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 \((E_j/E_1)\), 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 \((F_R)\) 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 \(y_2/y_1, H_j/y_1, E_j/E_1,\) 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].

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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 vertical distance between the weir and the gate and the sluice gate were investigated, showing that 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 [18], the flow characteristics downstream of a combination of a rectangular weir 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.

**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:

\[ f(F, E, E_u, y_u, y_i, y_j, H, L_i, W_j, Z, d, W, H, Q, \alpha, g, \mu, \sigma) = 0 \quad (1) \]

where \( E_i \) 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, \( y_i \) is the initial water depth, \( y_j \) is the sequent water depth, \( H \) is the hydraulic jump height, \( L_i \) is the hydraulic jump length, \( W_j \) and \( W_i \) 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, \( \rho \) is the water density, \( g \) is the gravitational acceleration, \( \mu \) is the water dynamic viscosity, and \( \sigma \) 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 \( \pi \)-Buckingham's theory and its characteristics to (1) as follows:

\[ f(F_1, R_e, W_j) = 0 \quad (2) \]

where \( F_1, R_e, \) and \( W_j \) are the initial Froude, Reynolds, and Weber numbers, respectively. It was assumed that \( R_e \) and \( W_j \) 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. \( W_j, W, \) 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].

\[ Q = C_d \left( \sqrt{2g(W_2 - W_1)h_1^2} + \frac{\pi}{2} \sqrt{2g} W_2 h_2^2 \right) + \frac{n_d}{2} \sqrt{2gh_2} \]  

(3)

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

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 \( h_1 \) and the weir heads \( h_2 \) and \( h_3 \) 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 combined 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.

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 \( W_2 \) and \( Z \). 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

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

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
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 $W_j/W$ on $E_l/E_u$ indicates that, as a general outcome, $E_l/E_u$ decreases as $F_{r1}$ increases. For example, for $W_j/W$ 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 $W_j/W$. For instance, for $F_{r1}$ of 1.48, $z/H$ of 0.18, and $d/H$ of 0.24, increasing $W_j/W$ from 0.17 to 0.3 results in decreasing $E_l/E_u$ from 0.741 to 0.694, i.e. a 7.47% increase in $W_j/W$ 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 $W_j/W$ and $z/H$ of 0.18, and $d/H$ of 0.24.](image)

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 $W_j/W$. The results show that $E_l/E_u$ has a direct relationship with $z/H$. For example, for $W_j/W$ 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 $W_j/W$, $z/H$, and $F_{r1}$. For example, for $F_{r1}$ of 1.48, $W_j/W$ 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:

$$\frac{E_l}{E_u} = 2.033 - 0.49 F_{r1} - 0.513 \frac{W_j}{W} - 1.34 \frac{z}{H} - 0.929 \frac{d}{H} \quad (4)$$

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

Eighteen experiments were performed to examine how $z/H$ affected $y_d/y_1$ and $H/y_1$ for given $d/H$ and $W/W$. The findings indicate a direct relationship between $z/H$, $y_d/y_1$, and $H/y_1$. For instance, increasing $z/H$ from 0.12 to 0.22 resulted in decreased $y_d/y_1$ and $H/y_1$ from 8.99 to 6.89 and 7.99 to 5.89, accordingly. The results exhibit a 30.48% and 35.65% increase in $y_d/y_1$ and $H/y_1$, respectively. For $F_{r1}$ of 1.48, $z/H$ of 0.18, and $d/H$ 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 $y_d/y_1$ and $H/y_1$ are affected by the below semicircular gate diameter ratio $d/H$. Figures 11 and 12 reveal that for the given $W/W$, $z/H$, and $F_{r1}$, $y_d/y_1$ and $H/y_1$ increase as $d/H$ increases. For instance, if $d/H$ increases from 0.16 to 0.3 for $F_{r1}$ of 1.48, $W/W$ of 0.23, and $z/H$ of 0.18, each $y_d/y_1$ and $H/y_1$ increases from 6.82 to 7.42 and from 5.82 to 6.42, respectively. This indicates that $y_d/y_1$ and $H/y_1$ increase by 8.8% and 10.31, accordingly, if $d/H$ increases by 87.5%. For each $y_d/y_1$ and $H/y_1$, regression analysis was performed along with other independent parameters, producing the following equations:

$$y_d/y_1 = -17.57 + 19.28 F_{r1} - 11.26 \frac{W}{W} - 20.94 \frac{z}{H} + 10.67 \frac{d}{H} \tag{5}$$

$$H/y_1 = -18.57 + 19.28 F_{r1} - 11.26 \frac{W}{W} - 20.94 \frac{z}{H} + 10.67 \frac{d}{H} \tag{6}$$

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

A regression analysis was carried out for $L_j/y_1$, along with other independent parameters, producing the following equation:

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

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:

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

The findings disclose that $H_j/y_1$ and $F_{r1}$ at different $d/H$ and $W_2/W$ of 0.23, and $z/H$ of 0.23.
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 \(L_j/y_1\).](image1)

![Fig. 19. Comparison between calculated \(L_j/y_1\) of the current study and calculated using other formulas.](image2)

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 \((W)\) and depth \((Z)\) of the weir’s lower rectangle, the diameter \((d)\) beneath the gate, and the initial Froude’s number \((F_i)\), on the hydraulic jump characteristics \((y_jy_1, H_jy_1, E_d/E_a,\) and \(L_j/y_1)\) were analyzed. The findings are as follows:

- The energy loss ratio through the formed hydraulic jump \(E_d/E_a\) decreases as \(F_i\) increases.
- Each of the sequent depth ratios \(y_jy_1\), hydraulic jump height ratios \(H_jy_1\) and hydraulic jump length ratios \(L_j/y_1\) increase with increasing \(F_i\).
- The energy loss ratio \(E_d/E_a\) has a direct proportional relationship with the lower rectangle height ratio of the weir \(z/H\). On the other hand, \(E_d/E_a\) has an inversely proportional relationship with the weir lower rectangle width ratio \(W/W\) and the semicircular gate diameter ratio \((d/H)\) for a given \(F_i\).
- Each of \(y_jy_1, H_jy_1,\) and \(L_j/y_1\) increases with \(d/H\) and decreases with \(z/H\) and \(W/W\) for a given \(F_i\).
- General equations were formulated to calculate the hydraulic jump characteristics \(y_jy_1, H_jy_1, E_d/E_a,\) 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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