Hydraulic Jump Characteristics Downstream of a Compound Weir consisting of Two Rectangles with a below Semicircular Gate

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ABSTRACT

Weirs are often used in laboratories, industries, and irrigation channels to measure discharge. The discharge capacity of a structure is vital for its safety and plays an important role in the combined gate-weir flow, which is a complicated phenomenon in hydropower. This study carried out experiments on a combined hydraulic structure, which included a compound sharp-crested weir made up of two rectangles along with an inverted semicircular sharp gate. Installed on a straight channel, this structure served as a control instrument. The study aimed to investigate the downstream hydraulic jump characteristics of this combined structure, specifically, the sequent depth ratio (y_2/y_1), the hydraulic jump height ratio (H_j/y_1), the energy loss ratio through the jump (E_L/E_u), and the jump length ratio (L_j/y_1). The width of the upper rectangle on the weir was set at 20 cm. The width of the lower rectangle (W_2) was set at 5, 7, and 9 cm, while its depths (z) were fixed at 6, 9, and 11 cm. The gate's diameters varied between 8, 12, and 15 cm. These measurements were alternated with varying initial Froude numbers (F_{n1}) ranging between 1.32 and 1.5. The results showed that the dimensions of both the weir and the gate influenced the hydraulic jump characteristics. Empirical formulas were developed to predict y_2/y_1, H_j/y_1, E_L/E_u, and L_j/y_1 based on the differing dimensions of the combined structure. The findings and analysis of this study are limited to the range of data that were tested.

Keywords-hydraulic jump; combined weir; semicircular gates; combined structure; open channels; head loss

I. INTRODUCTION

Heading-up structures serve mainly to measure discharge flow and control water levels. Their usage can be either individual or combined, depending on the intended purpose. Although these devices are considered old-fashioned, weirs and sluice gates are commonly used in open channels to measure, divert, and regulate flow. Weirs employ the principle of rapidly varied flow to measure the discharge in such channels. They are typically classified into two main categories: sharp-crested weirs and broad-crested weirs. Sharp-crowned weirs are also referred to as thin-plate weirs or notches and possess a cut on the top, giving them their name. The most common shapes for these weirs are triangular (V-notch), rectangular, and trapezoidal.

Weirs and gates can be used simultaneously and this is widely applicable in industries, laboratories, irrigation processes, and dam instrumentation applications. Utilizing sluice gates or sharp-crowned weirs separately is typically associated with morphological drawbacks, such as scour and sedimentation [1-3]. Additionally, one of the main passive functions of sluice gates is to trap floating materials. This ultimately results in a decrease in the accuracy of the discharge measurement and a decrease in the heading-up performance of the structure. Furthermore, the instability of the entire structure might be threatened by the local scouring process. Therefore, it is thought that installing a single hydraulic structure that houses both a weir and a sluice gate would be a practical way to optimize the benefits of installing both in straight open channels. Compared to the separate use of a traditional weir and gate, the combined structure conveys more discharge. However, the downward opening reduces the amount of sediment that the flow traps. Consequently, due to the simultaneous flow over the weir and beneath the gate, numerous studies have recently been conducted to accurately estimate discharge, discharge coefficient, and the geometric properties of the combined structures under various hydraulic settings, such as weir and gate angles, upstream water head, and combined structure width and height [4-5]. A governing equation to estimate discharge over a triangular sharp-crowned weir was expressed in [6]. Various empirical equations have been presented to estimate discharge in various weir types [7-9]. In [10], the discharge equation obtained by [11] was used as a basis to estimate the discharge for the inverted V-shaped gate of a combined system consisting of a rectangular weir and a triangular gate, showing that the combined discharge is significantly affected by the triangle gate. Experimental tests on rectangular compound sharp-crowned side weirs demonstrated the negligible relationship between the discharge coefficient and the upstream Froude number [12].

