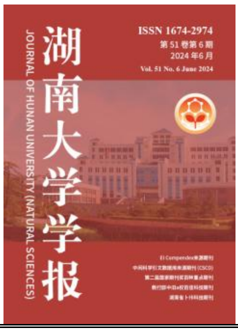

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Experimental Study of Hydraulic Jump Characteristics in a Double-Sill Stilling Basin

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Abstract: A stilling basin is a structure used in hydraulic engineering to dissipate the energy of flowing water, typically downstream of hydraulic structures like spillways, outlet works, and chutes. The primary purpose of a stilling basin is to reduce water velocity to prevent erosion and damage to downstream channels and infrastructure. The energy dissipation of water flow is crucial for designing structures like stilling basins. The United States Bureau of Reclamation (USBR) sets standards, including the Froude number (F_1) at the toe of the spillway, that must be considered in stilling basin planning. An alternative design to these standards is to use a double-sill stilling basin downstream of the chute channel, with specific spacing and height. This study's objective was to assess the efficacy of a double-sill energy dissipator in diminishing the flow energy within a stilling basin. The rationale behind this was that these energy dissipators are particularly adept at disrupting and weakening the water flow. Laboratory hydraulic physical model tests were conducted with double sills in fixed positions and at varying heights because previous studies indicated that the shape and size of sills affect energy dissipation. The results from these tests provide better insights into flow behavior in an overflow system regarding energy dissipation.

Keywords: hydraulic jump, double-sill stilling basin, energy dissipation.

双门槛式消力池水跃特性试验研究

摘要：消力池是水利工程中用来消散流水能量的一种结构，通常位于溢洪道、出水口工程和溜槽等水力结构的下游。消力池的主要目的是降低水流速度，防止下游河道和基础设施受到侵蚀和损坏。水流的能量消散对于消力池等结构的设计至关重要。美国垦务局(通用路由表)制定了标准，包括溢洪道脚的弗劳德数(F1)，在消力池规划中必须考虑这些标准。这些标准的替代设计是在溜槽渠道下游使用双门槛消力池，具有特定的间距和高度。本研究的目的是评估双门槛能量消散器在减少消力池内流动能量方面的功效。这背后的原因是这些能量消散器特别擅长扰乱和削弱水流。由于先前的研究表明，门槛的形状和大小会影响能量耗散，因此在实验室水力物理模型试验中使用固定位置和不同高度的双门槛进行。这些试验的结果可以更好地了解溢流系统中与能量耗散有关的流动行为。

关键词：水跃，双坎消力池，能量消能。

1. Introduction

Holding back water with a dam creates a significant difference in the water surface height between the top and bottom, leading to the formation of a plunge and a substantial energy change as the water flows over the dam [1, 2]. Consequently, the water flow undergoes a normal shock or hydraulic jump, transitioning from a supercritical flow to a subcritical flow [3].

Understanding the different types of hydraulic jumps can help engineers design effective energy dissipation structures and ensure the safety and stability of hydraulic systems. The hydraulic jump causes scour on the downstream side of the weir, leading to continuous erosion of the canal base and compromising the structure's integrity. To mitigate the energy from this hydraulic jump, a stilling basin or pond can be constructed at the end of the spillway [4]. Stilling basins with baffle blocks are designed to minimize the residual energy and reduce dangerous scours on the riverbed or structures. Effective design requires analysis and simultaneous laboratory observations. Energy dissipator structures with baffle blocks are built to mitigate degradation, and the sill height, configuration, and position of the baffle block influence the hydraulic jump [5, 6]. This study examines the effectiveness of varying distances between baffle blocks and the block heights using an energy dissipator with a double sill. This research provides valuable insights to enhance the effectiveness of energy-dissipating structures with baffle blocks.

2. Research Significance

This study focused on hydraulic jumps and energy dissipation in a double-sill stilling basin. Six series were tested, each with three variations in sill height: 10, 8, and 6 cm. Each series was evaluated at seven flow rates: 15, 17, 19, 21, 23, 25, and 27 L/s. This research is significant because it offers further insights into the use of double-sill stilling basins for energy reduction.

