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Effect of Porous Rectangular Type Baffle Block Angle on Hydraulic Jump Downstream of Spillway

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Abstract

The elevation of the water surface upstream of the spillway structure increases significantly due to damming, leading to a rapid, supercritical flow downstream. This flow transitions from supercritical to subcritical, resulting in hydraulic jumps (Lj). The placement of a porous rectangular baffle block in the chute acts as an energy dissipator within the channel. This study aimed to investigate the effect of the angle of the porous rectangular baffle block on energy dissipation and hydraulic jumps downstream of the spillway structure. The experiment utilized a two-dimensional (2D) approach to evaluate energy dissipation and hydraulic jumps under various placements of the porous rectangular baffle block in the chute. The results indicated that the water level above the weir (h_d) increased, along with turbulence downstream, while energy loss decreased. However, the efficiency of energy dissipation improved as variations in the water level above the weir decreased. A baffle block with an angle (α) of 60° was found to be the most effective in dissipating flow energy and shortening hydraulic jumps. Additionally, an empirical equation was developed for the hydraulic jump length as a function of the downstream Froude number (Fr): $L_j = y_t(k\,\alpha\,h_d\,(Fr-1)^4)$. The porous rectangular baffle block proved advantageous as it gradually dissipates flow velocity through its pore openings, preventing flow momentum reversal.

Keywords: Spillway; Baffle Block; Flow Energy; Hydraulic Jumps.

1. Introduction

The spillway is a critical component of dam design and management, serving to regulate water flow and protect downstream infrastructure and the surrounding environment from potential flood risks [1, 2]. During operation, spillway structures can handle various flow conditions, including extreme discharge events [3, 4]. To improve the performance of these structures, numerous innovations and research efforts have been undertaken, focusing on structural elements that influence efficiency and effectiveness [5].

Hydraulic jumps are common phenomena in open channel flows, such as weirs, dams, spillways, drains, or stilling basins. They occur when high-velocity water transitions into a low-velocity zone (from supercritical to subcritical flow) on a free surface [6, 7]. In open channels, hydraulic jumps act as energy dissipators, reducing excess kinetic energy through turbulence and air entrainment [8]. Hydraulic jumps that form with baffle blocks are considered forced jumps. Consequently, the forces exerted on baffle blocks are significant for both hydraulic and structural considerations [9-11]. Determining the drag force on baffle blocks is theoretically complex due to the interplay of separation and frictional forces, necessitating experimental investigation [12, 13].

The placement of baffle block models has garnered considerable attention as they play a vital role in reducing water flow energy and mitigating risks of erosion, scouring, and damage to the natural riverbed around spillway structures [14].

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Early studies on hydraulic jumps in inclined channels were conducted by Bakri et al. [15]. Basco & Adam [12] performed experimental studies on the drag forces exerted on bluff-shaped baffle blocks. Sunik [16] examined hydraulic jump characteristics using wedge-shaped baffle blocks with rough base materials. The study revealed that wedge-shaped blocks could reduce the hydraulic jump depth (y_t) and length (L_j) by 30% to 53%. Heidarzadeh & Feizi [17] conducted experiments to evaluate the effects of baffle walls and blocks in submerged hydraulic jumps, concluding that energy dissipation efficiency was strongly influenced by immersion depth. Maximum efficiency was observed at lower immersion levels, while energy dissipation decreased as immersion increased.

Ozbay [18] investigated the energy dissipation efficiency of *stepped*, *trapezoidal*, *T-shaped*, and *wedge-type* baffle blocks in open channels. Experimental results indicated that stepped baffle blocks exhibited slightly higher energy dissipation efficiency compared to other block types tested. Hager & Li [14] explored the effects of transverse weirs on hydraulic jumps in trapezoidal channels, classifying submerged and A-jump types. They provided drag force coefficients and detailed assumptions on extreme pressure fluctuations, comparing dissipation efficiency between various jump types and classical hydraulic jumps [20-22]. To address hydraulic jumps and energy dissipation in downstream channels, Hager (1992) [19] found that baffle blocks with an upstream angle of 120° and cat-back blocks with a 90° angle on the rear side were more effective at reducing flow energy and shortening hydraulic jumps without causing cavitation hazards.

This study is a laboratory-based investigation that directly observed flow parameters influencing hydraulic jumps on smooth base surfaces in rectangular open channels. The research aimed to enhance understanding of this phenomenon by analyzing the hydraulic behavior under varying angles of porous rectangular baffle blocks, focusing on their role in energy dissipation and reducing the hydraulic jump length downstream of a spillway structure.

Theoretical Approach

Important factors that affect efforts to dissipate flow energy and shorten hydraulic jumps downstream of spillway structures are water level above the weir (h_d), baffle block angle, the pore diameter, and water level downstream of baffle block. These parameters require experimental research to determine the impact on dissipation downstream of spillway structures. Baffle block is a set of elements arranged in one or several rows oriented perpendicular to flow direction. The placement of these elements contributes to the diversion of the main flow, directing water through the gaps and upper portion, thereby reducing flow velocity passing through baffle block. Specifically, it is positioned at the start of hydraulic jumps, serving as a collision element to reduce tailwater (water body) downstream or water beneath spillway structure, shortening the basin [23-25].

Steele (1926) [26], Steele & Monroe (1929) [27], and Ehrenberger (1930) [28], as stated in Hager (1992) [19], explored various geometries of "split piers" and "blocking blocks". The results showed that pyramid-shaped and diamond-shaped piers were ineffective in reducing the energy of water flow in protecting downstream areas. Stevens (1937) [29] as stated in Hager (1992) [19] described the effect of adopted blocks at the Bonneville Dam [29]. Inclined blocks placed on the downstream side were able to reduce flow energy more effectively than vertically positioned types. This was because the irregular flow direction could be more efficient with a model of two rows of trapezoidal blocks horizontally placed on the apron [30, 31]. The magnitude of energy damping that occurred in the baffle blocks can be obtained by comparing the magnitude of energy in the upstream with that in the downstream of the energy damper. Regarding the energy at the observation point downstream, the magnitude of the energy reduction is obtained by comparing the magnitude of energy at the initial observation point with the final observation point [32]. The magnitude of energy damping can be calculated using the formula:

$$(h_{e\%}) = \frac{(h_{e1}+P)-h_{e1}}{(h_{e1}+P)\times 100} \tag{1}$$

where $h_{e\%}$ is Flow energy dissipation (%), h_{e1} is Upstream flow energy (m), P is Height of the baffle block (m). The length of hydraulic jumps cannot be easily determined theoretically, but it has been extensively investigated by many hydraulic experts through laboratory experiments. Specifically, experimental data correlate with Froude number (Fr) to obtain non-dimensional hydraulic jumps lengths, $\frac{Lj}{(h2-h1)}$, $\frac{Lj}{h2}$., $\frac{Lj}{h1}$. The correlation between Froude number (Fr) and h_2 produces the best results, but for practical purposes, Froude number (Fr) and h_2 are preferred because the curve shows regularity or is relatively flat for various water jumps. Several formulas resulting from experiments conducted by Hager (1992) [19] in Dutch laboratories are also known, obtaining an equation where the length of hydraulic jumps is related to the downstream Froude number (Fr):

$$Lj = h_1(220\ tgh(Fr-1)) \tag{2}$$

where L_j is Hydraulic Jump, h_1 is Upstream water jump (m), h_1 is water surface height (m), and Fr is Froude number.

In this research, several issues were formulated and investigated to obtain optimal results. These include the effect of variations in the angle of porous rectangular-type baffle block (α) and pore diameter (D_o) on energy dissipation downstream of spillway structures. Furthermore, the function of water level above the weir was analyzed, with variations tested in three flow discharges, alongside water level downstream of baffle block generated in each flow.

2. Material and Methods

This research was conducted in several stages. First, a hydrological analysis was performed to determine the design discharge (Q_r) using rainfall data from the watershed. Next, the hydraulic dimensions were analyzed to develop a spillway structure model and variations in the angles of porous rectangular baffle blocks. The hydraulic dimensions of the spillway structure were derived based on hydrological data analysis, which identified a design rainfall with a 1,000-year return period of 201.17 mm and a design discharge (Q_r) of 402.37 m³/s.

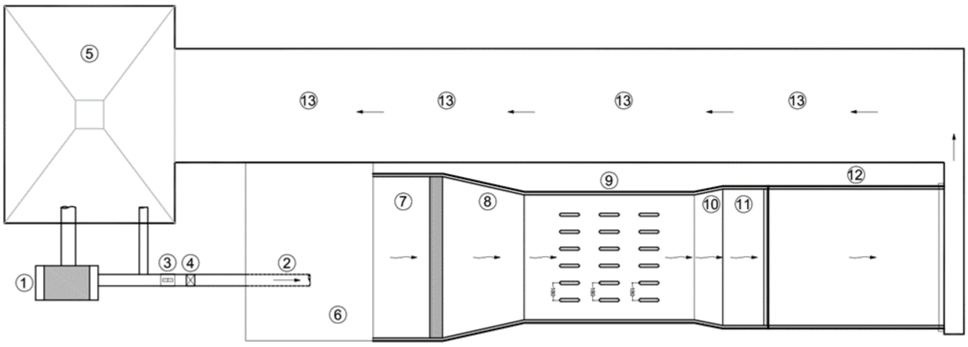
The hydraulic dimensions of the porous rectangular baffle blocks were calculated using the upstream flow velocity in the chute, determined through a trial-and-error approach. This yielded a flow velocity (v) of 2.431 m/s. The water flow characteristics were supercritical, with a Froude number (Fr) of 6.50. The calculated Froude number (Fr) served as the basis for designing the porous rectangular baffle blocks.

