is the coefficient of discharge,  $h_g$  is the water head on the below gate,  $h_n$  is the water head on the weir,  $B_n$  is the weir breadth,  $B_g$  is the breadth of the gate opening,  $L$  and  $B$  are the total length and breadth of the combined structure plate. The water surface tension is denoted by  $\sigma$ , the dynamic viscosity by  $\mu$ , the density by  $\rho$ , and the gravitational acceleration by  $g$ .

The dimensionless parameters influencing the simultaneous discharge coefficient for the flow over the weirs and through the gates can be obtained using Buckingham's theorem, given by:

$$C_d = f\left(\frac{h_g}{L}, \frac{h_n}{L}, \frac{B_n}{L}, \frac{B_g}{L}, \frac{B}{L}, R, W\right) \quad (2)$$

In (2), Reynolds and Weber numbers are denoted by  $R$  and  $W$ , respectively. With the exception of extremely low head situations, it is believed that these values have virtually no effect on the combined device. Utilizing the aforementioned non-dimensional parameters may be useful for creating a variety of dimensionless numbers. The connection between outflow and water depth for weirs and gates has been thoroughly examined. One of the most widely recognized equations for the flow over weirs is [19]:

$$Q_w = \frac{2}{3} C_{dw} \sqrt{2g} B_n h_n^{3/2} \quad (3)$$

where  $B_n$  is the weir's effective breadth,  $h_n$  is the effective head over the weir,  $C_{dw}$  is the weir's coefficient of discharge, and  $Q_w$

is the discharge flowing through the weir. The discharge through the gates is given by [22]:

$$Q_g = C_{dg} B_g d \sqrt{2gh_g} \quad (4)$$

where the gate discharge is denoted by  $Q_g$ ,  $C_{dg}$  is the discharge coefficient for the gate, and  $d$  is the gate opening height, which is constant for all experimental runs:

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

$$Q_{act} = C_{do} Q_{th} \quad (6)$$

$$Q_{act} = C_{do} \left( \frac{2}{3} C_{dw} \sqrt{2g} B_n h_n^{3/2} + B_g d \sqrt{2gh_g} \right) \quad (7)$$

where  $C_{do}$  is the combined structure's total discharge coefficient.

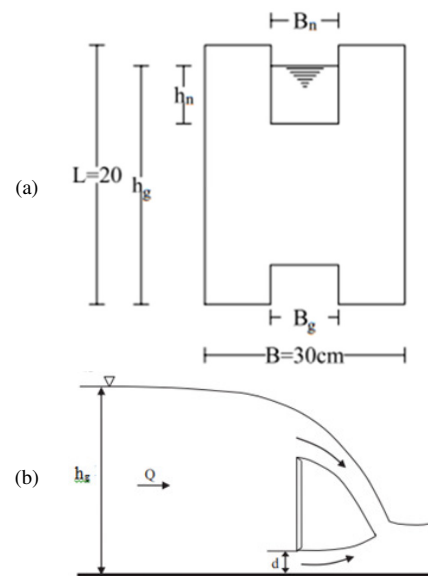


Fig. 1. Illustration of simultaneous flow over weirs and below gates: (a) front view and (b) side view.

## III. EXPERIMENTAL SETUP

An experimental flume of 4.0 m × 0.30 m × 0.50 m size was used for the tests. The flume employed a non-tilting design and was part of a self-contained system with a closed water cycle. A 3 Hp pump with was utilized to power the water circulation system within the flume. The side walls of the flume were constructed from transparent glass sheets, enabling clear observation during the experiments. To prevent vortex formation and stabilize the flow, vertical baffle plates were installed at the entrance of the flume to mitigate fluctuations. Water exiting the combined structure was flowed onto a hydraulic bench, where the actual discharge was measured by monitoring the collected water volume during a certain time period. Figure 2 depicts the flume and hydraulic bench used in the experiment. The average of three recorded discharge measurements was used to determine the actual discharge for each experimental run. A Vernier-type gauge with a 1 mm precision was utilized to measure the elevation of the bed and water surface. Calibration was performed before every

experimental run in order to reduce instrumental errors. The values of  $h_n$  and  $h_g$  were obtained by carefully adjusting the depth rod to the water's surface. During the water head measurement, it was made sure that the channel's flow stayed steady and continuous. During every trial, the discharge was kept at a steady pace. Rectangular sharp-crested weir plates of different breadths ( $B_n$ ), made of acrylic glass, were employed. Weir breadths of 3 cm, 5 cm, and 6 cm were tested, and the same values were used for the gate breadths positioned below the weir.