Energy reduction in a stilling basin is crucial for several reasons:

1. High-velocity flows can cause significant erosion of the channel bed and banks downstream of hydraulic structures. A stilling basin reduces the flow velocity, thereby minimizing erosion and protecting the channel structural integrity.
2. Hydraulic structures such as spillways and weirs are designed to withstand certain flow conditions. Reducing energy in a stilling basin helps protect these structures from excessive forces that can cause damage or failure.
3. High-energy flows can be dangerous to humans, animals, and infrastructure. By dissipating energy in a controlled environment, stilling basins enhance the overall safety of water management systems.
4. Reducing the flow energy helps stabilize the downstream flow conditions and promotes more uniform and predictable flow patterns. This is important for maintaining the efficiency and effectiveness of the downstream hydraulic structures and conveyance systems.
5. High-energy flows can carry large amounts of sediment, which can lead to sedimentation issues in downstream areas. By dissipating energy in a stilling basin, sediment transport is reduced, which helps to maintain channel capacity and prevent sediment buildup.
6. Controlling energy flow helps protect aquatic habitats and ecosystems. High-energy flows can disrupt habitats, harm aquatic life, and alter the natural balance of riverine systems. Energy dissipation in stilling basins helps mitigate these impacts.
7. Reducing energy in a stilling basin can extend the lifespan of hydraulic structures and reduce maintenance costs. Preventing erosion, protecting infrastructure, and minimizing sedimentation all contribute to lower operational and repair expenses over time.

In summary, energy reduction in stilling basins is essential for protecting infrastructure, ensuring safety, preserving the environment, and maintaining efficient and effective water management systems.

3. Physical Hydraulic Model Tests

3.1. Hydraulic Physical Model Data

The research was conducted at the River Engineering Laboratory, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya. The research involved testing the hydraulic physical model using various laboratory facilities and equipment: 1) a hydraulic physical model of a spillway with a height of 1.0 m; 2) a chute way channel with a 1:0.8 slope; 3) an open channel with a width of 0.4 m, height of 0.6 m, and 8 m long; 4) maximum pump discharge 30 L per second; 5) V-notch discharge measurement device upstream and downstream.

3.2. Research Variables

In this experimental study, two types of sills with different characteristics were used. Sill 1 (Z_1) features a combination of a sloping and vertical upstream rounded crest, while Sill 2 (Z_2) is a trapezoidal prism sill. The hydraulic model tests were conducted by varying the height of the sills and the distance between Sills 1 and 2 (L_2). Each series of tests included seven flow rates: 15, 17, 19, 21, 23, 25, and 27 L/s. The dimensions and shapes of the two types of sills were as follows:

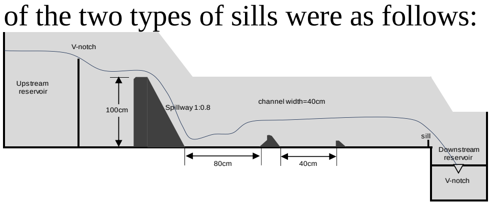
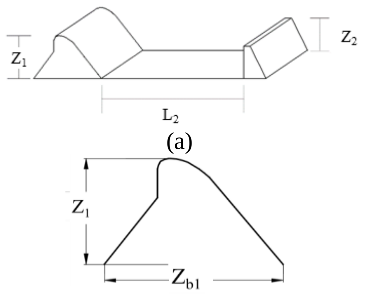


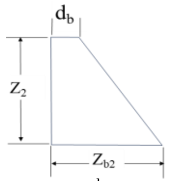
Fig. 1 Typical channel conditions in a double-sill stilling basin in

the laboratory (Own study)



(a)

(b) 1st sill



(c) 2nd sill

Fig. 2 Typical Sills 1 and 2 (Own study)

Table 1 Dimensions of Sills 1 and 2 (Own study)

Series	Z_1 (cm)	Z_{b1} (cm)	Z_2 (cm)	Z_{b2} (cm)	d_b (cm)
1	10.0	15.9	7.5	5.25	1.5
2	10.0	15.9	5.0	3.5	1.0
3	8.0	12.8	6.0	4.2	1.2
4	8.0	12.8	4.0	2.8	0.8
5	6.0	9. 6	4.5	3.2	0.9
6	6.0	9.6	3.0	2.1	0.4

Table 2 Variations in the double-sill dimension (Own study)

Series	Q (l/s)	Z_1 (cm)	Z_2 (cm)	L_1 (cm)	L_2 (cm)
1	15, 17, 19, 21, 23, 25, 27	10	7.5	80	40
2	15, 17, 19, 21, 23, 25, 27	10	5	80	40
3	15, 17, 19, 21, 23, 25, 27	8	6	80	40
4	15, 17, 19, 21, 23, 25, 27	8	4	80	40
5	15, 17, 19, 21, 23, 25, 27	6	4.5	80	40
6	15, 17, 19, 21, 23, 25, 27	6	3	80	40

3.3. Flow in Open Channels

The flow through an open channel is considered uniform if variables such as the flow depth, wetted area, flow velocity, and flow rate remain constant at each section along the flow. In a uniform flow, the energy line, water level line, and channel bed are parallel, resulting in equal slopes for these lines. The flow depth in a uniform flow is known as the normal depth. Uniform flow does not occur at high flow velocities or steep channel slopes [7]. When the flow velocity exceeds a certain threshold (critical velocity), the water surface becomes unstable, leading to wave formation. At extremely high speeds (over 6 m/s), air may enter the stream, causing the flow to become unsteady.