Theoretical study is the initial step in conducting energy immersion research with 2-dimensional experimental studies. The 2-dimensional research model design is adjusted to the purpose of the observation, so that the design of the spillway structure model is limited to observing the effect of fluid movement and flow energy on the baffle block model on the length of the hydraulic jump downstream. Preliminary testing of the model to validate the suitability of the parameters was tested using the model scale. To determine the geometric scale was adjusted to the capacity of the flume tank and pump in the laboratory, the available materials, and the accuracy when making measurements. The model was made with perfect geometric similarity (without distortion) and dynamic similarity according to the Froude number conditions. The model scale in this study used the model scale as shown in Table 1.

Table 1. Model scale

Variable	Notation	Scale
High Scale	n_H	50
Length Scale	n_L	50

Hydraulic dimensions of spillway and porous rectangular-type baffle block are shown in Table 2 and Figure 1.



Description:

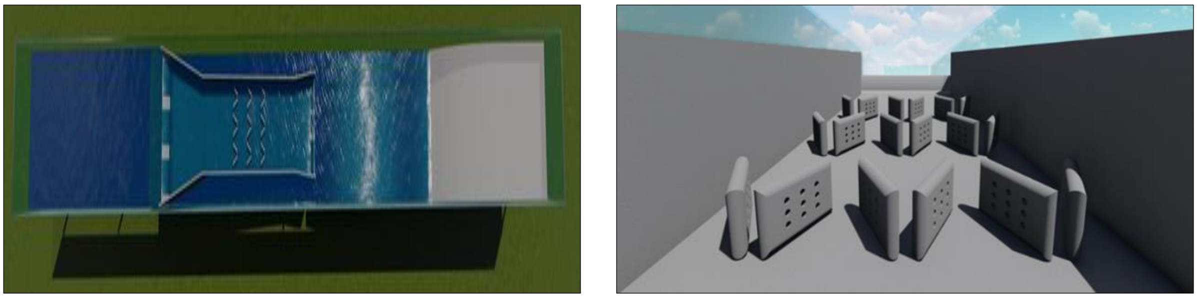
1. Pump
2. Water supply pipe
3. Flow Meter
4. Water Control Valve
5. Discharge Control Tub
6. Water Tank
7. Directional Channel
8. Transition Channel
9. Launcher channel and baffle block location
10. Trumpet Channel
11. Stilling Basin
12. Tranquilizer Channel
13. Dumping Channel

Figure 1. Open channel schematic

Table 2. Hydraulic dimensions of spillway and porous rectangular-type baffle block structures

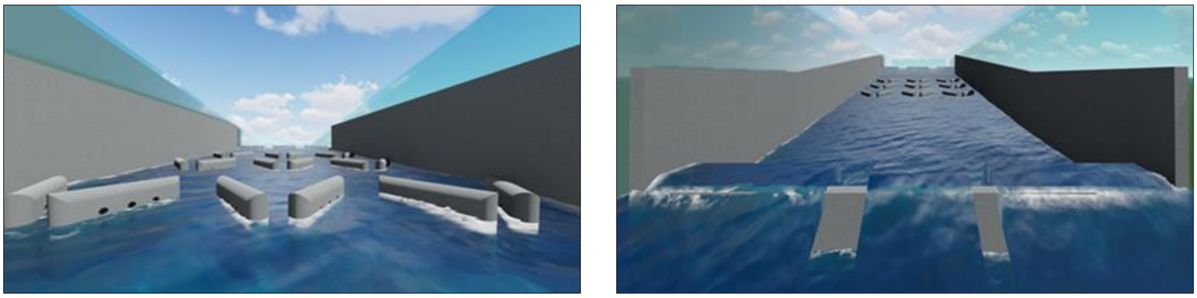
No	Description	Dimension Size (cm)
A	***Spillway Dimension***	
1	Lighthouse Type	Ogee I (upstream upright)
2	Lighthouse Height	5
3	Spillway Width	68
4	Regulating Channel Length	57.5
5	Straight Launcher Channel Length	120
6	Trumpet Launcher Channel Length	20
7	Stilling Basin Length	32
B	***Porous Rectangular-Type Baffle Block***	
1	Height	30
2	Length	50
3	Width	20
4	Pore Diameter	2.5

Hydraulic dimensions of spillway and porous rectangular-type baffle block structure are shown with a physical model scale in the form of 3D, as presented in Figures 2 and 3.



(a) (b)

Figure 2. 3D Spillway structures; (b) 3D Porous rectangular-type baffle block



(a) (b)

Figure 3. Simulated conveyance in 3D spillway structures model (a). Launcher channel, (b). Turning pond

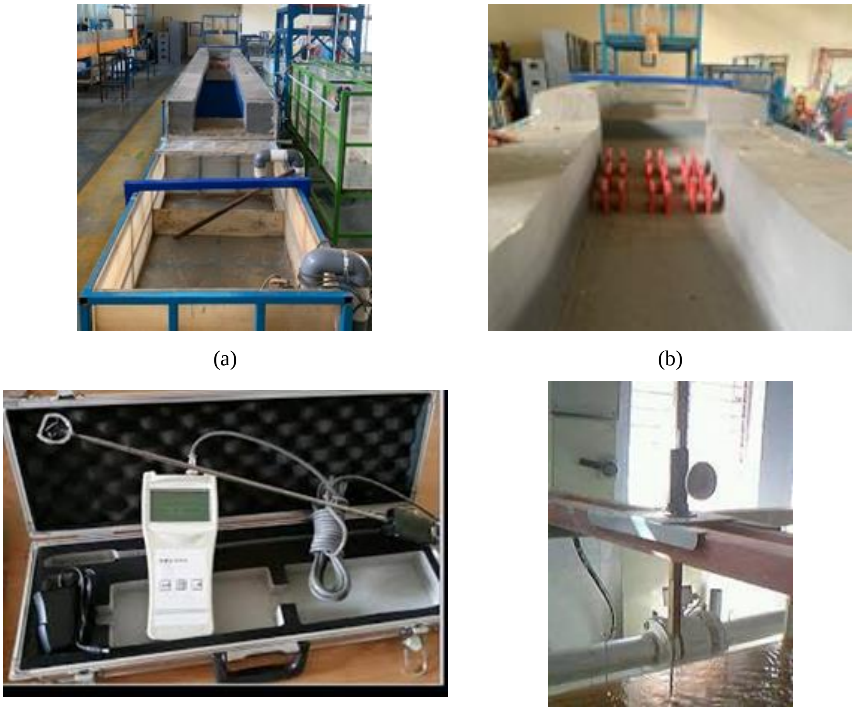
The second stage included testing flow discharge to determine water level above the lighthouse (h_d). In this research, three variations of discharge were used, leading to corresponding differences in water level above the lighthouse. The results of simulation testing and numerical analysis of flow patterns [33] were used to determine the location of porous rectangular-type baffle block angle variations in the launcher channel. This block was placed in the cross-flow at a distance of 22 cm from upstream of the spillway structures model, as shown in Figure 4.

Figure 4. Placement of porous rectangular-type baffle block model

In the simulation experiments, flow patterns were illustrated by the direction of flow arrows. Changes in flow patterns were observed as variations in the channel cross-section and flow velocity occurred, transitioning to the launcher channel. This transition resulted in flow turbulence and cross-flow (vortex) under supercritical flow conditions. To address this, variations in the angles of porous rectangular baffle blocks were strategically positioned within the vortex region of the launcher channel [34], as depicted in Figure 4.

During the third stage of the study, testing was conducted in an open channel flume, comparing the setup shown in Figure 5-a with the angle variations of the porous rectangular baffle blocks depicted in Figure 5-b. Four angle variations were tested: $\alpha=180°$, $\alpha=30°$, $\alpha=45°$, and $\alpha=60°$, as shown in Figure 6. The experiments were conducted using three distinct water levels above the weir (h_d): 1.5 cm, 2.0 cm, and 2.5 cm.

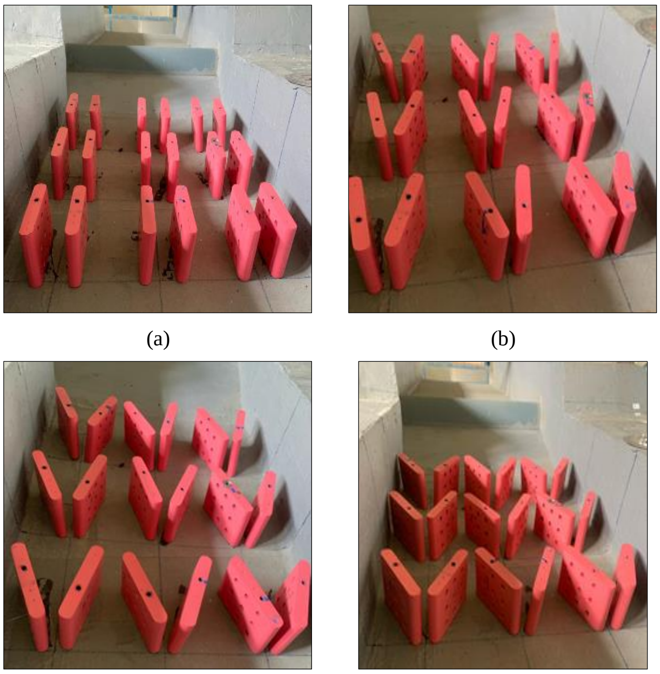
The flow velocity data were collected using a Portable Velocity Meter LS300-A (Figure 5-c), and the flow height was measured with a point gauge, achieving an accuracy of 0.001 mm (Figure 5-c). These measurements were obtained along the spillway structure model with varying angles of porous rectangular baffle blocks, as shown in Figure 2. The collected data were subsequently analyzed to identify the variables influencing energy dissipation and hydraulic jumps in the spillway model used in this study.