In [13], the numerical results produced by the Flow 3D software were compared with experimental results to examine the flow of a compound system that consisted of a vertical sharp-crowned weir and gate. In [14], the flow characteristics over a combined sharp-crowned rectangular triangular weir were studied. In [15], a combined structure made up of two triangular parts with different notch angles was used to measure the flow rates for a wide range of discharges. In [16], the properties of free flow through a combined triangular weir and rectangular sluice gate were investigated, showing that the vertical distance between the weir and the gate and the discharge coefficient was directly proportional and inversely related to the weir angle. In [17], the flow below an inverted rectangular sharp gate and over a rectangular sharp crested weir was investigated, demonstrating how surface tension and viscosity affected combined discharge. In [18], the flow characteristics downstream of a combination of a rectangular sluice gate and a V-notch weir were studied, showing that an increase in the weir vertex angle increased the conveyed discharge. Additionally, a semi-empirical equation was formulated to calculate the compound system's combined discharge coefficient. In [19], experimental tests were carried out to investigate the flow beneath a rectangular sluice gate and over a trapezoidal sharp-crested weir, showing that raising the separation between the upper and lower edges of the gate and the weir increased the combined structure's discharge coefficient. In [20], the discharge coefficient of a combined structure made up of a semicircular gate and a rectangular sharp-crowned weir was examined. In [21], the combined flow below gates and over sharply crowned weirs was investigated. In [22], a combination of the triangular weir and the rectangular gate structure was used to assess the discharge coefficient. In [23-24], the hydraulic properties of weirs and combined weirs were explored according to the following scenarios: rectangular, V-notch, semicircular, rectangular combined weir with a rectangular gate, V-notch combined weir with a rectangular gate, semicircular combined weir with a rectangular gate, and semicircular combined weir with a semicircular gate. The study investigated the significant effects of the combined structure geometry on downstream flow characteristics. In addition, many studies have presented various empirical equations based on experimental data to estimate the hydraulic jump length, focusing on this parameter as a focal point in the stilling basin design [25-35]. Table I contains a tabulation of these equations.

Very little data are available for the combination of a compound sharp-crested weir consisting of two rectangles and the inverted semicircular gate. Therefore, this study aims to explore the flow pattern and hydraulic jump characteristics downstream of this new shape. Different parameters were studied to formulate a clear understanding of the new combined structure. Data were experimentally examined to formulate empirical equations for predicting the hydraulic jump characteristics downstream of the proposed two-rectangle compound combined with an inverted semicircular gate structure. Three distinct semicircular gate diameters and three distinct lower rectangle heights and widths were used to achieve this purpose.

TABLE I. THE HYDRAULIC JUMP LENGTH, L_J FORMULAS

Reference	Lj, Formula
[25]	$L_j = y_2\left(4.5 - \frac{V_1}{V_c}\right)$
[26]	$L_j = 5.2\, y_2$
[27]	$L_j = 3\, y_2$
[28]	$L_j = 6.02(\, y_2 - y_1)$
[29]	$L_j = 5\ (\, y_2 - y_1)$
[30]	$L_j = 4.5$ - $7(\, y_2 - y_1)$
[31]	$L_j = C_j(\, y_2 - y_1)$ $(a)\ C_j = 6.3237 + 0.5974\frac{y_1}{y_2}$ $(b)\ C_j = 3.827 + 3.088\left(\frac{y_1}{y_2}\right)^{0.1}$
[32]	$\frac{L_j}{y_1} = 2.84 - 12.6F_{r1} + 14.9\frac{y_2}{y_1}$
[33]	$L_j = C_j(\, y_2 - y_1)$ $C_j = 10(F_{r1})^{-0.16}$
[34]	$L_j = C_j(\, y_2 - y_1)$ $C_j = 8 - 0.05\frac{y_2}{y_1}$
[35]	$L_j = C_j(\, y_2 - y_1)$ $C_j = 10.6\left(F_{r1}{}^2\right)^{-0.185}$

II. THEORETICAL STUDY

Figure 1 shows the combined structure's views and a sketch of the concurrent flow over the weir and below the gate. The hydraulic jump characteristics developed downstream of the combined structure can be ascertained using the list of independent variables as follows:

$$f(E_1, E_2, E_u, y_u, y_1, y_2, H_j, L_j, W_1, W_2, Z, d, W, H, Q, \rho, g, \mu, \sigma) = 0 \quad (1)$$

where E_1 is the initial specific energy, E_2 is the sequent specific energy, E_u is the energy upstream of the combined structure, y_u is the upstream water depth, y_1 is the initial water depth, y_2 is the sequent water depth, H_j is the hydraulic jump height, L_j is the hydraulic jump length, W_1 and W_2 are the upper and lower weir rectangle widths respectively, Z is the height of the lower rectangle, d is the semicircular gate diameter, W and H are the total width and height of the combined structure, Q is the discharge, ρ is the water density, g is the gravitational acceleration, μ is the water dynamic viscosity, and σ is the water surface tension.

Dimensionless groups affecting the hydraulic jump characteristics that form a downstream of the compound weir with a below semicircular gate can be obtained by applying the dimensional analysis π-Buckinghum's theory and its characteristics to (1) as follows:

$$f\left(\frac{E_1}{y_1}, \frac{E_2}{y_1}, \frac{E_u}{y_1}, \frac{y_u}{y_1}, \frac{y_2}{y_1}, \frac{H_j}{y_1}, \frac{L_j}{y_1}, \frac{W_1}{y_1}, \frac{W_2}{y_1}, \frac{Z}{y_1}, \frac{d}{y_1}, \frac{W}{y_1}, \frac{H}{y_1}, F_{r1}, R_e, W_e\right) = 0 \quad (2)$$

where F_{r1}, R_e, and W_e are the initial Froude, Reynolds, and Weber numbers, respectively. It was assumed that R_e and W_e have little bearing on the combined structure, except when it reaches a very low head. It should be stated that the non-dimensional groups mentioned above can be combined to create a variety of dimensionless numbers. W_1, W, and H had constant values throughout this study's experiments. Several studies investigated the connections between discharge and water depth for gates and weirs [36-37].