In addition to testing with a weir without a gate and a gate without a weir, these measurements were tested reciprocally. The computing discharge accuracy was ascertained by measuring the heads of the water upstream side of the weir after the calibration procedure was finished. The water heads were measured using a point gauge with a 1 mm accuracy Vernier scale. The point gauge was positioned upstream of the structure, four times the maximum head over the weir, according to [23]. The flow through the weir portion is categorized as free flow because of the bottom boundary effect. Therefore, the head above the weir within the weir section is used to measure the discharge.

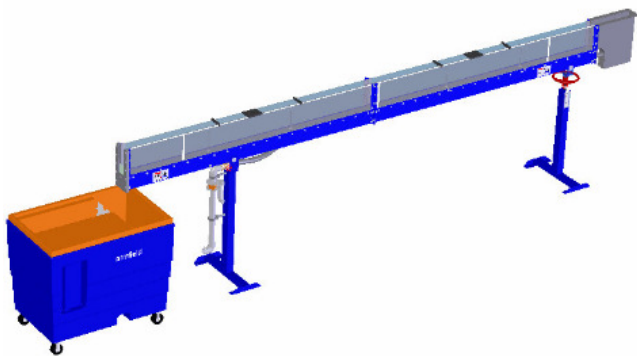


Fig. 2. The flume and the hydraulic bench set up used in the experiment.

IV. EXPERIMENTAL PROGRAM AND PROCEDURES

Acrylic glass sheets were used to create fifteen combined building models, each with a different weir and gate breadth ( $B_n$  and  $B_g$ ). The specifications for each model are shown in Table I, where  $L$  is the length of the structural plate and  $h_n$  and  $h_g$  stand for the water heads above the weir and gate, respectively. Using below gates with sill breadths of 3, 5, and 7 cm, three sill breadths of 3, 5, and 7 cm were employed and tested alternately. Table I provides a summary of the program's specifics. For each experimental run, the following procedure was followed: The model was positioned at the end of the flume, and the flume was gradually filled with water until the head over the weir reached the desired level. The experiment was conducted with a constant flow rate over the weir and through the gate, ensuring that the system reached a steady state. The hydraulic bench was used to measure the actual discharge during each run by dividing the volume of the collected water by the allotted time. The pump was shut off following each run, and the procedure was repeated using the subsequent combination.

TABLE I. EXPERIMENTAL PROGRAMS

Weir breadth $B_n$ (cm)	Gate breadth $B_g$ (cm)	Weir and gate heads, $h_n$ and $h_g$
0 (gate only)	3, 5, and 7	Six values for $h_g$ for each $B_g$
3 cm	0	Six values for $h_n$
	3, 5, and 7	Six values for each of $h_n$ and $h_g$ for each $B_g$
5 cm	0	Six values for $h_n$
	3, 5, and 7	Six values for each of $h_n$ and $h_g$ for each $B_g$
7 cm	0	Six values for $h_n$
	3, 5, and 7	Six values for each of $h_n$ and $h_g$ for each $B_g$

V. RESULTS AND DISCUSSION

This study demonstrates the effects of a sharp weir with a below gate as a hydraulic controlling device, with different weir and below gate breadths  $B_n$  and  $B_g$  installed in a straight channel on the combined structure discharge coefficient  $C_d$ . This was accomplished by analyzing the experimental results.

A. Discharge Coefficient Using Gate Only ( $B_n = 0$ )

In the absence of the weir, Figure 3 illustrates how the gate head ratio ( $h_g/L$ ) affects the gate discharge coefficient ( $C_{dg}$ ) regarding the flow through the gate with a constant gate opening. For gate breadths of 3, 5, and 7 cm, the graph shows that the gate discharge coefficient ( $C_{dg}$ ) falls as the gate head ratio rises. For instance, when the gate breadth is 5 cm, increasing the gate head ( $h_g$ ) from 12 cm to 17.84 cm (a 48.67% increase) results in a decrease in the gate discharge coefficient from 0.68 to 0.62 (a 9.7% reduction). Additionally,  $C_{dg}$  decreases as the gate breadth increases. For example, with a gate head of 13.8 cm, doubling the gate breadth ( $B_g$ ) leads to an 11.54% decrease in  $C_{dg}$ . This is because raising the gate breadth or the gate head ratio causes the theoretical discharge ( $Q_{th}$ ) to increase more quickly than the actual discharge ( $Q_{act}$ ), which lowers the discharge coefficient.