(a) (b)

(c) (d)

Figure 5. (a) Open channel flume, (b) Baffle block location, (c) Portable velocity meter LS300-A, (d) Point gauge



(a) (b)

(c) (d)

Figure 6. Variation of porous rectangular-type baffle block angle (a). Angle 180°, (b) Angle 30°, (c) Angle 45°, and (d) Angle 60^0

The fourth stage involved conducting observations at designated observation points. In this study, the observation points were divided into 36 sections. At each section, the water level and flow velocity were measured on the left, right, and middle sides of the channel. For the observation points where the baffle blocks were placed, measurements were taken at 12 specific points: on the left side, right side, middle side, and at each gap between the corners of the baffle blocks.

The fixed parameters during the observations included flow discharge (Q), water level above the crest (h_d), baffle block placement, flow velocity measurement location (v_m), and flow height measurement location (h_m), as illustrated in Figure 7. The hydraulic dimensions of the spillway structure model and the porous rectangular baffle blocks were calculated and designed, taking into account the physical model scale and dimensional analysis.

Figure 7. Observation points for each section

Figure 8 shows the flowchart of the research methodology through which the objectives of this study were achieved.

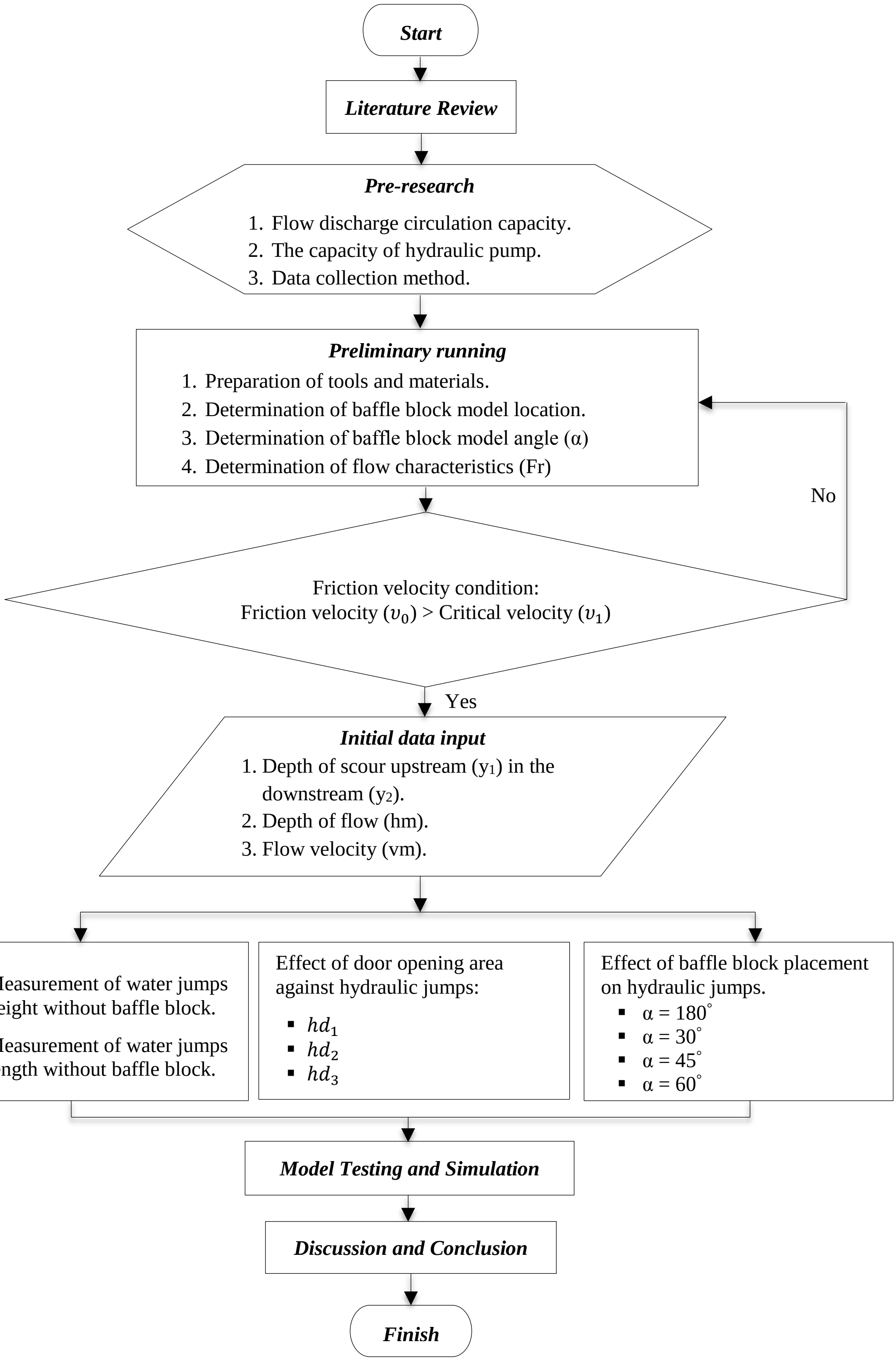


Figure 8. Flowchart of research

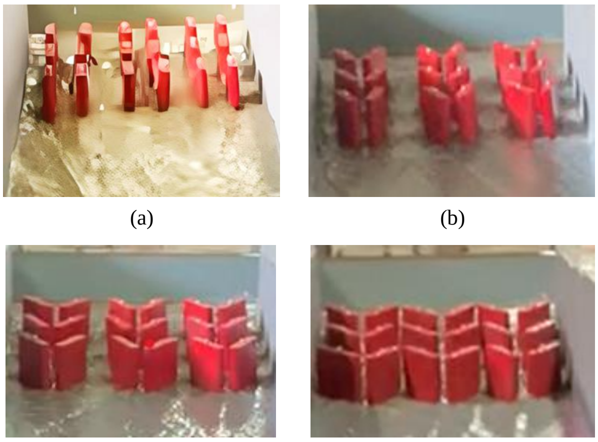
3. Results and Discussion

3.1. Flow Velocity Experiment as a Starting Point for Dampening Hydraulic Jumps Downstream of the Spillway

Experimental velocity, free surface profile, hydraulic jump and energy dissipation rate for different flow conditions and baffle block angles were different. The flow velocity in the launching channel with varying baffle block angles was measured parallel to the channel bottom. The instantaneous velocities on the left side, right side, and middle side were measured and recorded.

3.1.1. Velocity Profile

The flow direction velocity profile at various conditions in the launch channel is presented in Figure 9. The flow velocity increases with changes in the slope and cross-section of the channel from zero point in the launch channel to the maximum value at y = d_0, which is the depth of the boundary layer. The boundary layer increases with the distance from the transition channel into the launch channel. Momentum changes occur when the flow velocity flows in the direction of the flow and forms a cross flow. On the other hand, the flow direction velocity decreases with the presence of baffle blocks.



(c) (d)

Figure 9. Angle variations of the rectangular porous baffle blocks when passed by water flow (a). angle 180°; (b) angle 30°; (c). angle 45°; (d) angle 60°

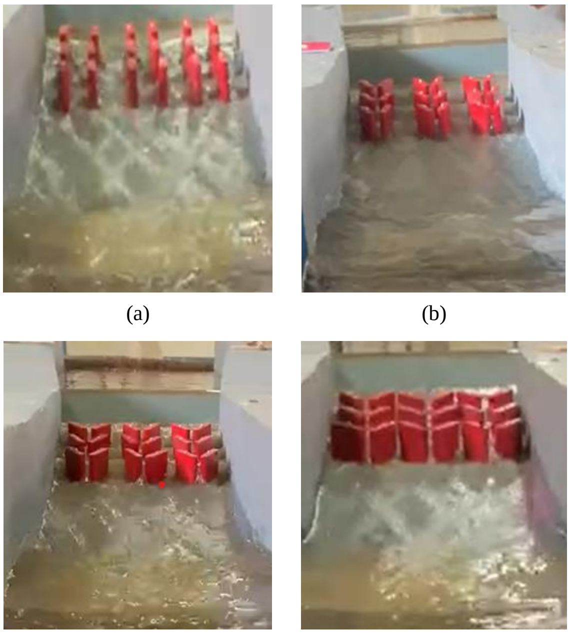
The maximum flow velocity in all experiments was observed immediately after passing through the baffle blocks, with the flow velocity gradually decreasing as the water moved downstream. The highest flow velocity occurred with a baffle block angle variation of α=180°, while the lowest flow velocity was recorded with an angle variation of α=60°. The peak flow velocity was slightly displaced toward the free surface, and the maximum velocity was observed with lower water flow volumes, decreasing as the baffle block angle varied.