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

where C_d is the discharge coefficient for the combined structure and Q is the total discharge through the combined structure.

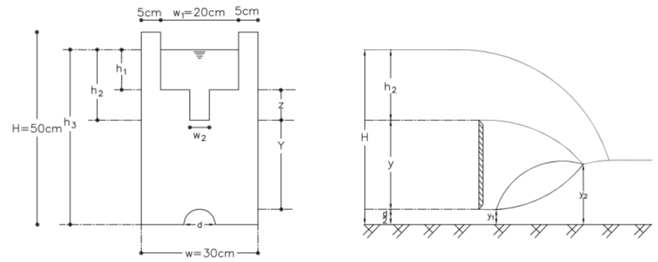

Fig. 1. Sketch of the compound weir with the below semicircular gate.

III. EXPERIMENTAL SETUP

Experimental tests were carried out with a rectangular flume measuring 4.0 m in length, 0.30 m in width, and 0.50 m in height, as presented in Figure 2, using a non-tilting type. The experimental setup uses a closed-water cycle. The effective water circulating system of the flume was powered by a three-horsepower pump. It was easy to observe the experimental tests due to the glassy sheets that form the side walls of the flume. The flume's entry was controlled by placing baffle vertical plates at the channel's entrance to prevent vortex motion and to regulate flow and damp fluctuations. The combined structure's exit water was collected in a hydraulic bench type F13, and the actual discharge was calculated by dividing the volume of water collected in the hydraulic bench by the corresponding time. The actual discharge for each experimental run was the average of three recorded discharge values. The semicircular gate head h_3 and the weir heads h_1 and h_2 were measured using a vernier type gauge with 1 mm accuracy. Calibration was performed before each experiment to prevent instrument errors. It was possible to maintain a steady flow through the channel by carefully adjusting the depth rod to the water surface. Each experiment was conducted with constant discharge. For the experimental study, a rectangular sharp compound weir with a lower semicircular gate, constructed of acrylic glass and having varying lower rectangle widths and depths (W_2 and Z), was used. The below semicircular gate also employed three diameters of 8, 12, and 15 cm, in addition to the case of utilizing the compound weir without the semicircular gate. Three weir lower rectangle widths W_2 of 5, 7, and 9 cm and depths Z of 6, 9, and 11 cm were used, while F_{r1} ranged from 1.3 to 1.5. The aforementioned measurements were applied equally. After the calibration process, the water heads on the weir's upstream side were measured to determine the accuracy of the discharge measurement. A point gauge featuring a 1 mm vernier scale was engaged to measure the water heads. According to [37], the point gauge was fixed four times the maximum head over the weir upstream. As the bottom boundary effect requires the flow through the weir section to be free, the discharge was calculated by measuring the head over the weir in the weir section.

Fig. 2. A model sample during operation for the rectangular flume.

IV. EXPERIMENTAL PROGRAM AND PROCEDURES

A total of fifty-four combined structure models were constructed using acrylic glass sheets, featuring varying semicircular gate diameters d and weir rectangles W_2, Z. In this study, the semicircular gate with diameters d of 8, 12, and 15 cm was utilized interchangeably with three weir lower rectangular widths W_2 of 5, 7, and 9 cm and depths Z of 6, 9, and 11 cm each. For each setup, six tests were carried out using various water heads. Therefore, 216 tests were performed, as shown in Table II.

TABLE II. THE EXPERIMENTAL PROGRAMS

Semicircular gate diameter, d (cm)	Lower weir width, W_2 (cm)	Lower weir depth, Z (cm)	Initial Froude's number F_{r1}
8 cm	5	6, 9, and 11	Six values (1.3 to 1.5)
	7	6, 9, and 11	Six values (1.3 to 1.5)
	9	6, 9, and 11	Six values (1.3 to 1.5)
12 cm	5	6, 9, and 11	Six values (1.3 to 1.5)
	7	6, 9, and 11	Six values (1.3 to 1.5)
	9	6, 9, and 11	Six values (1.3 to 1.5)
15 cm	5	6, 9, and 11	Six values (1.3 to 1.5)
	7	6, 9, and 11	Six values (1.3 to 1.5)
	9	6, 9, and 11	Six values (1.3 to 1.5)

The procedures mentioned below were followed for every experimental run. At the flume's end, the model was fixed. Water was gradually added to the flume until each head over the weir reached the desired level. The experiment was carried out with a constant flow rate over the weir and below the gate to ensure reaching a steady state. The actual discharge for each experiment was determined by dividing the volume of water collected by the corresponding time using the hydraulic bench. Each experiment was terminated by turning off the pump, and then the following combined structure model was tested.