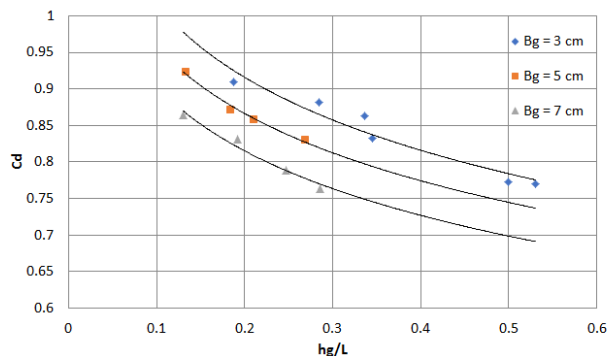


Fig. 3. Gate head ratio  $h_g/L$  with discharge coefficient for gate flow only.

Equation (8) is a general equation created by analyzing the results and using regression analysis to determine the discharge coefficient for gate flow without a weir:

$$C_{dg} = -0.4735 \frac{h_g}{L} - 0.7903 \frac{B_g}{B} + 1.0959 \quad (8)$$

Equation (6) used for calculating the gate discharge coefficient  $C_{dg}$ , was found to be acceptable in the case of the gate flow only. The agreement between the computed and measured gate discharge coefficients is displayed in Figure 4.

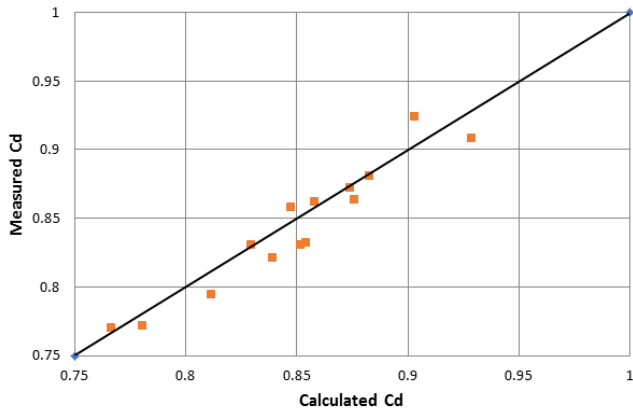


Fig. 4. Measured and calculated gate discharge coefficient for Gate flow only ( $B_n = 0$ ).

**B. Discharge Coefficient Using Weir Only ( $B_g = 0$ )**

Three weir models with breadths of 3, 5, and 7 cm, were used to develop an equation to calculate the weir discharge coefficient in case of weir flow only, *i.e.* in the absence of a below gate. As in the gate flow case, it was found that the weir discharge coefficient  $C_{dw}$  decreases as the weir head  $h_n$  and weir breadth  $B_n$  increase, as portrayed in Figure 5. For a weir breadth of 5 cm, increasing the weir head by 104% (from 3.42 cm to 6.98 cm) resulted in a 34.7% decrease in the discharge coefficient  $C_{dw}$ . Similarly, for a weir head  $h_g$  of 8 cm, increasing the weir breadth by 100% (from 3 cm to 6 cm) led to a 21.4% reduction in  $C_{dw}$  (from 0.51 to 0.42). This is because, the increase in weir breadth and weir head ratio leads to an increase in the actual discharge value, which is lower than the theoretical discharge value. Equation (9) was developed based on the analysis of the obtained results using the regression process:

$$C_{dw} = -1.514 \frac{h_n}{L} - 0.8186 \frac{B_n}{B} + 1.0568 \quad (9)$$

To investigate the applicability of (9) in the case of weir flow only, it was compared to the measured weir discharge coefficient  $C_{dw}$  values. Figure 6 demonstrates that (9) could be effectively utilized in the case of weir flow only.