The flow velocity reduction was most effective with baffle block angle variations of α=45° and α=60°, both of which demonstrated strong capabilities in dissipating flow velocity. These findings indicate that low-velocity flow entering the upstream section of the spillway gains significant velocity as it passes over the spillway structure. This high-energy flow results in a hydraulic jump, but the presence of baffle blocks at optimal angles effectively dissipates the flow energy, preventing damage to the structure and the channel bed.

3.1.2. Hydraulic Jump Profile

The length of the hydraulic jump was analyzed to provide insight into its geometric characteristics, as illustrated in Figure 10. Measurements of the hydraulic jump length were taken using a measuring ruler and documented with a high-resolution camera. The starting and ending points of the hydraulic jump downstream of the spillway were monitored and verified through direct measurements of the flow velocity profile.

Changes in the baffle block angle within the launch channel—ranging from α=180°, α=30°, α=45°, to α=60°—resulted in notable variations in the length of the hydraulic jump. At α=60°, the hydraulic jump length generally decreased due to the reduced flow velocity caused by the effective flow resistance provided by the baffle block. Conversely, at α=180°, the hydraulic jump length increased as the higher flow velocity resulted from less resistance to the water flow by the baffle block. These findings suggest that larger baffle block angles are more effective in controlling the hydraulic jump downstream of the spillway compared to smaller angles.



(a) (b) (c) (d)

Figure 10. The angle variation of the porous rectangular baffle block when a hydraulic jump occurred (a). Angle 180°; (b) Angle 30°; (c). Angle 45°; (d) Angle 60°

3.2. Flow Parameters

3.2.1. Flow Depth (h_m)

Measurement of water flow depth was carried out at each observation point along spillway structures model using a point gauge meter with an accuracy of 0.001 mm. The observations were divided into 36 points or pias, with each measurement taken on the left, middle, and right sides of the channel. Meanwhile, simulations with the installation of porous rectangular-type baffle block angle, and flow depth measurements were also made at the end, middle, and back of each variation. The results of the measurements of the flow depth can be seen in Table 3 and Figure 11 as follows:

Table 3. Flow depth

The Angle of Baffle Block (α)	Water Level above the Crest (h_d)	Flow Depth (h_m)
Non BBP	1.5	1.235
	2.0	1.891
	2.5	2.104
180°	1.5	1.343
	2.0	1.910
	2.5	2.183
30°	1.5	3.107
	2.0	4.385
	2.5	5.193
45°	1.5	4.051
	2.0	5.276
	2.5	6.096
60°	1.5	4.200
	2.0	5.605
	2.5	6.760

The increase in water level elevation was observed as a result of higher flow discharge, accompanied by an elevated water level above the lighthouse, and the variation in the angle of the porous rectangular-type baffle block. This phenomenon contributed to an increase in the depth of water flow in the launcher channel. The highest increase was observed at a flow discharge (Q_3) of 6861.66 cm^3/sec and a water level above the lighthouse (h_{d3}) of 2.5 cm, with an angle variation (α) of 60°, resulting in a flow depth (h_m) of 6.760 cm. This increase can be attributed to water flowing through the gaps between the angular variations of the porous rectangular-type baffle block and its pore holes, which in turn led to a decrease in water level.

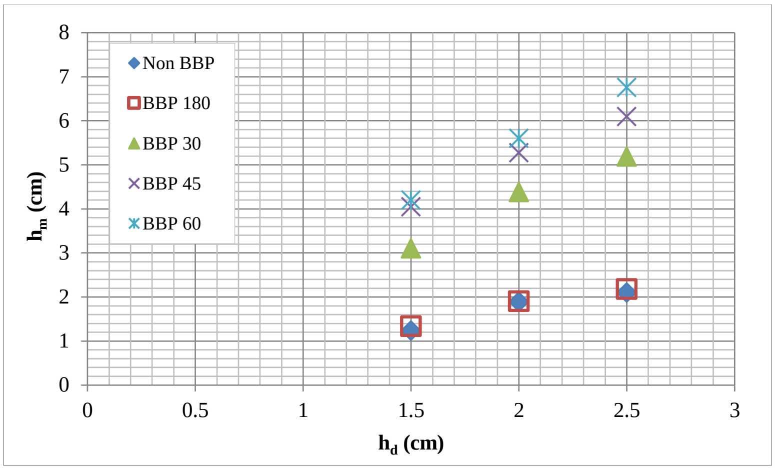


Figure 11. The depth of flow (h_m) at the angle variation of porous rectangular-type baffle block

3.2.2. Flow Velocity (v_m)

Flow velocity (v_m) was measured using a Portable Velocity Meter LS300-A, which automatically provides velocity data corresponding to the flow in the spillway structure model at the specified observation points. In this study, three discharge variations were tested to determine the flow velocity, which changed in response to the alterations in the spillway structure model. Additionally, changes in flow velocity were influenced by variations in the shape of the channel cross-section through which the water flow passed. The results of the flow velocity measurements are presented in Table 4 and Figure 12 as follows:

Table 4. Flow velocity

The Angle of Baffle Block (α)	Water Level above the Crest (h_d)	Flow Velocity (v_m)
Non BBP	1.5	1.235
	2.0	1.891
	2.5	2.104
180^0	1.5	1.019
	2.0	1.269
	2.5	1.331
30^0	1.5	0.564
	2.0	0.568
	2.5	0.568
45^0	1.5	0.416
	2.0	0.531
	2.5	0.548
60^0	1.5	0.345
	2.0	0.409
	2.5	0.727

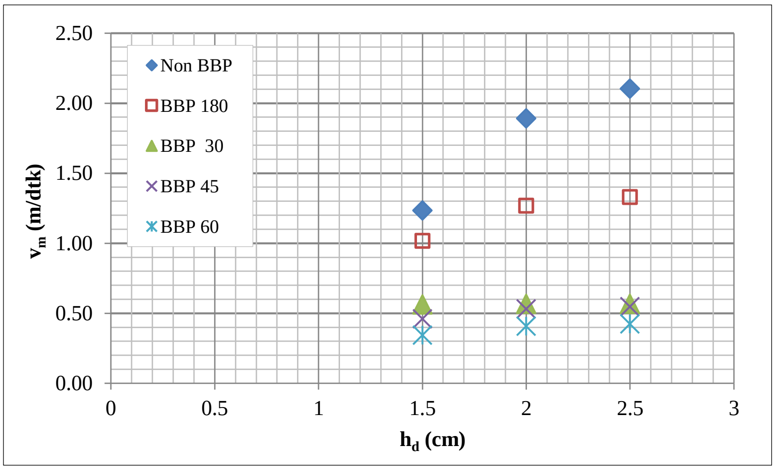


Figure 12. Flow height (h_m) at the angle variation of porous rectangular-type baffle block

The increase and decrease in flow velocity are influenced by variations in the water level above the crest. The highest flow velocity occurs in the model without the porous rectangular-type baffle block, at a flow discharge (Q_3) = 6861.66 cm³/s. Under these conditions, the water level above the crest (h_d) is 2.5 cm, with a flow velocity (v) of 2.104 m/s. A decrease in flow velocity is observed when variations in the porous rectangular-type baffle block angle are introduced, along with a reduction in the water level above the crest. This is due to the water flowing through the gaps and pore holes between the baffle block's angular variations, causing a significant reduction in flow velocity as the water moves slowly through these openings.

3.3. Flow Energy (he)

The energy in the spillway structure model is determined by comparing the energy upstream of the launch channel with that downstream in the stilling basin. The flow energy downstream of the spillway structure model, with variations in the porous rectangular-type baffle block angle in the launch channel, is obtained by comparing the energy values upstream of the launch channel and downstream of the stilling basin. The results of the flow energy calculations are presented in Table 5 and Figure 13.

Table 5. Flow energy

The Angle of Baffle Block (α)	Water Level above the Crest (h_d)	Flow Energy (h_e)
Non BBP	1.5	8.837
	2.0	9.493
	2.5	23.994
180^0	1.5	6.576
	2.0	9.523
	2.5	11.039
30^0	1.5	4.735
	2.0	6.012
	2.5	6.928
45^0	1.5	4.618
	2.0	5.483
	2.5	6.944
60^0	1.5	4.265
	2.0	5.481
	2.5	6.715

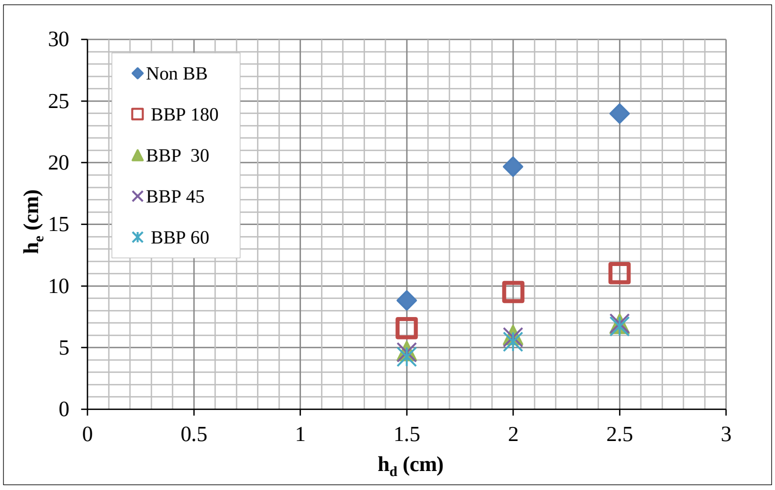


Figure 13. Flow energy (h_e) downstream of spillway structures

The flow energy, resulting from changes in flow parameters and variations in the porous rectangular-type baffle block, leads to an increase in flow energy within the stilling basin. This is observed in the model without the baffle block, where the flow discharge (Q_1) is 3303.91 cm³/s and the water level above the lighthouse (h_d) is 2.5 cm, yielding a water flow energy (he) of 23.994 cm. The flow energy decreases at the end of the stilling basin when the flow rate (Q_3) reaches 6861.66 cm³/s and the water level above the lighthouse (h_d) is 1.5 cm, with an angle variation (α) of 60°, resulting in a flow energy (h_e) of 3.749 cm.