V. RESULTS AND DISCUSSION

This study focused on demonstrating the effects of the sharp compound weir with two rectangles and the below semicircular gate as a hydraulic controlling device on the hydraulic jump characteristics downstream of it. These characteristics were the energy loss ratio E_L/E_u, the sequent depth ratio y_2/y_1, the hydraulic jump height ratio H_j/y_1, and the hydraulic jump length ratio L_j/y_1. Different lower weir rectangle width and depth values W_2 and Z, respectively, and the below semicircular gate diameter d values were applied throughout the experimental tests. After analyzing the results obtained from these tests, an equation was finally formulated for each hydraulic jump characteristic using regression analysis.

A. *Effect of combined Structure Parameters on Energy Loss Ratio*

The head loss ratio E_L/E_u through a hydraulic jump is a crucial factor in open-channel flow and water engineering. The hydraulic jump formed downstream of the combined structure causes extra energy to be released as waves and turbulence. The effectiveness of energy dissipation in the hydraulic jump is measured by the head loss ratio, which is defined as the ratio of energy loss to the upstream flow of energy. The result analysis on the effect of W_2/W on E_L/E_u indicates that, as a general outcome, E_L/E_u decreases as F_{r1} increases. For example, for W_2/W of 0.23, z/H of 0.18, and d/H of 0.24, increasing F_{r1} by 13% resulted in a decrease in E_L/E_u by 17.62%. Furthermore, E_L/E_u has an inverse relationship with W_2/W. For instance, for F_{r1} of 1.48, z/H of 0.18, and d/H of 0.24, increasing W_2/W from 0.17 to 0.3 results in decreasing E_L/E_u from 0.741 to 0.694, i.e. a 76.47% increase in W_2/W leads to 6.8% decrease in E_L/E_u, as illustrated in Figure 3.

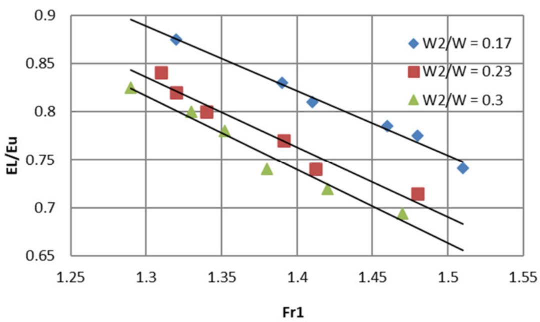

Fig. 3. Relationship between E_L/E_u and F_{r1} at different W_2/W and z/H of 0.18, and d/H of 0.24.

Eighteen experiments were conducted to investigate the effect of the weir lower rectangle height ratio z/H on the energy loss ratio E_L/E_u for given d/H and W_2/W. The results show that E_L/E_u has a direct relationship with z/H. For example, for W_2/W of 0.23, d/H of 0.22, and F_{r1} of 1.48, increasing z/H from 0.12 to 0.22 results in increasing E_L/E_u from 0.804 to 0.842, i.e. a 4.72% increase in E_L/E_u corresponds to 83.33% increase in z/H, as displayed in Figure 4. In addition, eighteen experiments were carried out to show the impact of the below semicircular gate diameter ratio d/H on the energy loss ratio through the formed hydraulic jump E_L/E_u. Figure 5 shows that E_L/E_u increases as d/H decreases for given W_2/W, z/H, and F_{r1}. For example, for F_{r1} of 1.48, W_2/W of 0.23, and z/H of 0.18, if d/H increases from 0.16 to 0.3, E_L/E_u decreases from 0.741 to 0.606. This means that if d/H increases by 87.5%, E_L/E_u decreases by 22.28%. Regression analysis was applied for the energy loss ratio with other independent parameters. So, an equation was formulated for the different discussed cases as follows:

$$\frac{E_L}{E_u} = 2.033 - 0.49\, F_{r1} - 0.513\, \frac{W_2}{W} - 1.34\, \frac{z}{H} - 0.929\, \frac{d}{H} \qquad (4)$$

Equation 4 was validated using the experimentally measured data versus the calculated values for the energy loss ratio E_L/E_u as portrayed in Figure 6. The findings demonstrate a good agreement between the measured and calculated values.

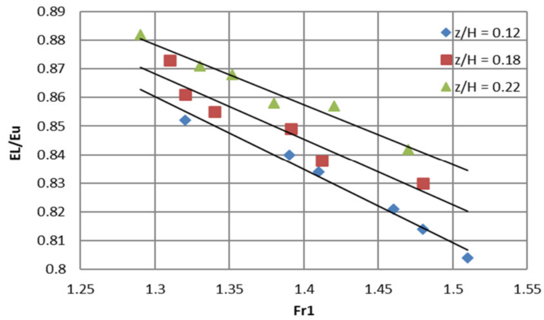

Fig. 4. Relationship between E_L/E_u and F_{r1} at different z/H and W_2/W of 0.23, and d/H of 0.22.