Flow is characterized as non-uniform or varied when flow variables, including flow depth, wetted area, and flow rate, exhibit variations across different sections of the channel. Rapidly varied flow transpires when alterations emerge within a brief spatial expanse, whereas gradually varied flow manifests across an extended distance. Flow is considered steady if the flow variables at a point do not change and unsteady if they change. In addition, open channel flow can be divided into subcritical, critical, and supercritical categories based on the Froude number [8].

Empirical equations applicable to open channel flow with a rectangular cross-section are presented in [9].

$$F = \frac{V}{\sqrt{\frac{gy}{\alpha}}} \tag{1}$$

$$y_c = \sqrt[3]{\frac{\alpha q^2}{g}} \tag{2}$$

3.4. Specific Energy

In an open channel, the energy carried by one unit weight of water has three components: kinetic energy, pressure energy, and elevation energy. The kinetic energy is expressed as ($V^2/2g$), where (V) is the velocity of the water and (g) is the acceleration due to gravity. The pressure energy depends on the water level, and the elevation energy represents the vertical distance from a reference line (usually the channel bottom) to the water surface. Under uniform flow conditions, the slopes of the energy grade line $S_f = S_w = S_0 = \mathrm{Sin}\Theta$ are equal. The expression employed is as follows [2], [11], [13]:

$$z_1 + y_1 + \alpha_1 \frac{V_1^{\,2}}{2g} = z_2 + y_2 + \alpha_2 \frac{V_2^{\,2}}{2g} + h_f \tag{3}$$

$$S_0 \Delta x + y_1 + \alpha_1 \frac{V_1^{\,2}}{2g} = y_2 + \alpha_2 \frac{V_2^{\,2}}{2g} + S_f \Delta x \tag{4}$$

$$\Delta x = \frac{E_2 - E_1}{S_0 - S_f} = \frac{\Delta E}{S_0 - S_f} \tag{5}$$

$$S_f = \frac{n^2 V^2}{R^{4/3}} \tag{6}$$

$$h_f = S_f \Delta x \tag{7}$$

Assuming $\alpha_1 = \alpha_2 = 0$ and $h_f = 0$, then:

$$z_1 + y_1 + \frac{V_1^{\,2}}{2g} = z_2 + y_2 + \frac{V_2^{\,2}}{2g} = constan \tag{8}$$

The energy at the cross-section of the channel, which is calculated relative to the bottom of the channel, is called the specific energy or specific height [11]:

$$E_s = y + \frac{\alpha V^2}{2g} \tag{9}$$

where:

A - wetted area (m^2)

B - channel bottom width (m)

E - energy height (m)

E_s - specific energy (m)
E_c - critical energy height (m)
E_0 - upstream energy head (m)
E_1 - energy head at the spillway toe (m)
E_2 - downstream energy head (m)
ΔE - loss of energy head (m)
g - acceleration gravity (m/s^2)
h - drop height (m)
n - Manning roughness coefficient
Q - flow rate (m/s)
q - discharge per unit width (m^2/s)
q - Q/B
R - average hydraulic radius (m)
S_0 - canal bottom slope
S_f - slope of the energy line
V - average velocity (m/s)
y - depth of water flow (m)
y_c - critical depth (m)
z_1 - bottom height of Channel Section 1 (m)
z_2 - bottom height of Channel Section 2 (m)
x - horizontal distance (m)
α - energy coefficient

3.5. Hydraulic Jump

A hydraulic jump occurs when a high-velocity supercritical flow transitions to a slower subcritical flow. During this process, a sudden increase in water level and a significant dissipation of energy occur. At the beginning of the jump, a large turbulent vortex forms, drawing energy from the main flow. Downstream, the vortex breaks into smaller eddies. The momentum equation is crucial for calculating the energy changes during a hydraulic jump.

The conjugate depth equation is derived as follows [7], [11-13]:

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1 + 8F_1^{\,2}} - 1\right) \tag{10}$$

where y_1 and y_2 are the water depths before and after the jump (m), respectively, and F_1 is the Froude number before the hydraulic jump.