The analysis of flow energy in the spillway structure model shows that the porous rectangular-type baffle block with a 60° angle variation causes a significant reduction in flow energy. This is due to the large angle, which reduces the flow gap space and velocity.

3.4. Flow Energy Damping (h_e%)

The placement of variations in the angle of the porous rectangular-type baffle block upstream of the launcher channel significantly contributes to energy dissipation downstream of the spillway. When placed on the slope of the launcher channel, the porous rectangular-type baffle block increases bistable flow and stabilizes water jumps downstream. An increase in flow discharge correlates with greater turbulence downstream of the stilling basin, resulting in smaller energy loss values. Specifically, energy loss efficiency improves as discharge variation decreases, demonstrating the effect of placing porous rectangular-type baffle block angle variations at the start of the launcher channel to reduce energy and water surges in spillway structures, as shown in Equation 1. The results of the flow energy dissipation calculations are presented in Table 6 and Figure 14.

Table 6. The flow energy damping

The Angle of Baffle Block (α)	Water Level above the Crest (h_d)	The Flow Energy Damping (h_e%)
	1.5	70.59
180^0	2.0	68.82
	2.5	66.11
	1.5	69.20
30^0	2.0	65.07
	2.5	62.70
	1.5	65.36
45^0	2.0	64.81
	2.5	63.77
	1.5	61.55
60^0	2.0	58.51
	2.5	54.65

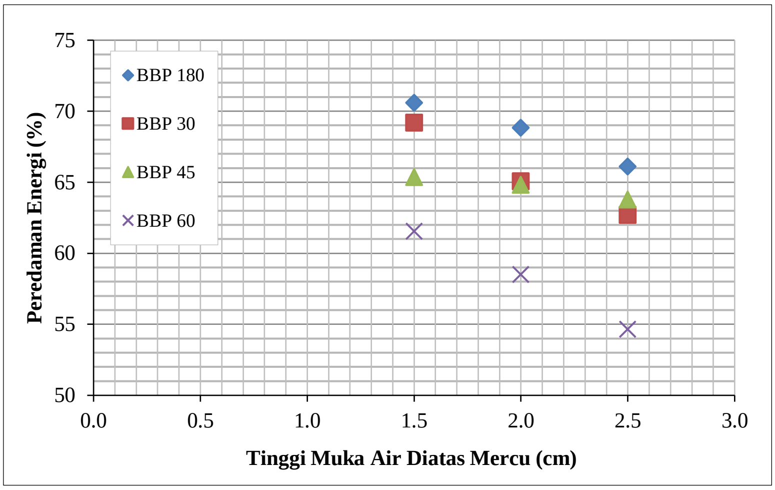


Figure 14. Damping of flow energy (h_e%) downstream of spillway structures

The presentation of flow energy dissipation in the spillway structure model with variations in the angle of the porous rectangular-type baffle block occurs at a flow discharge (Q_1) of 3303.91 cm³/s, a water level above the lighthouse (h_d) of 1.5 cm, and an angle variation (α) of 180°, resulting in a flow energy attenuation percentage (h_e%) of 70.59%. A decrease in flow energy downstream of the launcher channel is observed at a flow rate (Q3) of 6861.66 cm³/s, a water level above the lighthouse (h_d) of 2.5 cm, and an angle variation (α) of 60°, leading to a flow energy attenuation percentage (h_e%) of 54.65%.

Flow energy dissipation with larger variations in the angle of the porous rectangular-type baffle block is significantly more effective in reducing flow energy compared to smaller variations. Larger angular variations are better at retaining and slowing down the water flow. Additionally, the presence of pore holes helps regulate and slow the water flow passing through the porous rectangular-type baffle block. The 180° angle (α) baffle block model demonstrates that overflow during water jumps exceeds the length of the energy reduction zone, making it difficult to measure water levels accurately with a level meter. Therefore, a baffle block design with an angle (α) of 180°, parallel to the flow direction, is considered ineffective and not recommended for reducing energy levels.

3.5. Flow Characteristics (Fr)

The placement of porous rectangular-type baffle block angles upstream in the launcher channel can reduce the speed of the water flow. This phenomenon significantly affects the flow characteristics, particularly the Froude number (Fr), as higher water flow velocities correlate with a greater Froude number (Fr). Variations in the channel cross-section and the dimensions of the stilling basin notably influence changes in flow characteristics and the magnitude of the Froude number (Fr). Water flowing through the holes or pores at a certain speed requires energy to pass through the structures. However, every effort to pass through porous structures results in energy loss due to the pore openings. The results of the flow energy dissipation calculations can be seen in Table 7 and Figure 15, as follows:

Table 7. Flow characteristics

The Angle of Baffle Block (α)	Water Level above the Crest (h_d)	Flow Characteristics (h_e)	Flow Properties
	1.5	1.0	critical
Non BBP	2.0	1.3	supercritical
	2.5	1.3	supercritical
	1.5	1.0	critical
180^0	2.0	1.1	supercritical
	2.5	1.2	supercritical
	1.5	0.7	subcritical
30^0	2.0	0.8	subcritical
	2.5	1.1	supercritical
	1.5	0.6	subcritical
45^0	2.0	0.9	subcritical
	2.5	0.9	subcritical
	1.5	0.3	subcritical
60^0	2.0	0.5	subcritical
	2.5	0.6	subcritical

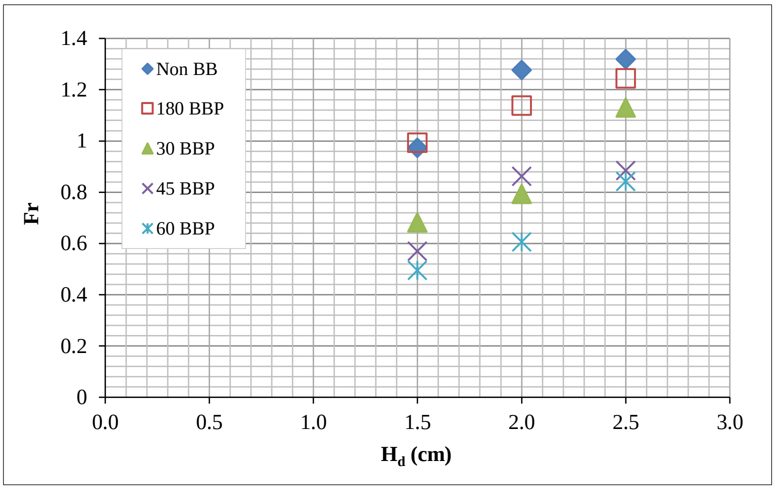


Figure 15. Froude number (Fr) in spillway structures

The flow characteristics and the highest Froude number (Fr) value occur in the model variation without a porous rectangular-type baffle block, at a flow discharge (Q_3) = 6861.66 cm³/s and a water level above the lighthouse (h_d) = 2.5 cm, resulting in a Froude number (Fr) of 1.3, indicating supercritical flow characteristics. The smallest flow characteristics and Froude number (Fr) values are observed in the model with a porous rectangular-type baffle block, at a flow rate (Q_1) = 3303.91 cm³/s, a water level above the lighthouse (h_d) = 1.5 cm, and an angle variation (α) of 60°, resulting in a Froude number (Fr) of 0.3, indicating subcritical flow characteristics.

The Froude number (Fr) is significantly affected by flow velocity and energy. As the water flow velocity increases, it correlates with greater energy generation and a higher Froude number (Fr). Additionally, the Froude number (Fr) is influenced by changes in the channel cross-section along the spillway structure, which significantly affect the flow parameters. These variations in the channel cross-section, as well as the corresponding large and small Froude number (Fr) values, impact the dimensions of the stilling basin and the occurrence of water jumps in the spillway structure.

