The Hydraulic Performance Evaluation of a Compound Sharp Crested Weir with a Modified Trapezoidal–Semicircular Configuration

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ABSTRACT

In this study, experimental work was performed to represent the flow within an open channel and through a compound weir of semi-circular and trapezoidal sections for different flow conditions. This study aims to evaluate the hydraulic performance of the compound weir by finding the value of the coefficient of discharge, C_d, and deriving an equation linking the value of C_d to the rest of the hydraulic and geometric parameters governing the flow conditions. Fifteen laboratory models of a sharp-crested compound weir were tested inside a laboratory channel with dimensions of 0.3 m wide, 0.45 m high, and 15 m long. The dimensions of the compound weir opening were changed while maintaining the general shape, which consisted of a trapezoidal part with a different side slope (θ) and a semicircular part that remained constant. The effects of water depth over the crest of compound weir (h), the depth of water upstream compound weir (h_u), the diameter of the semi-circular part (D), the width of the first base of the trapezoidal part (b_1), the width of the second base of the trapezoidal part (b_2), the perpendicular height of the trapezoidal part, and the slope of the trapezoidal side (θ) were taken into consideration in deriving a non-dimensional formula representing the relationship between these parameters and C_d. Using Excel 365 and SPSS 26 software, a non-linear relationship was derived to estimate C_d, and a good value of the coefficient of determination (R^2) was achieved.

Keywords-compound weir; coefficient of discharge; trapezoidal weir; semi-circular weir; actual discharge

I. INTRODUCTION

Weirs are the most common structures that are used for measuring the flow in irrigation channels. Many researchers have investigated the hydraulic performance of different types of weirs according to many classifications, depending on the type of edge (i.e., sharp or broad) or the geometry of the weir. Sharp crested weirs are formed as rectangular, triangular, trapezoidal, and semi-circular weirs or compounds of two or more of the above-mentioned shapes.

Authors in [1] experimentally investigated scour hole dimensions downstream of combined gate and compound weir structures. They conducted 75 experiments in a laboratory flume using 15 models with varying gate shapes and derived the relationships between the discharge coefficient, C_d, and non-dimensional depth and length. The hydraulic characteristics of combined flow beneath rectangular gates and over curved weirs were experimentally investigated in [2]. The authors conducted several laboratory experiments using 6 models of combined parabolic bottom triangular weirs with two different weir angles (θ_w = 45° and 60°), varying parameters such as the distance between the weir and the gate (Z), the weir opening ratio (b_w/h_w) and head over the weir (h_w). They developed discharge equations relating these parameters to the discharge coefficient, which showed good agreement with the experimental results.

In [3], the flow characteristics over sharp-crested weirs in rectangular open channels were numerically investigated using the k-ε turbulence model. The study focused on predicting water surface profiles, velocity, and pressure distributions, and validated the results using experimental data. The Volume of Fluid (VOF) method was applied to accurately simulate the free surface. The model effectively estimated all the geometric and hydraulic parameters of the weir and was extended to simulate the flow over broad-crested weirs. This approach significantly reduces the need for costly and time-consuming laboratory experiments and helps to evaluate the influence of geometric details, especially at the inlet and outlet boundaries. Authors in [4] investigated the flow over sharp-crested weirs of different shapes and openings using numerical simulations. They analyzed the effects of geometry on the velocity, pressure, water surface profiles, and discharge coefficients. The VOF method and renormalization group k-ε model in OpenFOAM software were used for the simulations, and they showed good agreement with a correlation coefficient of 0.96. For a discharge of 0.05183 m³/s without contraction, the discharge coefficients were 1.20, 0.68, and 0.51 for the rectangular, trapezoidal, and triangular weirs, respectively. In [5], C_d was analyzed and determined for a combined structure consisting of a semicircular sluice gate and compound weir of trapezoidal and rectangular notches. Fifteen models were built from 3 mm thick Plexiglas with 2 mm beveled edges. The results showed that C_d increases with higher non-dimensional parameters (H/D, H_1/D, H_2/D, and H_3/D) and with increasing W at a constant X. However, C_d decreases as Z and Y increase. The C_d ranged between 0.427 and 0.54. Al-Saadi experimentally investigated the hydraulic performance of various weirs and combined weir-gate structures, including rectangular, V-notch, semicircular weirs, and combinations with rectangular or semicircular gates [6]. The results showed that semicircular gates and compound semicircular weirs achieved the highest discharge coefficients C_d compared to other shapes.

This study contributes to improving the accuracy of flow measurement and the efficiency of hydraulic structures by introducing a modified compound weir geometry that enhances discharge capacity and offers a practical, low-cost alternative for flow control in open channels.