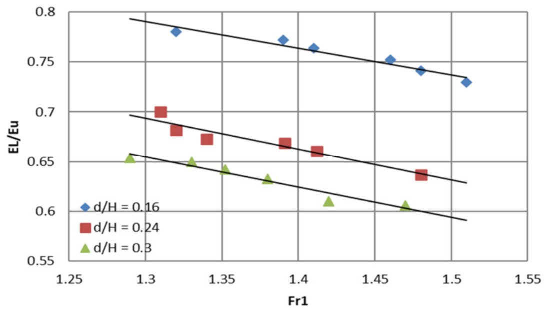

Fig. 5. Relationship between E_L/E_u and F_{r1} at different d/H and W_2/W of 0.23, and z/H of 0.23.

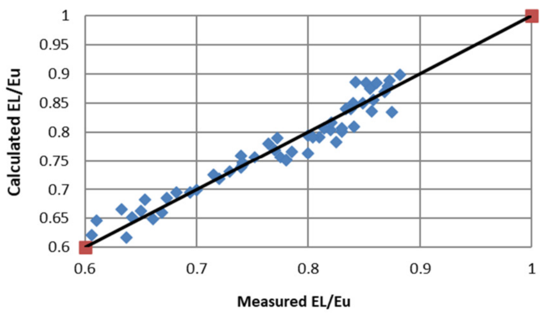

Fig. 6. Comparison between observed and calculated values for E_L/E_u.

B. *Effect of the combined Structure Parameters on the Sequent Depth and the Jump Height Ratios*

The sequent depth ratio y_2/y_1 and the hydraulic jump height ratio H_j/y_1 are crucial parameters in the analysis of hydraulic jumps. y_2/y_1 represents the ratio of the downstream hydraulic jump depth y_2 to the upstream hydraulic jump depth y_1 and

H_j/y_1 represents y_2/y_1-1. Overall, the results of the analysis demonstrating the impact of W_2/W on y_2/y_1, and H_j/y_1 indicate that y_2/y_1 and H_j/y_1 increase as F_{r1} increases. For example, a 13% increase in F_{r1} causes a 100.62% and 151.5% increase in y_2/y_1 and H_j/y_1 respectively, for W_2/W of 0.23, z/H of 0.18, and d/H of 0.24. Furthermore, there are inverse relationships between W_2/W and y_2/y_1 and H_j/y_1, as shown in Figures 7 and 8. For example, increasing W_2/W from 0.17 to 0.3 causes y_2/y_1 and H_j/y_1 to decrease from 7.99 to 5.32 and from 6.99 to 4.32, respectively, for F_{r1} of 1.48, z/H of 0.18, and d/H of 0.24. This means that a 76.47% increase in W_2/W results in a 50.19% and 61.81% decrease in y_2/y_1 and H_j/y_1, respectively.

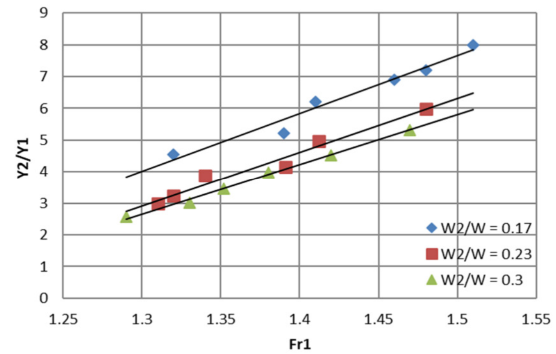

Fig. 7. Relationship between y_2/y_1 and F_{r1} at different W_2/W and z/H of 0.18, and d/H of 0.24.

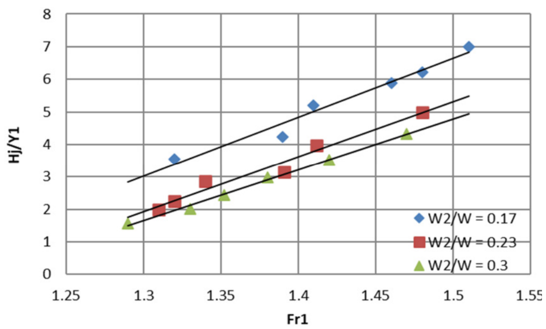

Fig. 8. Relationship between H_j/y_1 and F_{r1} at different W_2/W and z/H of 0.18, and d/H of 0.24.