**C. Discharge Coefficient Using Different Weirs and Below Gates**

The results of different combined structures, consisting of sharp rectangular weir with below gate models, were analyzed. The sharp weir breadth achieved values of 3, 5, and 7 cm, while the below gate breadth obtained the same values, which were used interchangeably. Nine models were tested based on the discussed procedures. For each model the theoretical and actual discharges were calculated, and hence the gate, weir, and total discharge coefficients,  $C_{dg}$ ,  $C_{dw}$ , and  $C_{do}$ , were respectively estimated. It was found that, the total discharge coefficient  $C_{do}$  value was between those of the weir and the gate discharge

coefficients  $C_{dw}$  and  $C_{dg}$ , as shown in Figures 7 and 9. Also, all discharge coefficients' relationship with the weir head to the gate head ratio exhibits the same trend. For example, for  $B_g = 5$  cm and  $h_n = 5.5$  cm, the total discharge coefficient of the combined structure  $C_{do}$  decreases from 0.64 to 0.54 (18.5%) as a result of increasing the weir breadth  $B_n$  by 133% (3 to 7 cm). Similarly, for  $B_n = 5$  cm and  $h_n = 5.1$  cm, if the gate breadth increases from 3 to 7 cm,  $C_{do}$  decreases from 0.63 to 0.6.

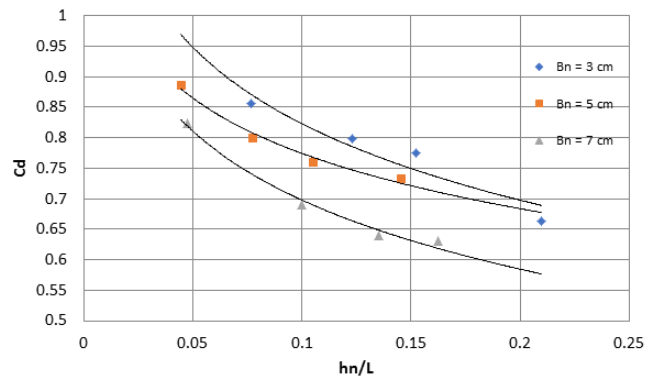


Fig. 5. Weir head ratio with the weir discharge coefficient for weir flow only.

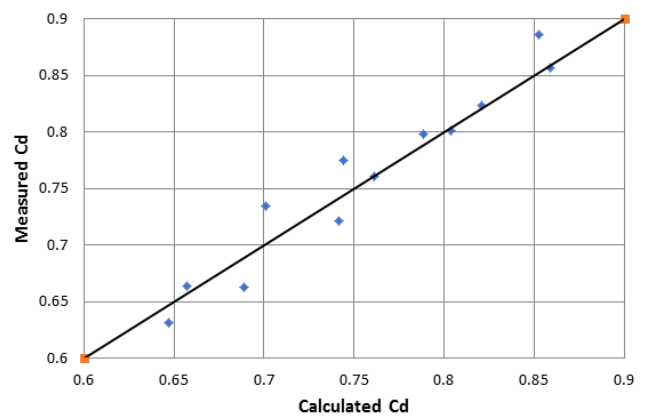


Fig. 6. Measured and calculated weir discharge coefficient for weir flow only ( $B_g/B = 0$ ).

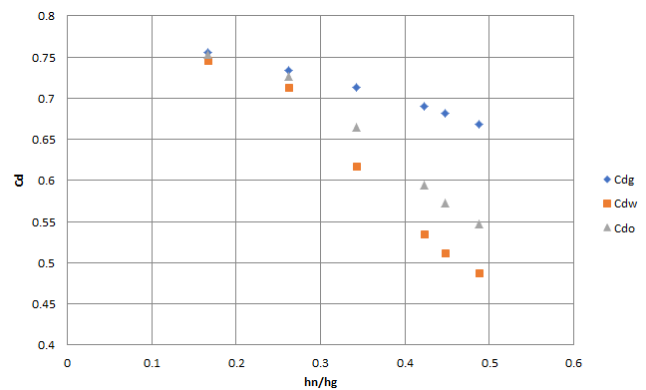


Fig. 7. Weir, gate, and total discharge coefficients  $C_{dg}$ ,  $C_{dw}$ , and  $C_{do}$  for  $B_n = 3$  cm, and  $B_g = 3$  cm.