In a horizontal rectangular channel, supercritical flow experiences energy reduction due to channel friction. This results in decreased velocity and an upward shift in water height along the flow direction. Hydraulic jumps occur on horizontal surfaces and can be categorized based on the flow's Froude number (F_1). These types of jump include undular, weak, oscillating, steady, and strong jumps [2], [9, 10].

The basic properties of hydraulic jumps in rectangular channels with a horizontal base can be described as follows [2]:

3.5.1. Loss of Energy

The energy loss during a jump is equal to the difference in the specific energy before and after the jump [10, 11]. The amount of energy loss is

$$\Delta E = E_1 - E_2 = \frac{(y_2 - y_1)^3}{4 y_1 y_2} \tag{11}$$

3.5.2. Efficiency

The ratio between the specific energies after and before the jump is defined as the jump efficiency. The magnitude of the jump efficiency is:

$$\frac{E_2}{E_1} = \frac{\left(8F_1^2 + 1\right)^{3/2} - 4F_1^{\,2} + 1}{8F_1^{\,2}\left(2 + F_1^{\,2}\right)} \tag{12}$$

This equation shows that the jump efficiency is a dimensionless function and depends only on the Froude number of the flow after the jump. The relative loss equals $1 - E_2/E_1$, and this quantity is also a dimensionless function of the Froude number [12].

3.5.3. Jump Height

The jump height can be defined as the difference between the depth before and after the jump.

$$y_j = y_2 - y_1 \tag{13}$$

3.5.4. Jump Length

The hydraulic jump's length is measured as the distance from the front surface of the hydraulic jump to a point on the downstream surface of the wave roll. The length of the jump is difficult to determine theoretically, but it has been investigated experimentally by several hydraulic experts [13, 14].

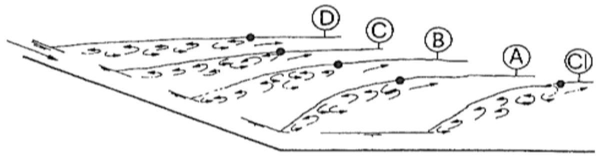


Fig. 3 Hydraulic jumps on slopes according to Kindsvater [17] (Own study)

Table 3 Equations for hydraulic jump length [16] (Own study)

Researchers	Hydraulic jump length
Riegel and Beebe (1917)	$Lj = 5(Y_2 - Y_1)$
Safranez (1927)	$Lj = 5 \times 2Y_2$
Ludin and Barnes (1934)	$Lj = \left(4{,}5 - \frac{V_1}{V_c}\right)Y_2$
Woycieki (1934)	$Lj = (Y_2 - Y_1)\left(8 - 0{,}05\frac{Y_2}{Y_1}\right)$
Smetana (1934)	$Lj = 6(Y_2 - Y_1)$
Douma (1934)	$Lj = 5 \times 2Y_2$
Aravin (1935)	$Lj = 5{,}4(Y_2 - Y_1)$
Kinney (1935)	$Lj = 6{,}02(Y_2 - Y_1)$
Page (1935)	$Lj = 5{,}6Y_2$
Chertoussov (1935)	$Lj = 10{,}3Y_1(Fr - 1)^{0.81}$
Bakhmetef and Matzke (1936)	$Lj = 5(Y_2 - Y_1)$
Ivanchenko (1936)	$Lj = 10{,}6(Y_2 - Y_1)(Fr^2)^{-0.185}$
Posey (1941)	$Lj = c(Y_2 - Y_1)$
Wu (1949)	$Lj = 10(Y_2 - Y_1)(Fr^{-0.16})$
Elevatorski (1959)	$Lj = 6{,}9(Y_2 - Y_1)$
Silvester (1964)	$Lj = [9{,}75(Fr - 1)^{1.01}]y_1$
Hager et al. (1992)	$\frac{Lj}{y_1} = 220 \tan h[Fr - 1]$

Researchers	Hydraulic jump length
Simões et al. (2012)	$Lj = 9{,}52(Y_2 - Y_1)$

3.6. Energy Dissipator

Generally, plunge pools are not designed to withstand the entire duration of a free fall due to their high cost. Consequently, mechanisms for managing jumps are typically incorporated into the stilling pond. The primary function of such controls is to decrease the time between jumps, thus minimizing the dimensions and expenses of the plunge pool. This control offers several benefits, such as enhancing the efficiency of the plunge pool damping, stabilizing the jumping motion, and, in some cases, improving safety [2].