Eighteen experiments were performed to examine how z/H affected y_2/y_1 and H_j/y_1 for given d/H and W_2/W. The findings indicate a direct relationship between z/H, y_2/y_1, and H_j/y_1. For instance, increasing z/H from 0.12 to 0.22 resulted in decreased y_2/y_1 and H_j/y_1 from 8.99 to 6.89 and 7.99 to 5.89, accordingly, i.e. 30.48% and 35.65% increase in y_2/y_1 and H_j/y_1 correspond to an 83.33% decrease in z/H, for W_2/W of 0.23, d/H of 0.22, and F_{r1} of 1.48, as illustrated in Figures 9 and 10.

Additionally, eighteen experiments were carried out to demonstrate how y_2/y_1 and H_j/y_1 are affected by the below semicircular gate diameter ratio d/H. Figures 11 and 12 reveal that for the given W_2/W, z/H, and F_{r1}, y_2/y_1 and H_j/y_1 increase as d/H increases. For instance, if d/H increases from 0.16 to 0.3 for F_{r1} of 1.48, W_2/W of 0.23, and z/H of 0.18, each y_2/y_1 and H_j/y_1 increases from 6.82 to 7.42 and from 5.82 to 6.42, respectively. This indicates that y_2/y_1 and H_j/y_1 increase by 8.8% and 10.31, accordingly, if d/H increases by 87.5%. For each y_2/y_1 and H_j/y_1, regression analysis was performed along with other independent parameters, producing the following equations:

$$\frac{y_2}{y_1} = -17.57 + 19.28\,F_{r1} - 11.26\,\frac{W_2}{W} - 20.94\,\frac{z}{H} + 10.67\,\frac{d}{H} \quad (5)$$

$$\frac{H_j}{y_1} = -18.57 + 19.28\,F_{r1} - 11.26\,\frac{W_2}{W} - 20.94\,\frac{z}{H} + 10.67\,\frac{d}{H} \quad (6)$$

As observed in Figures 13 and 14, (5) and (6) were verified by comparing the calculated values for each y_2/y_1 and H_j/y_1 with the experimentally measured data. The calculated and measured values exhibited good agreement.

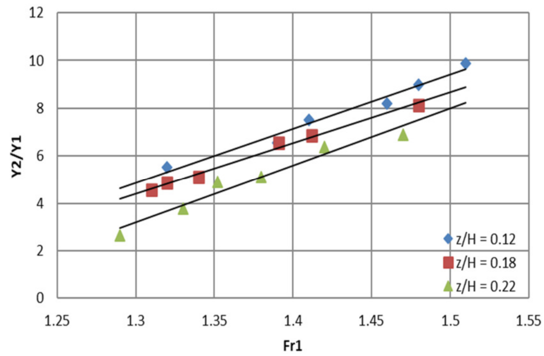

Fig. 9. Relationship between y_2/y_1 and F_{r1} at different z/H and W_2/W of 0.23, and d/H of 0.22.

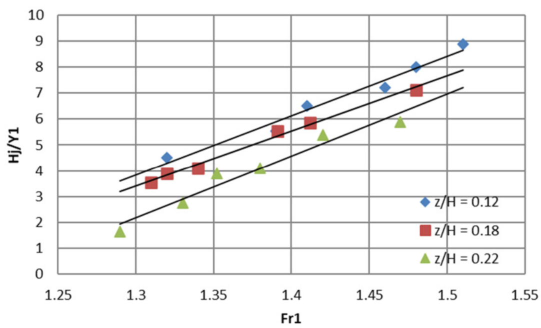

Fig. 10. Relationship between H_j/y_1 and F_{r1} at different z/H and W_2/W of 0.23, and d/H of 0.22.

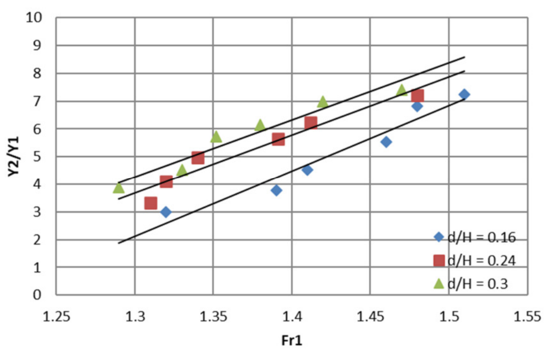

Fig. 11. Relationship between y_2/y_1 and F_{r1} at different d/H and W_2/W of 0.23, and z/H of 0.23.

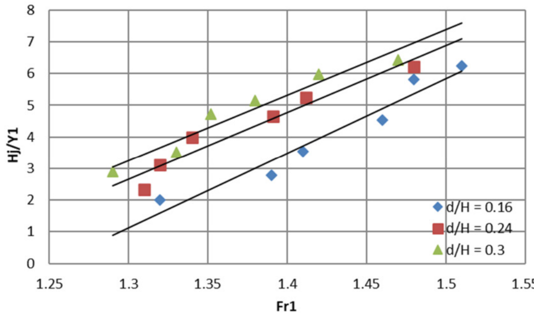

Fig. 12. Relationship between H_j/y_1 and F_{r1} at different d/H and W_2/W of 0.23, and z/H of 0.23.