II. DIMENSIONAL ANALYSIS

As shown in Figure 1(a), the structure of the compound weir consists of circular and trapezoidal weirs with different dimensions. By utilizing dimensional analysis for the variables shown in Figure 1(b), the free actual discharge can be expressed in a functional form as:

$$Q_{act} = f(h_u, h_i, h_{cr}, h_s, h_t, b_1, b_2, y, \theta, D, \rho, g, \mu, \sigma) \quad (1)$$

where, Q_{act} is the actual discharge of compound weir (L^3T^{-1}), h_u is the depth of water upstream compound weir (L), h_i is the initial depth of hydraulic jump formed D/S compound weir (L), h_{cr} is the critical depth of hydraulic jump downstream compound weir (L), h_s is the sequent depth of hydraulic jump downstream compound weir (L), h_t is the tailwater depth near the tailgate of the flume (L), b_1 is the lower width of the trapezoidal part of the compound weir (L), b_2 is the upper width of the trapezoidal part of the compound weir (L), y is the height of the trapezoidal part of the compound weir (L), θ is the inclination for both sides of the trapezoidal section of compound weir, D is the diameter of the circular part of compound weir (L), P is the mass density of water (ML^{-3}), G is the gravitational acceleration (LT^{-2}), μ is the dynamic viscosity of water ($ML^{-1}T^{-1}$), and Σ is the surface tension of water (MT^{-2}). Using Buckingham's Pi-theorem, we can obtain [7, 8]:

$$C_d = f\left(\frac{h_i}{D}, \frac{h_{cr}}{D}, \frac{h_s}{D}, \frac{h_t}{D}, \frac{b_1}{D}, \frac{b_2}{D}, \frac{y}{D}, \theta, Re, We\right) \quad (2)$$

where C_d is the discharge coefficient, Re is the Reynolds number, and We is the Weber number. The values of the Reynolds and Weber numbers are not affected by turbulent flow and neglecting surface tension (2) can be written as:

$$C_d = f\left(\frac{h_i}{D}, \frac{h_{cr}}{D}, \frac{h_s}{D}, \frac{h_t}{D}, \frac{b_1}{D}, \frac{b_2}{D}, \frac{y}{D}, \theta\right) \quad (3)$$

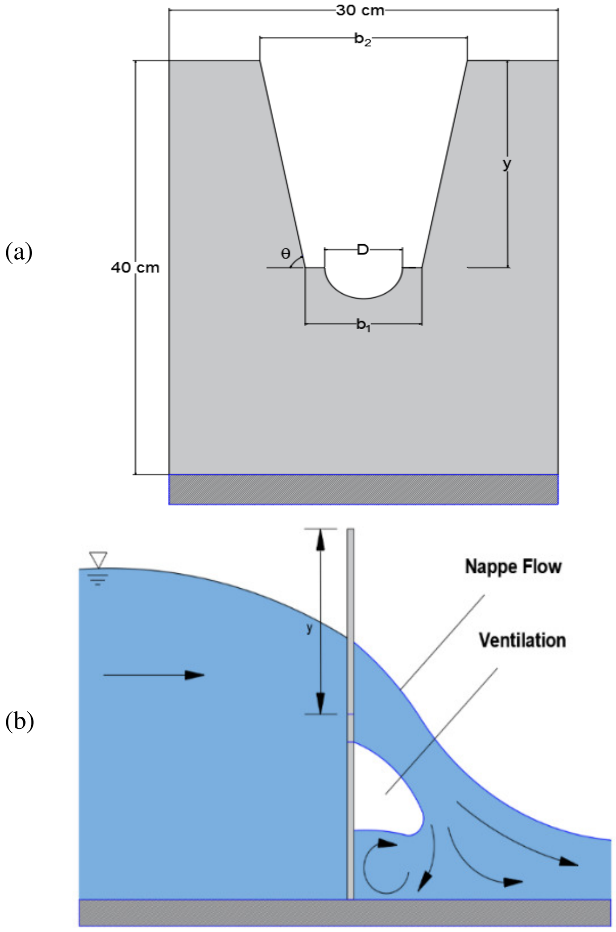

Fig. 1. General sketch of the laboratory model, a) front view and b) side view.

III. LABORATORY MODELS

Five groups of 15 combined models were manufactured using 0.8 cm thick MDF sheets. The specifications and dimensions for each model are detailed in Table I. The compound weir components and all the examined models shared the following geometric parameters:

1. Uniform model dimensions 0.3 m width × 0.4 m height.
2. Circular section dimensions 6 - 14 cm.
3. Trapezoidal section side slopes of 80°- 90°.