Increasing the Froude number involves either increasing the velocity (V) or reducing the water depth (y). These parameters are linked through discharge per unit width (q), which can be adjusted by narrowing the structure (where q=Q/B). Alternatively, if this method is not practical, two types of stilling ponds can be utilized: (1) USBR Type IV, which employs large face blocks to increase vortex strength, and (2) baffle-block-basin type stilling ponds [12].

A major drawback of the latter type is its propensity to trap all floating and drifting objects, potentially leading to overflow and damage to barrier blocks, necessitating reinforced concrete during construction [15].

For Froude numbers exceeding 4.5, the water jump can achieve a stable state, facilitating effective energy dissipation. The USBR Type III surge pool was developed specifically for such scenarios. In cases in which the use of baffle blocks and face blocks is not practical (e.g., when the structure is masonry), designing the pond as a shallow but elongated plunge pool with end sills is recommended [15].

4. Results and Discussion

Measurements taken during the hydraulic model test included monitoring the flow depth, velocity, and conditions of the hydraulic jumps. This study investigated the energy dissipation under initial design parameters: flow rates ranging from 15 to 27 L/s and a channel slope of 1:0.8. The theoretical analysis predicts that these conditions will induce supercritical flow with a Froude number (F_1) ranging from 9 to 11, leading to the formation of a strong hydraulic jump.

This research was developed to obtain a double-sill composition that provides the best attenuation results.

Laboratory observations indicate that the hydraulic jump was of type B. The hydraulic jump occurs in the sloped area and terminates in the stilling basin.

Based on the measurements of flow depth and velocity, higher flow rates lead to increased velocity and water levels. Similarly, when measuring the height and length of hydraulic jumps, higher flow rates were correlated with greater velocity and water levels. In addition, shorter hydraulic jump lengths indicate more efficient energy dissipation at the tested distances and sill heights. Moreover, as the discharge increases, the length of the hydraulic jump also tends to increase, illustrating its dependence on the flow rate.

Based on the measured water level, the Froude values for y_1 and y_2 can be calculated, and it can be concluded that the Froude value varies.

The observation and analysis results are presented in the following graphs:

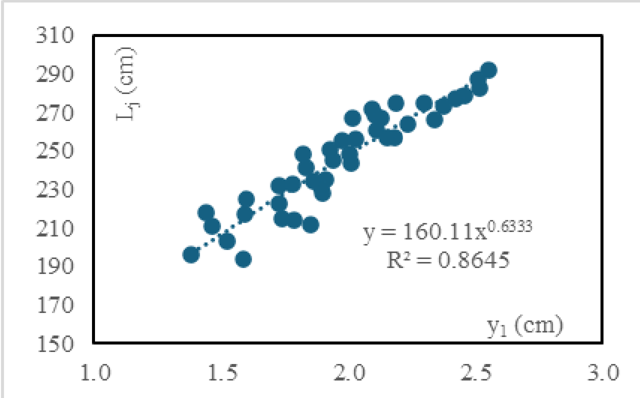


Fig. 4 Relationship between L_j and y_1 (Own study)

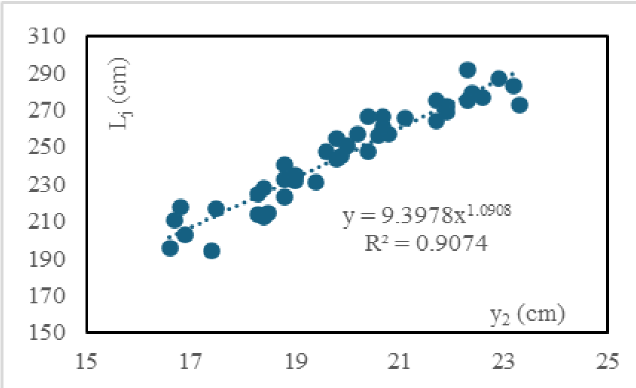


Fig. 5 Relationship between L_j and y_2 (Own study)

A strong correlation is also shown between L_j and y_2, with the following regression equation:

$L_j = 9.3978\ y_2^{1.0908}$ with $R^2 = 0.9074$

This relationship between L_j and y_2 is consistent with the findings by Safranez (1927), Douma (1934), and Page (1935) [16], although it exhibits larger values. The model results indicate that the coefficient for y_2 is higher than that in previous studies.