3.6. Hydraulic Jumps (L_j)

The length of the hydraulic jump is measured from the upstream side of the transition arch channel to the far end of the stilling basin. Observations indicate that as the flow discharge increases, the length of the hydraulic jump also increases. The placement of variations in the angle of the porous rectangular-type baffle block upstream of the spillway channel is aimed at analyzing its effectiveness in reducing the length of the hydraulic jump in the spillway model. The results of the flow energy damping calculations are shown in Table 8 and Figure 16 as follows:

Table 8. Hydraulic jumps

The Angle of Baffle Block (α)	Water Level above the Crest (h_d)	Hydraulic Jump (L_j)
	1.5	7.80
Non BBP	2.0	12.20
	2.5	19.00
	1.5	3.87
180^0	2.0	6.00
	2.5	8.77
	1.5	3.03
30^0	2.0	5.00
	2.5	7.90
	1.5	2.53
45^0	2.0	4.80
	2.5	6.50
	1.5	2.17
60^0	2.0	3.90
	2.5	5.53

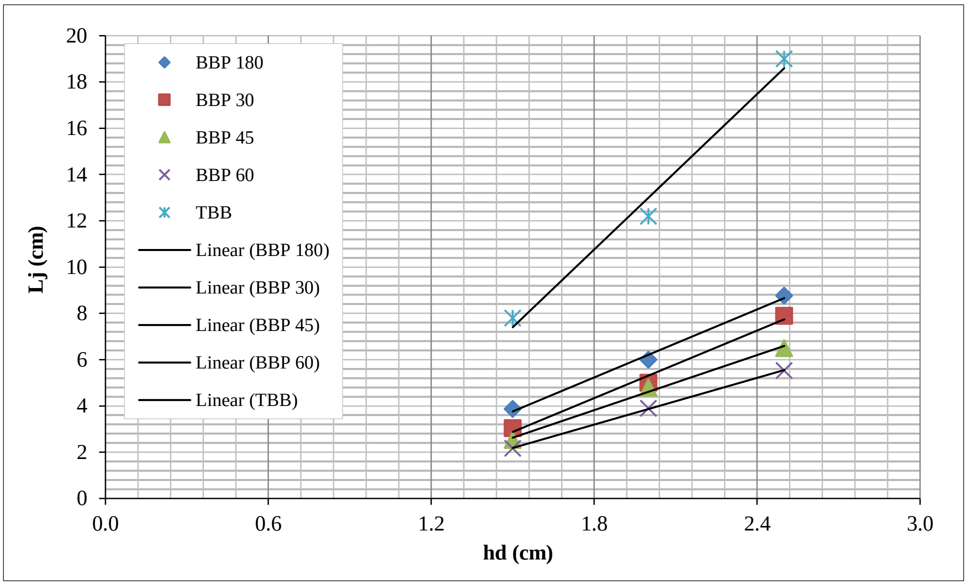


Figure 16. The length of hydraulic jumps at the end of spillway structures

Hydraulic jumps occur in the spillway structures model as the water level above the lighthouse increases. The longest hydraulic jumps are observed in the model without a porous rectangular-type baffle block, with a flow discharge (Q_3) of 6861.66 cm³/s and a water level above the lighthouse (h_d) of 2.5 cm, resulting in a hydraulic jump length (L_j) of 19.00 cm. A reduction in hydraulic jump length is observed with the introduction of the porous rectangular-type baffle block angle and a decrease in the water level above the lighthouse. The angle variation leads to a decrease in the length of the hydraulic jumps, as observed at a flow rate (Q_1) of 3303.91 cm³/s, a water level (h_d) of 1.5 cm, and a baffle block angle (α) of 60°, resulting in a hydraulic jump length (L_j) of 2.17 cm.

The length of the hydraulic jumps in the spillway structures model varies in each experiment, depending on the flow rate and the variation in the porous rectangular-type baffle block angle. Specifically, as flow discharge increases, greater turbulence occurs, leading to smaller energy loss values and shorter hydraulic jump lengths at the end of the stilling basin.

3.7. Relationship between Parameters Affecting Hydraulic Jumps (Hj/Lj)

The research on energy attenuation and hydraulic jump protection downstream of spillway structures was conducted in an open channel system. The design was based on the relationship between the water level height above the lighthouse (h_d), the angle of the porous rectangular-type baffle block (α), and the pore diameter of the baffle block (D_o). According to the literature, the investigation could be performed by placing baffle blocks in energy-absorbing structures to shorten the hydraulic jumps downstream. In this research, porous rectangular-type baffle blocks were placed in the launcher channel to reduce flow energy caused by water flow turbulence. This placement helped reduce the inflow energy downstream, thereby shortening the occurrence of hydraulic jumps. The results of the calculations examining the relationship between the influential parameters can be found in Table 9 and Figures 17 to 19 below.

Table 9. The relationship ratio of dimensionless numbers

Model	Hj/Lj	α	D_0/h_d	h_m/h_d	y_o/y_t	Fr
Non BBP	0.937	0	0.53	0.823	0.717	0.973
	0.994	0	0.40	0.946	0.797	1.277
	0.973	0	0.32	0.841	0.860	1.319
BBP	0.880	180	0.53	0.895	0.970	0.993
	0.862	180	0.40	0.955	0.963	1.139
	0.886	180	0.32	0.873	0.920	1.244
	0.777	30	0.53	2.071	0.879	0.682
	0.779	30	0.40	2.192	1.073	0.793
	0.797	30	0.32	2.077	1.000	1.131
	0.629	45	0.53	2.701	0.286	0.570
	0.623	45	0.40	2.638	0.240	0.863
	0.679	45	0.32	2.439	0.240	0.885
	0.572	60	0.53	2.800	0.238	0.495
	0.544	60	0.40	2.802	0.260	0.606
	0.551	60	0.32	2.704	0.264	0.842