TABLE I. THE GEOMETRIC DETAILS FOR EACH MODEL

Groups	Model	b_1 (cm)	b_2 (cm)	D (cm)	θ^o	y (cm)
G1	1	16	9	6	80	20
	2		12.5		85	
	3		16		90	
G2	4	18	11	8	80	17.5
	5		15		85	
	6		18		90	
G3	7	20	14.7	10	80	15
	8		17		85	
	9		20		90	
G4	10	22	17.6	12	80	12.5
	11		19.8		85	
	12		22		90	
G5	13	24	20.5	14	80	10
	14		22.3		85	
	15		24		90	

IV. EXPERIMENTAL WORK

Laboratory experiments were conducted in a flume (0.3 m width × 0.45 m height × 15 m length), as shown in Figure 2. The laboratory models were divided into five groups based on the diameter of the circular part, the dimension b_1, and the height of the trapezoidal part (y).

Fig. 2. The laboratory flume.

A calibration process was conducted on the flume using a standard weir designed according to the United States Department of the Interior Bureau of Reclamation (USBR) limitations for a standard sharp-crested weir with a 90° V notch [9]. The laboratory model was installed 3 m downstream of the main gate of the flume (Figure 3). Figure 4 shows the model used in the experiment. Five flow values were applied to each model to assess the hydraulic performance of the compound weir. The water depth upstream of the structure h_u was monitored for each run. Additionally, the hydraulic jump that occurred downstream of the structure was used to estimate the initial depth h_i, the critical depth, h_{cr}, and the subsequent depth, h_s. For every test, the tailwater depth near the tailgate was considered and measured.

Fig. 3. Laboratory model attached to the flume.

Fig. 4. Laboratory model under run.

V. RESULTS AND DISCUSSION

A. Variation of Coefficient of Discharge

The experimental data for the 15 models are presented in Figures 5-8. These figures illustrate the variation in C_d with the actual discharge through the combined structure. Notably, the results indicate an inverse relationship between C_d and the dimensionless parameters h_i/D, h_{cr}/D, h_s/D, and h_t/D, where C_d increases as these ratios decrease.

As shown in Figure 5, the relation between C_d and h_i/D is negative because for larger h_i/D values (greater initial depth relative to D), the jump is less intense because the relative energy difference is smaller. This reduces energy dissipation and results in lower resistance, leading to a lower C_d. Conversely, for smaller h_i/D values, the flow has more kinetic energy relative to its depth, creating a more turbulent jump. This turbulence increases energy loss and raises the value of C_d. The relationship between the C_d and the non-dimensional critical depth, h_{cr}/D, for hydraulic jump is closely tied to the physical processes governing energy dissipation, flow behavior, and geometry of the structure.

Figure 6 illustrates the negative correlation between C_d and dimensionless parameter h_{cr}/D. This relationship can be attributed to the intensified hydraulic jump that occurs when the critical depth (h_{cr}) is small relative to the diameter, resulting in higher velocity and lower depth during the flow transition. Consequently, increased turbulence and energy dissipation lead to reduced discharge efficiency, which paradoxically corresponds to higher C_d values due to the inherent definition of the discharge coefficient. Figure 7 reveals a relationship between the sequent depth ratio (h_s/D) and the flow regime. At lower h_s/D values, the flow is predominantly subcritical, characterized by stable flow conditions and minimal energy losses, resulting in higher discharge coefficients. As h_s/D increases, the flow transitions to a supercritical regime, marked by high velocities, turbulence, and increased energy dissipation, ultimately leading to decreased flow efficiency and reduced C_d values. According to Figure 8, the coefficient of discharge decreases when the value of non-dimensional tailwater depth (h_t/D) increases. When tailwater drops that means the flow is in a free-flow condition, where gravity dominates, and the discharge follows the classical theoretical equations. As tailwater levels rise, the flow over the weir becomes submerged, and the discharge behavior shifts to a submerged flow.

Therefore, under submerged conditions, the free jet across the structure loses energy rapidly, leading to increased energy dissipation and reduced discharge coefficient owing to decreasing flow efficiency.