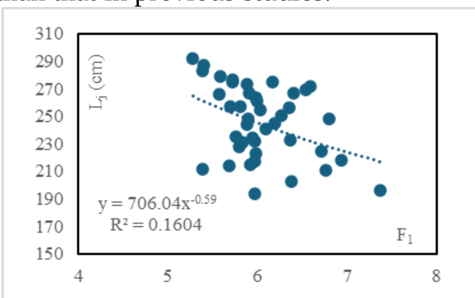


Fig. 6 Relationship between L_j and F_1 (Own study)

L_j has a weak correlation with F_1 but strongly correlates with F_2. These relationships are expressed as follows:

$L_j = 706.04\ F_1^{-0.59}$ with $R^2 = 0.1604$

$L_j = 2665\ F_2^{1.421}$ with $R^2 = 0.7376$

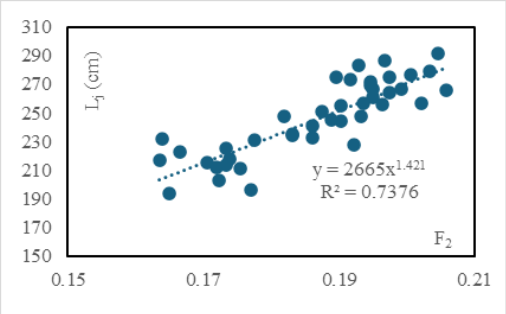


Fig. 7 Relationship between L_j and F_2 (Own study)

The type of downstream flow conditions, characterized by the Froude number after the jump, is closely related to the length of the hydraulic jump (L_j). Given this condition, it can be explained that the hydraulic jump length behavior is predominantly determined by subcritical flow conditions downstream rather than supercritical flow conditions before the jump.

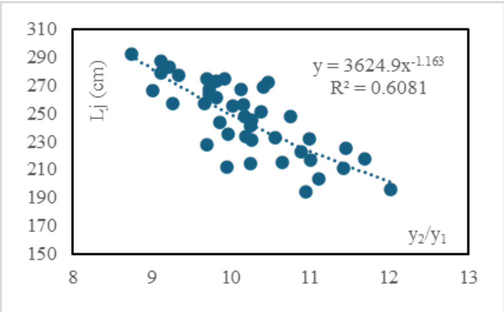


Fig. 8 Relationship between L_j and y_2/y_1 (Own study)

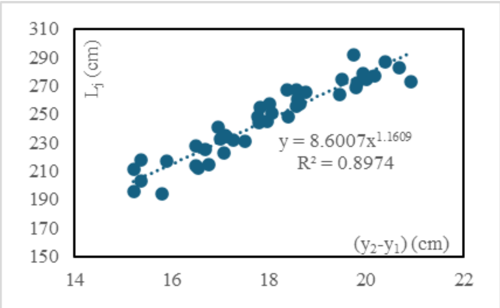


Fig. 9 Relationship between L_j and (y_2-y_1) (Own study)

Based on the laboratory research conducted, a strong correlation between L_j and y_2/y_1 and (y_2-y_1) was found, as indicated by the following regression relationships:

$L_j = 3624.9\ (y_2/y_1)^{-1.163}$ with $R^2 = 0.6081$

$L_j = 8.6007\ (y_2\text{-}y_1)^{1.1609}$ with $R^2 = 0.8974$

This condition demonstrates that the jump length is primarily related to the ratio of depths before and after the jump (conjugate depth) (y_2/y_1) and the height of the jump ($y_j = y_2\text{-}y_1$). These findings are consistent with previous research conducted by Riegel and Beebe (1917), Smetana (1934), Aravin (1935), Kinney (1935), Bakhmetef and Matzke (1936), Posey (1941), Elevatorski (1959), and Simoes et al. (2012) [16].

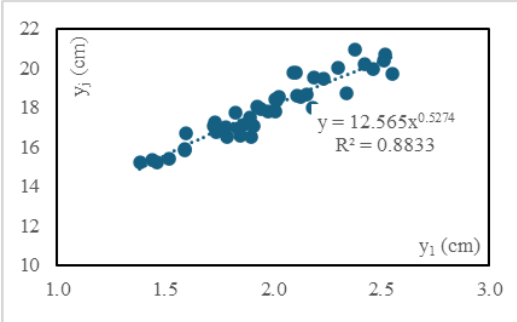


Fig. 10 Relationship between y_j and y_1 (Own study)

A strong correlation is also shown between the hydraulic jump height y_j and the depth of flow before the jump y_1, the depth of water after the jump y_2, F_2, and the ratio y_2/y_1. However, there is a weak correlation with the Froude number before the jump, F_1. The regression equations for these relationships are as follows:

$y_j = 12.565\ y_1^{0.5274}$ with $R^2 = 0.8833$

$y_j = 1.0965\ y_2^{0.9344}$ with $R^2 = 0.9968$

$y_j = 100.24\ F_2^{1.0256}$ with $R^2 = 0.5683$

$y_j = 152.29\ (y_2/y_1)^{-0.924}$ with $R^2 = 0.5549$

$y_j = 48.263\ F_1^{-0.553}$ with $R^2 = 0.1985$

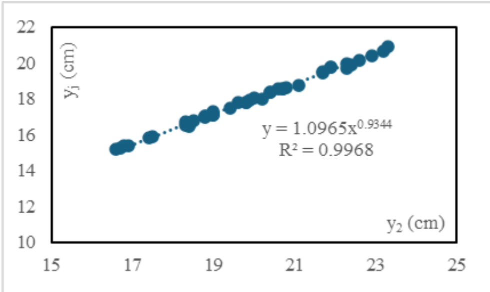


Fig. 11 Relationship between y_j and y_2 (Own study)

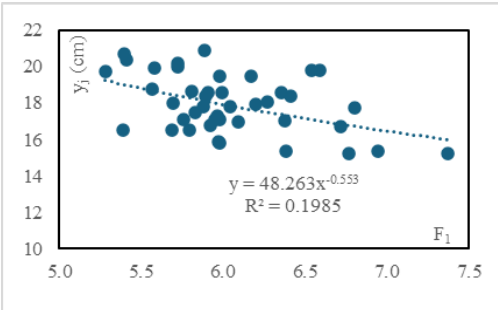


Fig. 12 Relationship between y_j and F_1 (Own study)

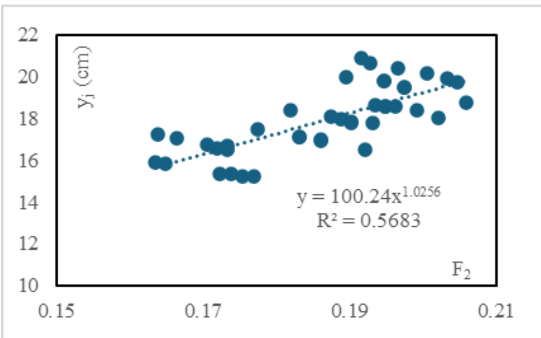


Fig. 13 Relationship between y_j and F_2 (Own study)

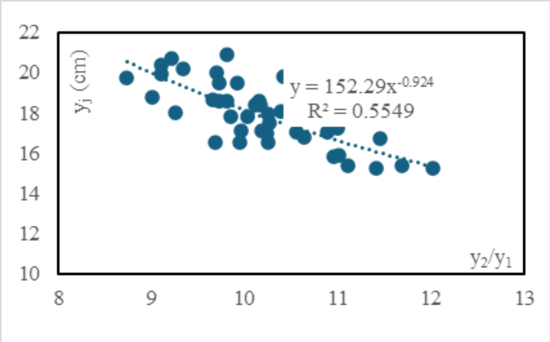


Fig. 14 Relationship between y_j and y_2/y_1 (Own study)

The conjugate depth ratio (y_2/y_1) in this study was strongly correlated with the Froude number before and after the hydraulic jump. However, a stronger relationship is indicated between y_2/y_1 and F_1. Therefore, the conjugate depth ratio is predominantly influenced by the Froude number before the hydraulic jump occurs (F_1). The regression equations for these relationships are as follows:

$y_2/y_1 = 2.361\ F_1^{0.8122}$ with $R^2 = 0.6624$

$y_2/y_1 = 2.4509\ F_2^{-0.846}$ with $R^2 = 0.5669$

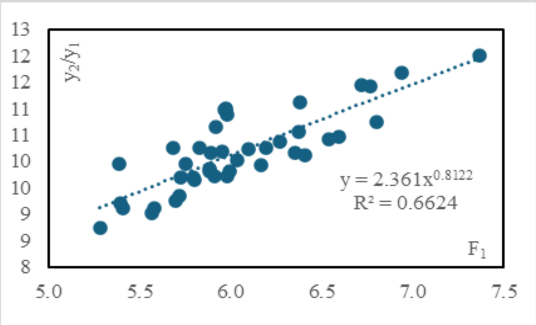


Fig. 15 Relationship between y_2/y_1 and F_1 (Own study)