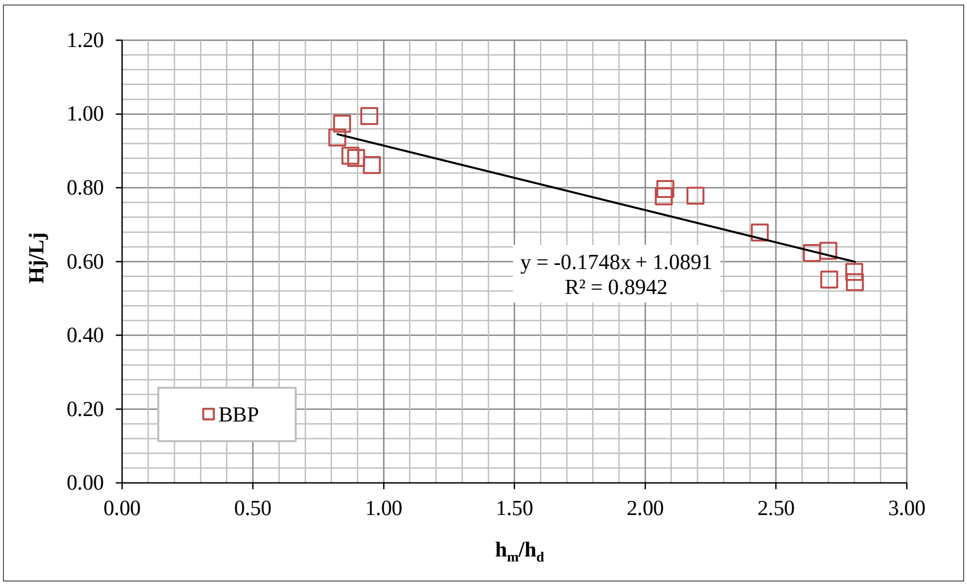


Figure 17. Relationship graph between h_m/h_d and H_j/L_j

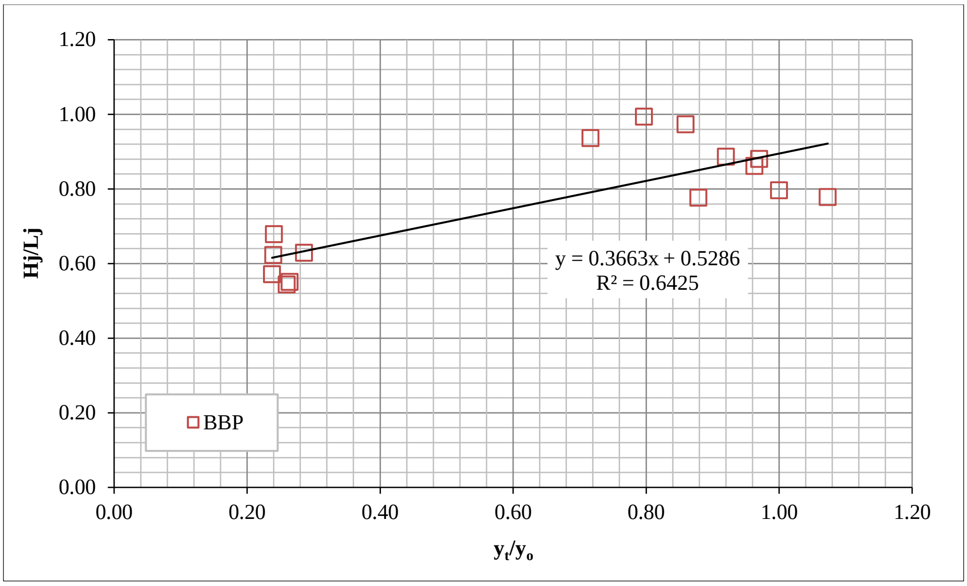


Figure 18. Relationship between y_o/y_t and H_j/L_j

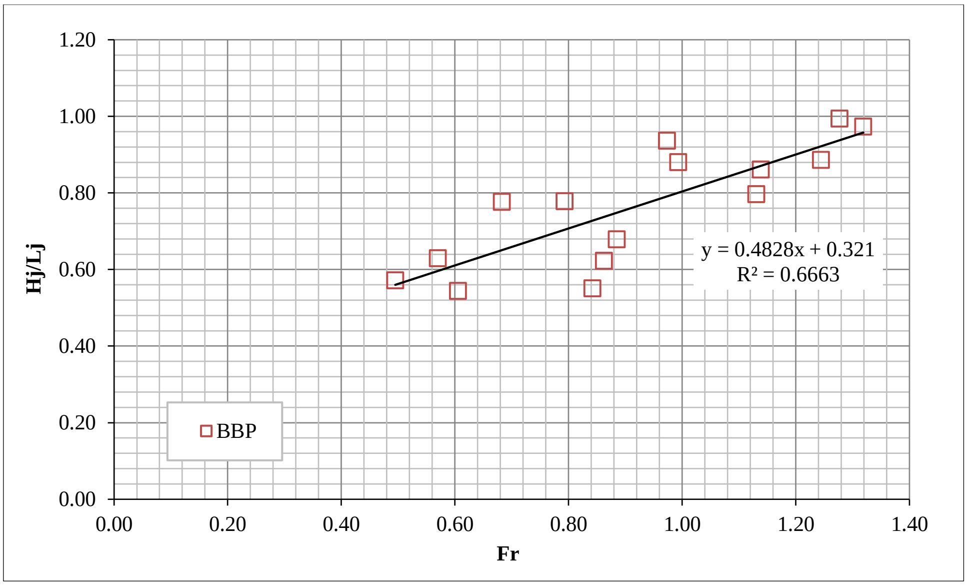


Figure 19. Relationship between Fr and H_j/L_j

Flow parameters are critical for analyzing the dimensionless number of hydraulic jumps in spillway structures. According to the relationship, a smaller dimensionless number value corresponds to greater energy attenuation. This relationship is inversely proportional to the ratio of dimensionless numbers to hydraulic jumps, where a greater value of flow depth (h_m/h_d) results in smaller dimensionless numbers. The ratio between the dimensionless number and energy reduction indicates that higher hydraulic jumps, both upstream and downstream (y_t/y_0), on models with porous rectangular-type baffle block angles in the spillway channel, lead to greater values downstream of the spillway structures (H_j/L_j). Similarly, higher Froude numbers (Fr) are associated with larger hydraulic jumps downstream (H_j/L_j) in the spillway model.

Flow velocity significantly influences the occurrence of hydraulic jumps and the magnitude of the Froude number (Fr). The analysis of dimensionless numbers, regarding variables affecting downstream water jumps in the spillway, is largely impacted by the Froude number (Fr). Therefore, the relationship ratio (H_j/L_j) due to variations in the porous rectangular-type baffle block angle (α) shows that hydraulic jumps decrease as the angle (α) increases.

The placement of varying porous rectangular-type baffle block angles as energy dissipators should not be considered optimal for reducing flow energy and hydraulic jumps to protect downstream spillway structures. This is because such placements require a series of simulations or experiments to better understand flow characteristics and Froude number (Fr). These parameters are crucial in developing empirical equations for hydraulic jumps downstream in spillway structures through dimensionless analysis using physical models.

The correlation between the influencing variables and the non-dimensional parameters includes the downstream flow height of the porous rectangular-type baffle block (y_t), the angle of the baffle block (α), the pore diameter (D_0), and the water level above the weir, as shown in Table 9. Dimensional analysis using the Buckingham π method [14, 26] produced four non-dimensional numbers that can simplify the analysis of water jumps, as shown in Figures 20 to 23.

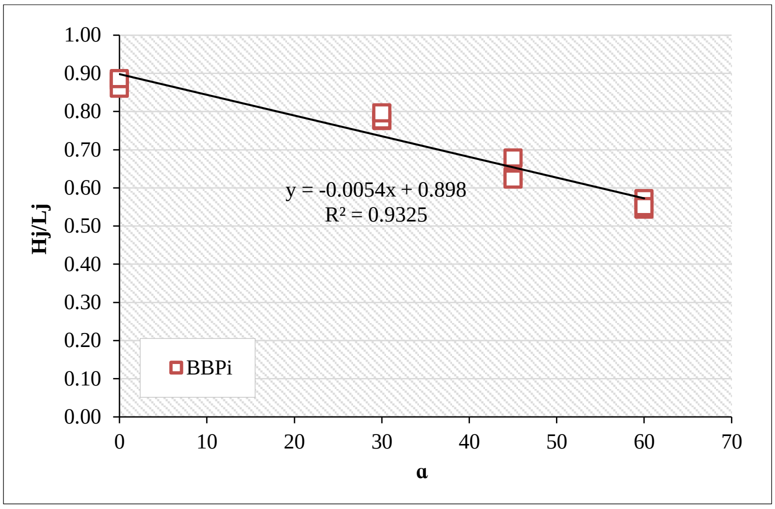


Figure 20. Graph of the relationship between α and H_j/L_j

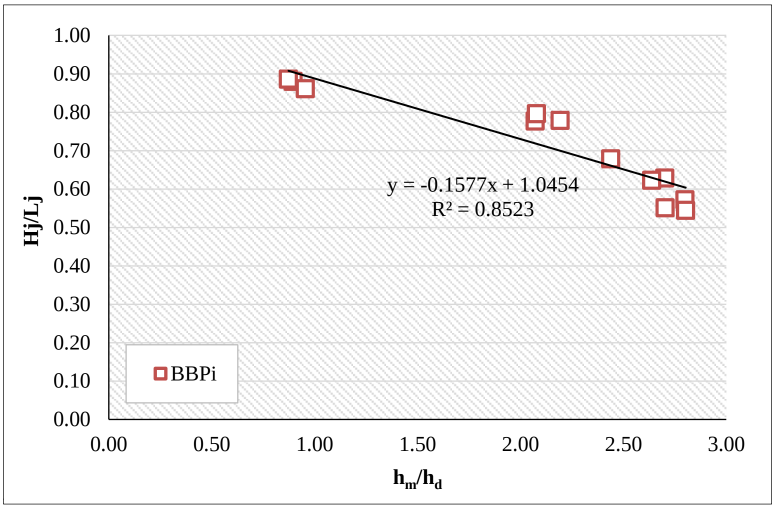


Figure 21. Graph of relationship between h_m/h_d and H_j/L

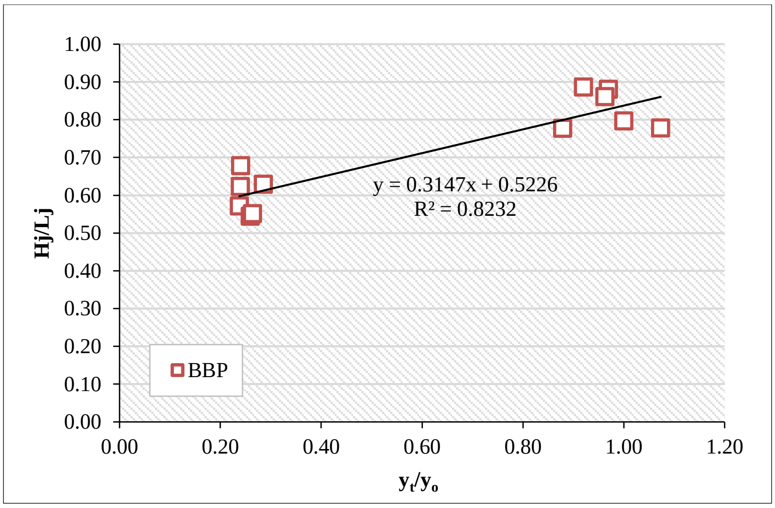


Figure 22. Graph of relationship between y_t/y_o and H_j/L_j

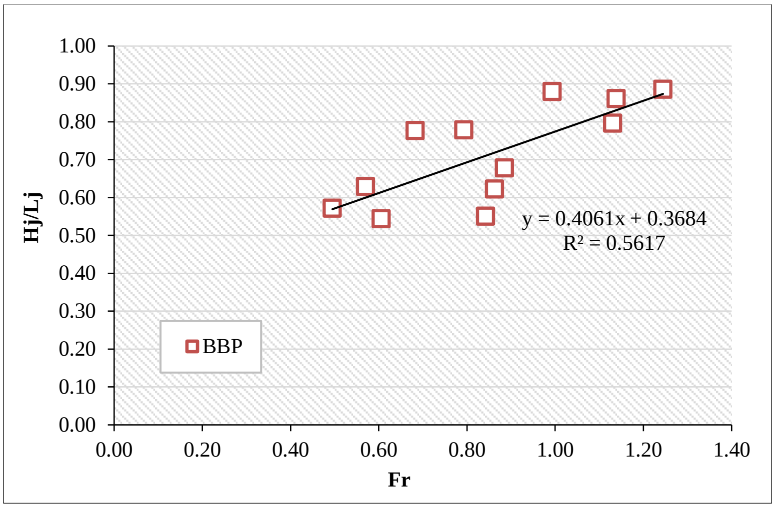


Figure 23. Graph of the relationship between Fr and H_j/L_j

The length of hydraulic jumps downstream (H_j/L_i) at the spillway structure, for each flow stage with varying flow rates, shows a linear relationship. The coefficient of determination (R-squared) values, based on the data distribution patterns in the graph, indicate that each flow stage exhibits a strong and consistent trend. By combining several dimensionless parameters, a dimensionless equation is derived to analyze the relationship between energy dissipation and changes in hydraulic jump length.

The simplification of these dimensionless parameters leads to the expression of a dimensionless function for the length of hydraulic jumps downstream.

$$\frac{Hj}{Lj} = f\left(\alpha, \frac{D_0}{h_d}, \frac{h_m}{h_d}, \frac{y_t}{y_0}, \frac{v}{\sqrt{gh_d}}\right) \tag{3}$$

Using multiple linear regression analysis, the relationship between dimensionless parameters obtains an equation, which tests the research variables dominating or having the strongest effect on hydraulic jumps downstream of spillway model (H_j/L_i) as follows:

$$\frac{H_j}{L_j} = 0.7868 - 0.00484\ (\alpha) + 0.01427\left(\frac{hm}{hd}\right) + 0.07041\left(\frac{y_0}{y_t}\right) + 0.01298(Fr) \tag{4}$$

The correlation equation for hydraulic jumps, derived from regression analysis, shows that only four influential parameters are included, as shown in Equation 3. These parameters are the ratio of the porous rectangular-type baffle block angle (α), flow depth (h_m/h_d), the ratio of upstream to downstream hydraulic jumps (y_o/y_t), and the Froude number (Fr), with constant values of -0.00484, 0.01427, 0.07041, and 0.01298, respectively, as shown in Equation 4. Additionally, the results of the hydraulic jump equation for each influential parameter are presented in Table 10.