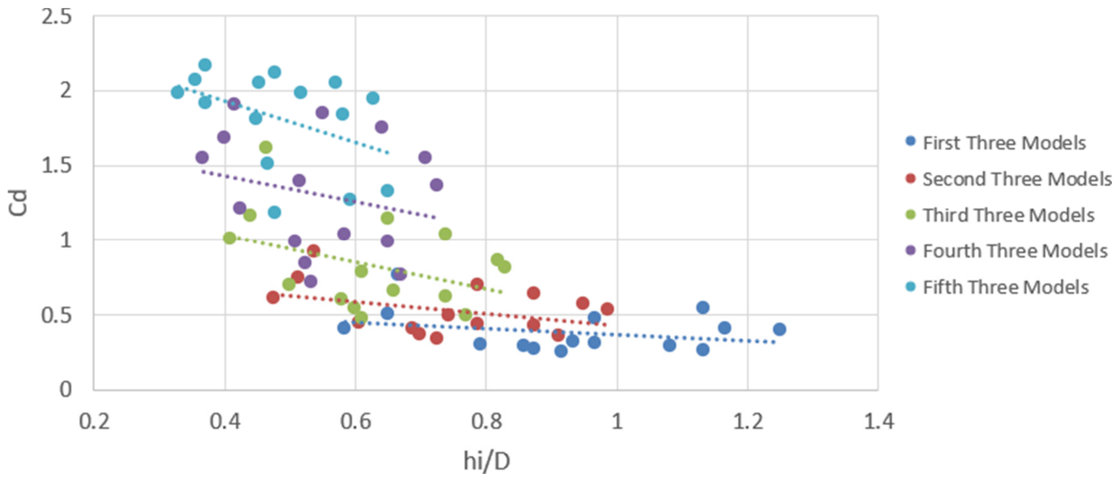

Fig. 5. Variation of the discharge coefficient C_d and $\frac{h_i}{D}$ for different groups.

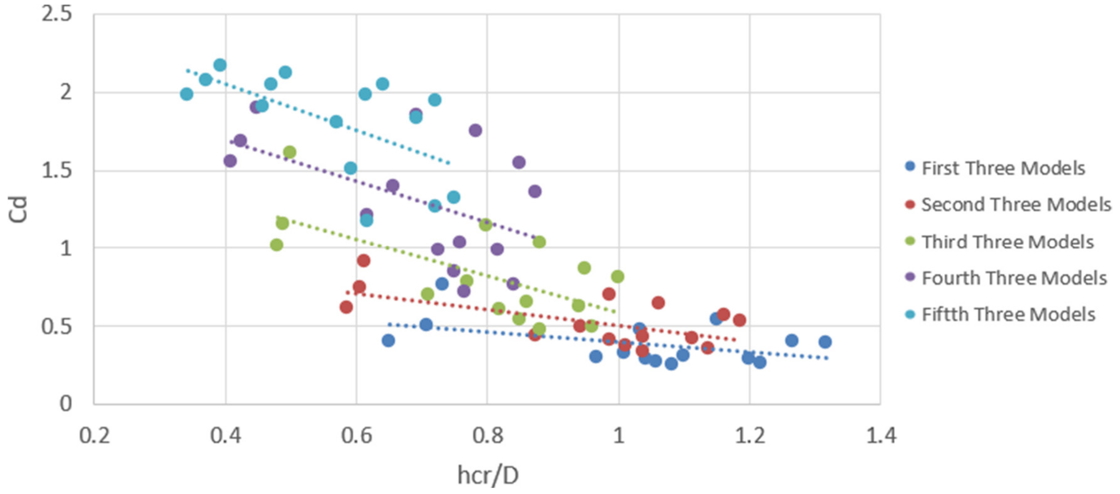

Fig. 6. Variation of the discharge coefficient C_d and $\frac{h_{cr}}{D}$ for different groups.

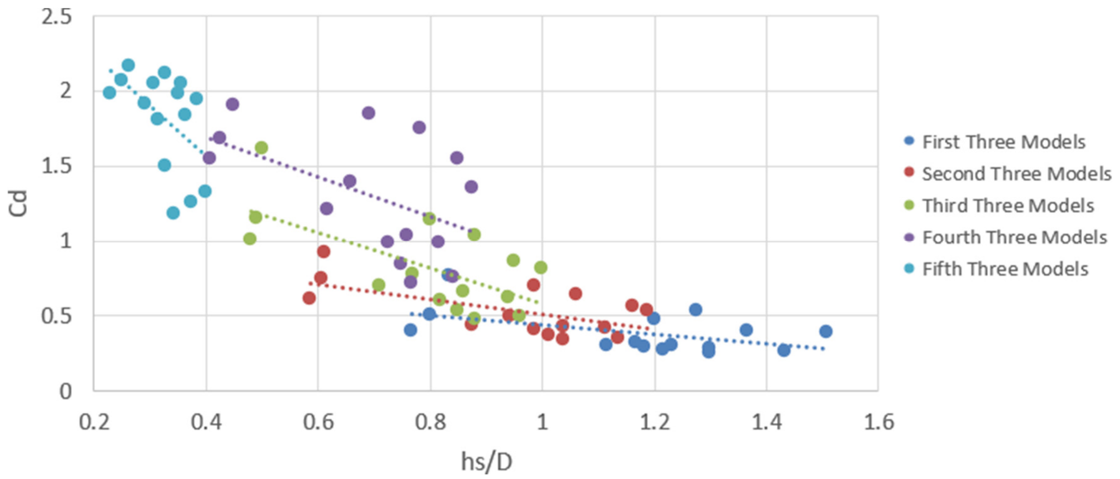

Fig. 7. Variation of the discharge coefficient C_d and $\frac{h_s}{D}$ for different groups.