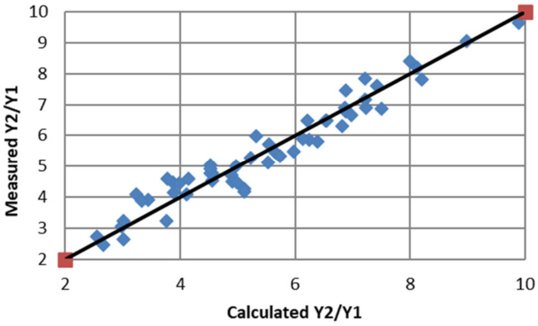

Fig. 13. Comparison between observed and calculated values for y_2/y_1.

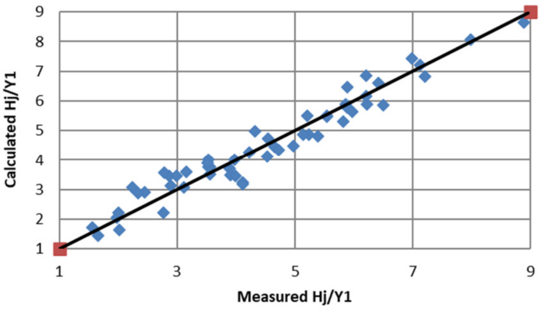

Fig. 14. Comparison between observed and calculated values for H_j/y_1.

C. *Effect of combined Structure Parameters on the Jump Length Ratio*

The findings disclose that L_j/y_1 increases with an increase in F_{r1}. For instance, for W_2/W of 0.23, z/H of 0.18, and d/H of 0.24, a 13% increase in F_{r1} results in an increase of L_j/y_1 by 168.4%,. Additionally, Figure 15 shows that there are inverse relationships between W_2/W and L_j/y_1. For example, increasing W_2/W from 0.17 to 0.3 causes L_j/y_1 to decrease from 25.62 to 18.11, for F_{r1} of 1.48, z/H of 0.18, and d/H of 0.24. This means that a 76.47% increase in W_2/W leads to a 41.46% decrease in L_j/y_1.

The effects of the weir lower rectangle height ratio z/H were investigated for the hydraulic jump length ratio L_j/y_1 in experimental tests, for given d/H and W_2/W. The results exhibit that L_j/y_1 has an inverse relationship with z/H. For example, when z/H increases from 0.12 to 0.22, L_j/y_1 decreases from 35.12 to 23.45. This means that a decrease of 49.77% in L_j/y_1 corresponds to an 83.33% increase in z/H for W_2/W of 0.23, d/H of 0.22, and F_{r1} of 1.48, as evidenced in Figure 16.

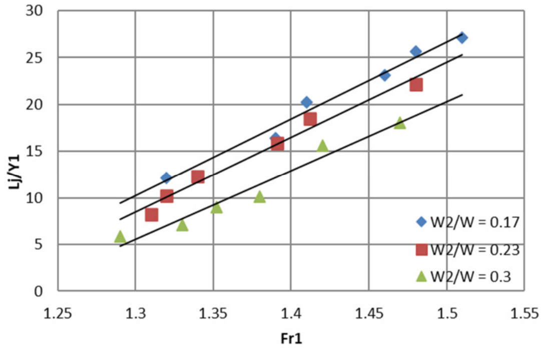

Fig. 15. Relationship between L_j/y_1 and F_{r1} at different W_2/W, z/H of 0.18, and d/H of 0.24.

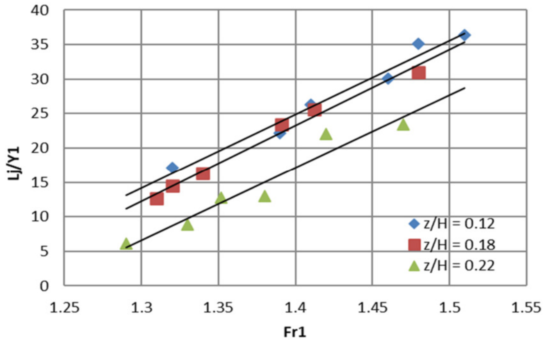

Fig. 16. Relationship between L_j/y_1 and F_{r1} at different z/H, W_2/W of 0.23, and d/H of 0.22

In addition, experimental tests were conducted to show how the below semicircular gate diameter ratio d/H influences the hydraulic jump length ratio L_j/y_1. Figure 17 indicates that L_j/y_1 increases as d/H increases for given W_2/W, z/H, and F_{r1}. For example, L_j/y_1 increases from 27.5 to 31.5 if d/H increases from 0.16 to 0.3, for F_{r1} of 1.48, W_2/W of 0.23, and z/H of 0.18. This means that if d/H increases by 87.5%, then L_j/y_1 increases by 14.55%. A regression analysis was carried out for L_j/y_1, along with other independent parameters, producing the following equation:

$$\frac{L_j}{y_1} = -94.26 + 92.26\,F_{r1} - 37.62\,\frac{W_2}{W} - 90.77\,\frac{z}{H} + 38.88\,\frac{d}{H} \qquad (7)$$