Table 10. Linear regression and correlation

Model	Hj/Lj	α	h_m/h_d	y_o/y_t	Fr	D_0/h_d
BBP	0.880	0	0.895	0.970	0.993	0.53
	0.862	0	0.955	0.963	1.139	0.40
	0.886	0	0.873	0.920	1.244	0.32
	0.777	30	2.071	0.879	0.682	0.53
	0.779	30	2.192	1.073	0.793	0.40
	0.797	30	2.077	1.000	1.131	0.32
	0.629	45	2.701	0.286	0.570	0.53
	0.623	45	2.638	0.240	0.863	0.40
	0.679	45	2.439	0.240	0.885	0.32
	0.572	60	2.800	0.238	0.495	0.53
	0.544	60	2.802	0.260	0.606	0.40
	0.551	60	2.704	0.264	0.842	0.32

The relationship between non-dimensional numbers and the impact of hydraulic jumps downstream of the spillway structure, with variations in the placement of the porous rectangular-type baffle block angle, effectively dissipates flow energy and shortens the hydraulic jumps. Additionally, four variables are identified through multiple linear regression analysis of the parameters affecting changes in hydraulic jumps downstream of the spillway. These variables include the Froude number (Fr), baffle block angle (α), pore diameter (D_o), water level above the weir (h_d), and downstream baffle block hydraulic jump height (y_t).

3.8. The Comparison of the Results Between this Research and Previous Research

Hydraulic jumps length from the analysis of dimensionless numbers resulted in two influential parameters. These included $Fr\,\frac{v}{\sqrt{gh_d}}$ to baffle block angle (α), and $Fr\,\frac{v}{\sqrt{gh_d}}$ to the ratio of pore diameter ($\frac{D_0}{h_d}$). The relationship $\frac{D_0}{h_d}$ and $\frac{v}{\sqrt{gh_d}}$, derived from laboratory model testing produced an empirical equation for hydraulic jumps length associated with downstream Froude number (Fr) in the following form:

$$\mathrm{Lj} = \mathrm{y_t}(\mathrm{k}\,\alpha\,\mathrm{h_d}\,(\mathrm{Fr}-1)^4) \tag{5}$$

where Hj: Hydraulic jumps length (m); y_t: water jumps downstream height of baffle block (m), k: constant $\frac{1}{D_0}$ (m), α: angle of variation of baffle block (m); h_d: water level above the weir (m); Fr: Froude number; and D_o: pore diameter of baffle block (m).

The derived empirical formula was developed using the model scale and dimensionless numbers. This equation incorporates additional parameters, such as the angle and pore diameter, into the existing empirical formula. Hager's (1992) [19] empirical formula accounts for the hydraulic jump parameters upstream (h_1) of the barrier block, which are associated with the Froude number (Fr). In contrast, the empirical formula derived from the laboratory results considers the hydraulic jump parameters downstream (y_t) of the baffle blocks, which are influenced by flow damping and the Froude number (Fr). The accuracy of the empirical equation from this research was validated by comparing it with previous formulas, as shown in Equation 5. The validation process involved comparing the laboratory-derived empirical equation with Hager's (1992) [19] formula, focusing on the downstream Froude number (Fr), as presented in Equation 2. The comparison of results is shown in Table 11 and Figure 25.

Increased flow discharge (Q_{max}) has a significant impact on the flow energy and hydraulic jumps downstream at spillway structures. The empirical equation by Hager (1992) [19] shows that the shortest hydraulic jump length (L_j) of 7.15 cm occurs at a variation angle (α) of 60° for the porous rectangular-type baffle block, while the longest hydraulic jump length of 71.54 cm occurs at a variation angle (α) of 180° for the same baffle block.

The laboratory-derived empirical equation indicates that the shortest hydraulic jump length (L_j) of 6.31 cm occurs at a variation angle (α) of 60° for the porous rectangular-type baffle block, with the longest value observed at an angle (α) of 180°. The difference in the calculated hydraulic jump lengths between the laboratory equation and Hager's (1992) equation is due to variations in the parameters or variables influencing the empirical equation. However, the results from the laboratory empirical equation closely approximate the values obtained using Hager's equation (1992) [19].

Table 11. Comparison of result research

Model	Debit (Q)	Hydraulic Jumps (Lj)	
		Laboratory	Hager (1992) [19]
180^0	0.0033	32.25	61.34
	0.0057	50.61	66.08
	0.0069	70.00	71.84
30^0	0.0033	27.00	56.93
	0.0057	33.00	62.25
	0.0069	46.00	70.49
45^0	0.0033	9.24	10.80
	0.0057	12.03	12.19
	0.0069	12.29	13.37
60^0	0.0033	6.31	6.58
	0.0057	6.69	7.53
	0.0069	7.72	8.29

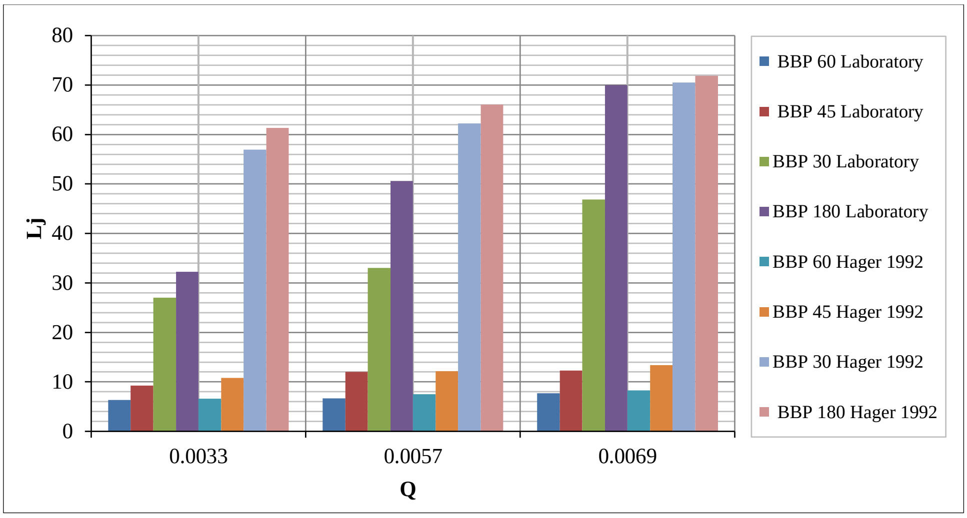


Figure 24. Comparison of results and previous research with empirical equations

Based on the two empirical equations, it can be concluded that the relative length of the hydraulic jump decreases as the obstacle block angle increases. This is due to the significant increase in energy dissipation with a higher Froude number. Consequently, the energy loss downstream of the spillway structure is reduced when the angle is increased. Furthermore, the depth of the water jump downstream also contributes to the reduction in energy dissipation.

4. Conclusion

In conclusion, this research found that the variation in the angle of the porous rectangular-type baffle block played a crucial role in reducing flow energy and shortening hydraulic jumps downstream of spillway structures. The results demonstrated that energy dissipation downstream of the spillway structures involved nine influential parameters, which contributed to the reduction in the length of hydraulic jumps. These parameters included headwater depth above the weir, channel water depth (h_m), headwater depth upstream of the baffle block (y_0), headwater depth downstream of the baffle block (y_t), pore diameter of the baffle block (D_0), variation angle of the baffle block (α), water mass density (ρ_w), specific energy (E_s), and flow velocity (v).

The effect of varying the angle of the porous rectangular-type baffle block was significant in reducing or dissipating flow energy. Based on the results, it was observed that a larger angle variation correlated with a greater reduction in flow energy. The process of dissipating flow energy during the transition from the channel to the spillway structures, through the placement of the baffle block, was essential to protect downstream spillway structures from scour hazards, riverbed damage, and to shorten the stilling basin.

The empirical equation for the length of hydraulic jumps, derived from dimensionless analysis, identified six influential parameters affecting hydraulic jumps downstream of spillway structures. These parameters included the height of hydraulic jumps downstream of the porous rectangular-type baffle block (y_t), the pore diameter constant (k), the variation angle of the baffle block model (α), the headwater depth above the weir (h_d), the Froude number (Fr), and the pore diameter (D_0). Based on laboratory results, the empirical equation for the length of hydraulic jumps associated with the downstream Froude number (Fr) was derived as follows: $Lj = y_t\ (k\ \alpha\ h_d\ (Fr - 1)^4)$.

5. Declarations

5.1. Author Contributions

Conceptualization, L.H.D., M.S.P., R.K., and B.B.; methodology, L.H.D.; software, L.H.D.; validation, M.S.P., R.K., and B.B.; formal analysis, L.H.D.; investigation, L.H.D.; resources, L.H.D.; data curation, L.H.D.; writing—original draft preparation, L.H.D.; writing—review and editing, L.H.D.; visualization, L.H.D.; supervision, M.S.P., R.K., and B.B.; project administration, L.H.D.; funding acquisition, L.H.D. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this research are available upon request from the corresponding author.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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