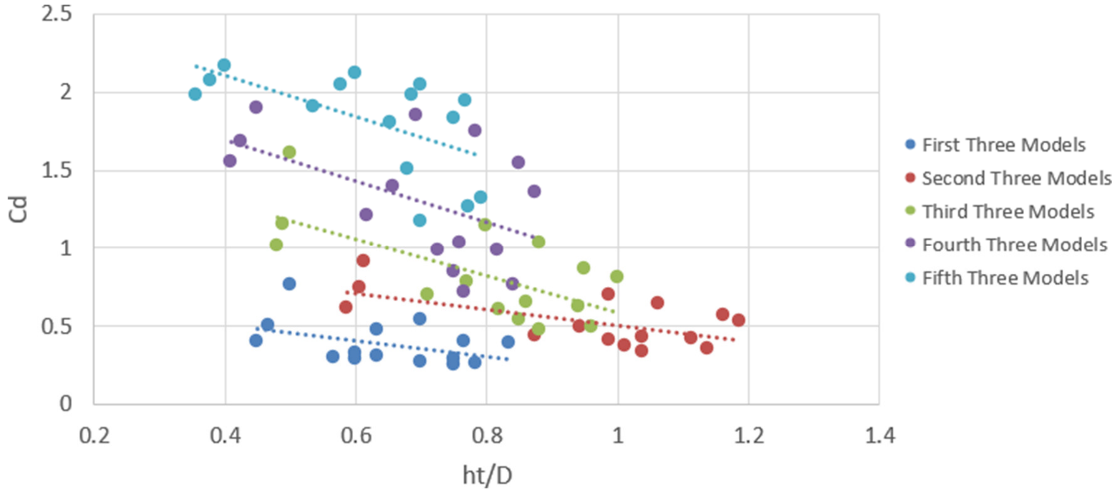

Fig. 8. Variation of the discharge coefficient C_d and $\frac{h_t}{D}$ for different groups.

B. Derivation of a New Formula

Using the experimental results for dimensional analysis parameters as input data in (IBM Statistics SPSS 26) and for non-linear regression between C_d and other parameters, the resulting relationship is:

$$C_d = 4.201\left(\frac{h_i}{h_s}\right) + \left(\frac{h_{cr}}{D}\right)^{-0.89} + 0.681\left(\frac{h_t}{D}\right)^{1.619} + 0.334\left(\frac{b_1}{b_2}\right) + \frac{\theta^{0.023}.D}{y} - 5.066 \qquad (4)$$

The coefficient of determination (R^2) for this formula is 0.906.

VI. CONCLUSIONS

The following conclusions were drawn based on the limitations of this study. First, the values of C_d increased with decreasing values of the other non-dimensional parameters (h_i/D, h_{cr}/D, h_s/D, and h_t/D). For the first three models, the value of C_d ranges from 0.25 to 0.76, and for the second three models range between 0.34 to 0.92. For the third three models, the values of C_d ranged from 0.473 to 1.61, and for the fourth three models, they ranged from 0.715 to 1.9. The values of C_d for the fifth three values ranged from 1.17 to 2.16.

At lower h_i/D, the flow was dominated by inertial forces, leading to higher momentum exchange during the hydraulic jump. This enhanced turbulence and energy dissipation, thereby increasing C_d. At higher h_i/D values, gravitational forces dominated over inertial forces, stabilizing the flow and reducing energy losses.

At smaller h_{cr}/D ratios, the flow is faster and shallower, making it more susceptible to boundary friction and turbulence. This increases the efficiency of the flow (C_d increases and decreases the energy loss). When the value of h_{cr}/D increases, the flow becomes deeper and the velocity decreases, and that leads to a reduction in both the turbulent and friction losses, which decreases the value of C_d.

As the value of the non-dimensional sequent depth (h_s/D) increases, there is a larger interaction between the walls of the structure (as boundaries) and the flow lines. This interaction leads to more resistance resulting from turbulent and friction effects, and that reduces the hydraulic performance (i.e., the value of C_d decreases).

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