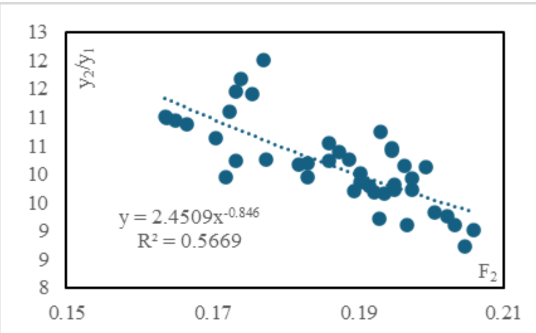


Fig. 16 Relationship between y_2/y_1 and F_2 (Own study)

Meanwhile, for the analysis of the energy dissipation efficiency in the laboratory-tested double-crested weir stilling basin, it is shown that the energy dissipation efficiency (E_2/E_1) correlates closely with the Froude number before the jump, as indicated by the regression:

$E_2/E_1 = 384.98\ F_1^{-1.095}$ with $R^2 = 0.7766$

The relationship between the energy dissipation efficiency (E_2/E_1) and the Froude number after the jump was very weak.

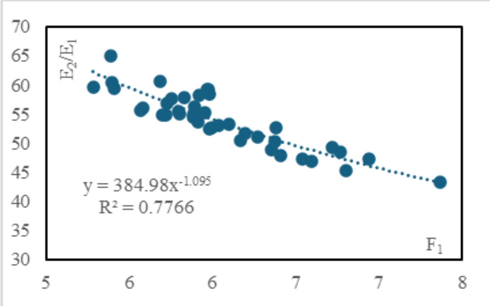


Fig. 17 Relationship between E_2/E_1 and F_1 (Own study)

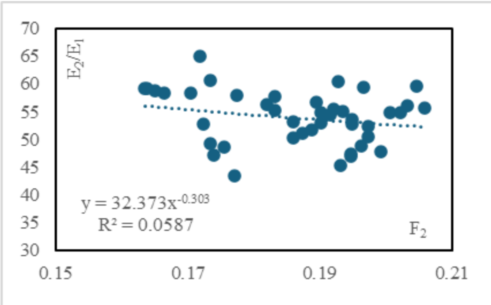


Fig. 18 Relationship between y_2/y_1 and F_2 (Own study)

Overall, the laboratory observation results show the following:

Table 4 Results of F_2 and L_j in a double-sill stilling basin (Own study)

Series	F_2 minimum	F_2 average	L_j minimum (cm)	L_j average (cm)
1	0.1635	0.1860	217	254
2	0.1665	0.1866	211	244
3	0.1733	0.1887	218	247
4	0.1650	0.1875	194	241
5	0.1719	0.1863	196	244
6	0.1705	0.1844	203	247

Table 5 Results of y_j and E_2/E_1 in a double-sill stilling basin (Own study)

Series	y_j minimum (cm)	y_j average (cm)	E_2/E_1 maximum (%)	E_2/E_1 average (%)
1	15.91	17.99	59.63	54.14
2	15.24	17.94	58.42	54.45
3	15.36	17.88	56.00	49.20
4	15.81	17.83	60.60	56.68
5	15.22	17.96	64.96	54.35
6	15.38	18.09	60.35	55.47

Effective energy dissipation is critical for the longevity and safety of hydraulic structures and for minimizing environmental impacts. Properly designed energy dissipation structures ensure that high-velocity flows are controlled, thereby reducing the risk of erosion, structural damage, and other negative effects on downstream areas.

The efficiency of energy dissipation in hydraulic structures is critical for the design and performance of systems handling high-velocity water flows. Efficient energy dissipation prevents erosion, structural damage, and downstream flooding.

5. Conclusion

This study focused on hydraulic jumps and energy dissipation in a double-sill stilling basin. Therefore, this research aimed to provide valuable insights to enhance the effectiveness of energy-dissipating structures with baffle blocks.

Based on the summary of the results above: 1) Series 6 shows the smallest average Froude number F_2, indicating the calmest flow downstream; 2) Series 4 has the shortest average hydraulic jump length (L_j), implying the shortest stilling basin requirement; 3) Series 4 shows the lowest average depth of the hydraulic jump (y_j), suggesting the need for the lowest side wall channel compared to other series; 4) Series 4 exhibits the best energy dissipation efficiency (56.68%).

The double sill stilling basin in Series 4 (Z_1 = 8 cm, Z_2 = 4 cm, L_1 = 80 cm, L_2 = 40 cm, Z_1/Z_2 = 2, L_1/L_2 = 2) represents the optimal combination, providing the shortest average hydraulic jump length (L_j), lowest hydraulic jump height (y_j), highest energy dissipation efficiency (E_2/E_1), and subcritical downstream flow conditions.

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