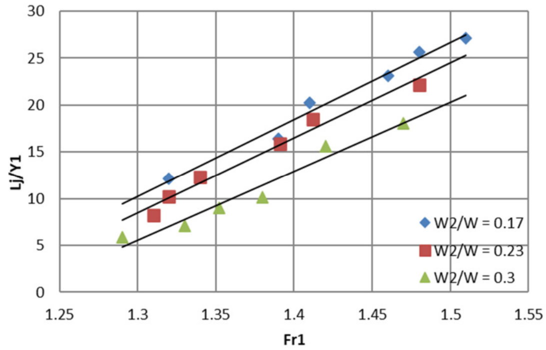

Fig. 17. Relationship between L_j/y_1 and F_{r1} at different W_2/W and z/H of 0.18, and d/H of 0.24.

Figure 18 presents a comparison of (7) with the experimentally measured data for L_j/y_1. The calculated and measured values exhibited good agreement. To assess the precision of the hydraulic jump length measurements and verify (7), the results were compared with the previously published equations shown in Table 1. Figure 19 displays the plotted results. The results were within the range of the calculated values, and the figure denotes a good correlation and a similar trend to that of earlier studies.

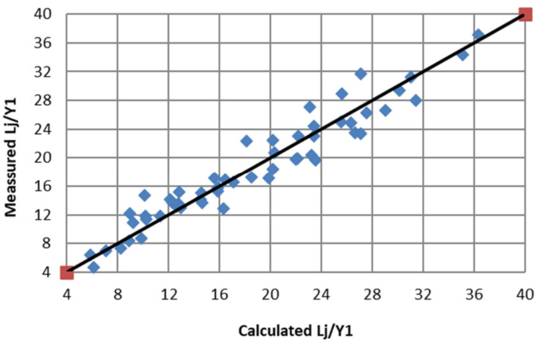

Fig. 18. Comparison between observed and calculated values For L_j/y_1.

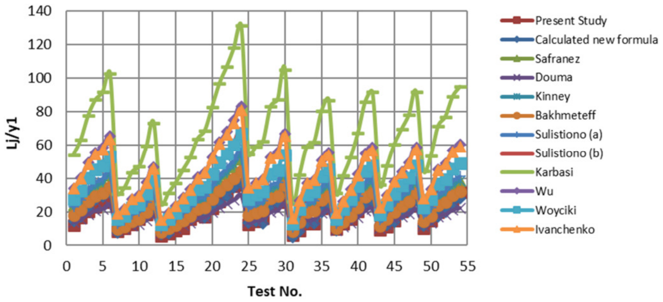

Fig. 19. Comparison between calculated L_j/y_1 of the current study and calculated using other formulas.

VI. CONCLUSION

This study carried out experiments to examine the characteristics of hydraulic jumps that form downstream of a combined hydraulic structure composed of a compound weir and a semicircular gate. The impact of various parameters, width (W_2) and depth (Z) of the weir's lower rectangle, the diameter (d) beneath the gate, and the initial Froude's number (F_{r1}), on the hydraulic jump characteristics (y_2/y_1, H_j/y_1, E_L/E_u, and L_j/y_1) were analyzed. The findings are as follows:

- The energy loss ratio through the formed hydraulic jump E_L/E_u decreases as F_{r1} increases.
- Each of the sequent depth ratios y_2/y_1, hydraulic jump height ratios H_j/y_1 and hydraulic jump length ratios L_j/y_1 increase with increasing F_{r1}.
- The energy loss ratio E_L/E_u has a direct proportional relationship with the lower rectangle height ratio of the weir z/H. On the other hand, E_L/E_u has an inversely proportional relationship with the weir lower rectangle width ratio W_2/W and the semicircular gate diameter ratio (d/H) for a given F_{r1}.
- Each of y_2/y_1, H_j/y_1, and L_j/y_1 increases with d/H and decreases with z/H and W_2/W for a given F_{r1}.
- General equations were formulated to calculate the hydraulic jump characteristics y_2/y_1, H_j/y_1, E_L/E_u, and L_j/y_1 for different combined structure parameters.
- The observed hydraulic jump length values were in good agreement with those calculated in previous studies.

This study provides insights into the complex dynamics of hydraulic jumps, particularly in the context of compound weirs, and offers valuable information for the design and optimization of hydraulic structures. The findings of this study have implications for hydraulic engineering, offering a deeper understanding of flow characteristics, and aiding in the development of optimal design techniques for hydraulic structures.

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