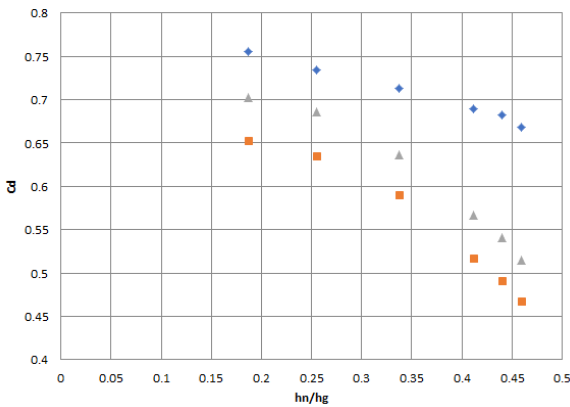


Fig. 8. Weir, gate, and total discharge coefficients  $C_{dg}$ ,  $C_{dw}$ , and  $C_{do}$  for  $B_n = 5$  cm, and  $B_g = 3$  cm.

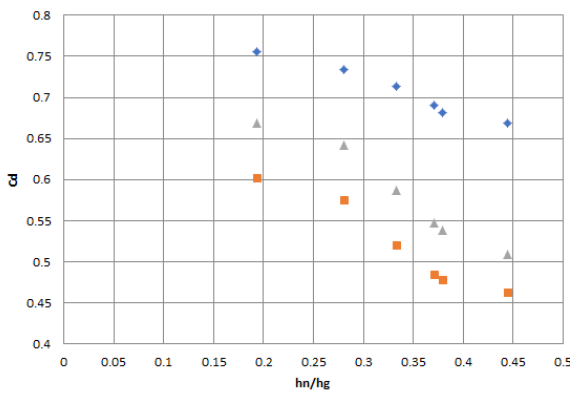


Fig. 9. Weir, gate, and total discharge coefficients  $C_{dg}$ ,  $C_{dw}$ , and  $C_{do}$  for  $B_n = 7$  cm, and  $B_g = 3$  cm.

For each gate breadth, general equations were developed for the weirs with three different weir breadths. For instance, for a gate breadth ( $B_g$ ) of 3 cm with weir breadths ( $B_n$ ) of 3 cm, 5 cm, and 7 cm, the corresponding equations were (8-10), and can be used for the calculation of the total discharge coefficient  $C_{do}$  for given  $B_g$ ,  $B_w$ ,  $h_g$ , and  $h_n$ .

For  $B_g/B = 0.1$ :

$$C_{dw} = -0.9393 \frac{h_n}{h_g} - 0.9501 \frac{B_n}{B} + 0.9802 \quad (10)$$

For  $B_g/B = 0.167$ :

$$C_{dw} = -1.5757 \frac{h_n}{h_g} - 1.54 \frac{B_n}{B} + 1.187 \quad (11)$$

For  $B_g/B = 0.233$ :

$$C_{dw} = -1.3093 \frac{h_n}{h_g} - 1.4313 \frac{B_n}{B} + 1.114 \quad (12)$$

#### D. Developing the General Mathematical Equation

Using a regression approach based on various dimensionless groups considered in the calculation of the total discharge coefficient of the combined structure ( $C_{do}$ ), the experimental findings were analyzed and employed to develop a general empirical equation. The relationship between the computed dimensionless groups and the dependent values of

$C_{do}$  was examined. The dimensionless groups ( $h_n/h_g$ ,  $B_g/B$ ,  $B_n/B$ , and  $C_{do}$ ) were shown to have a significant correlation; the empirical equation created can be expressed as:

$$C_{do} = \left(0.6675 \frac{B_g}{B} - 0.2506\right) \ln\left(\frac{h_n}{h_g}\right) + \left(0.675 \frac{B_g}{B} - 0.19\right) \ln\left(\frac{B_n}{B}\right) + 1.8287 \frac{B_g}{B} - 0.0094 \quad (13)$$

By contrasting the calculated and experimentally measured values of the total discharge coefficient ( $C_{do}$ ) for the combined structure, as seen in Figure 10, (13) was verified. The findings show that the anticipated and experimental values correspond quite well. The results were compared with equations from previous research to confirm (13) and further evaluate the accuracy of the measured  $C_{do}$ . The results were within the range of the calculated values, as displayed in Figure 11, where a good correlation and a comparable trend with prior research are also demonstrated.

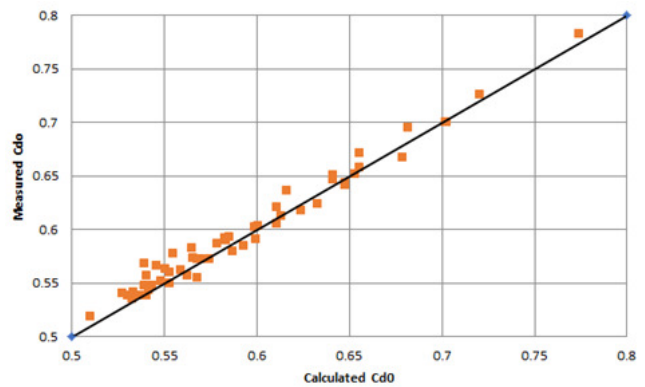


Fig. 10. Comparison between observed and calculated values of total discharge coefficient.

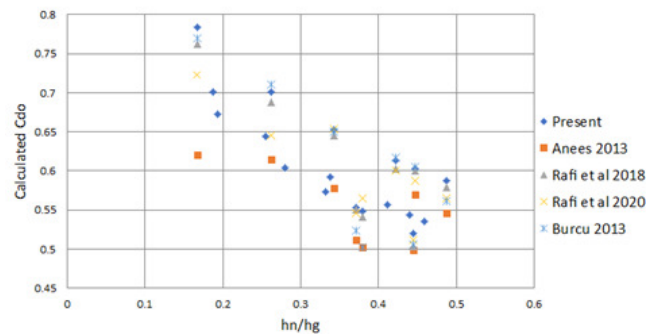


Fig. 11. Comparison between the calculated  $D_{do}$  of the present study and  $D_{do}$  calculated using other formulas .

## VI. CONCLUSION

In this study, the total discharge coefficient of a combined hydraulic structure consisting of a submerged rectangular gate positioned below a sharp crested weir was experimentally investigated to address the limited understanding of flow characteristics through such integrated systems. Traditional weirs and gates are widely used for flow regulation, yet the behavior of combined systems, particularly regarding discharge

efficiency, remains underexplored. The present work attempted to fill this gap by systematically examining the influence of various hydraulic and geometric parameters on discharge performance.

A series of laboratory experiments were conducted using three different sill breadths (3, 5, and 7 cm) for both the weir and the gate, under constant water head conditions. The main variables studied included the water head above the weir sill ( $h_n$ ), the water head at the submerged gate ( $h_g$ ), the weir breadth ( $B_n$ ), and the gate breadth ( $B_g$ ). These factors were assessed in terms of their impact on the total discharge coefficient of the structure.

The results demonstrated that the combined weir-gate configuration significantly enhances discharge capacity compared to the conventional sharp-crested weir. In particular, the discharge conveyed by the proposed structure was found to be 2-10 times greater than that of a traditional rectangular notch weir, depending on the breadth ratio between the gate and the weir. The total discharge coefficient ranged from 0.50 to 0.78, with an average value of 0.64. It was observed to decrease with an increasing  $h_n/h_g$  ratio for fixed gate and weir breadths, but it increased with larger weir and gate breadth ratios ( $B_n/B$  and  $B_g/B$ , respectively) when the water heads were held constant.

Furthermore, the combined structure's total discharge coefficient consistently fell between the discharge coefficients of the individual components, with the gate discharge coefficient ( $C_{dg}$ ) representing the upper bound and the weir discharge coefficient ( $C_{dw}$ ) the lower bound. This positioning highlights the complementary hydraulic behavior of the integrated system. A general empirical equation was developed to predict the total discharge coefficient based on the key dimensionless ratios  $h_n/h_g$ ,  $B_g/B$ , and  $B_n/B$ , offering a practical tool for engineering applications.

This study provides a novel approach by quantifying the discharge characteristics of a combined weir-gate system and offering a predictive model for its performance. Compared to conventional weirs, the integrated design exhibits substantially higher discharge efficiency, underscoring its potential for more effective water management in hydraulic engineering applications.

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