

Experimental Study of Hydraulic Jump Controlled by a Square Perforated Weir in a Rectangular Channel

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Abstract:

This study presents a comparative analysis of the hydraulic behavior of a hydraulic jump controlled by a solid weir and a square perforated weir. The main objective is to evaluate the influence of perforation on hydraulic performance, particularly in terms of energy dissipation and flow stability. The investigated parameters include the conjugate depth ratio $Y = h_2/h_1$, the relative jump length L_j/h_1 , the roller length L_r/h_1 , and the energy dissipation efficiency η . A statistical analysis based on multiple regression was carried out using SPSS software in order to establish empirical models relating these parameters to flow conditions. The results show that the square perforated weir significantly reduces the conjugate depth ratio and the characteristic lengths of the hydraulic jump, leading to a more compact flow structure and enhanced energy dissipation. In contrast, the solid weir exhibits longer jump characteristics and lower dissipation efficiency. The developed models demonstrate high coefficients of determination ($R^2 > 0.97$), confirming their reliability. These findings demonstrate that the square perforated configuration is an efficient and optimized solution for controlling high-energy flows and improving energy dissipation systems.

1. Introduction

The hydraulic jump is a fundamental phenomenon in open-channel hydraulics and is widely used for energy dissipation in hydraulic structures such as spillways and stilling basins. This phenomenon reduces flow velocity and limits downstream erosion risks.

In conventional configurations, hydraulic jump control is generally ensured by solid weirs. However, these devices present certain limitations, particularly insufficient energy dissipation under high-energy flow conditions and relatively long jump lengths requiring large hydraulic structures.

To improve hydraulic performance, alternative solutions such as perforated weirs have been proposed. The introduction of perforations modifies the flow structure, increases turbulence intensity,

and enhances energy dissipation. In particular, the geometry of the openings plays a determining role in hydraulic jump behavior.

In this context, the square perforated weir appears to be a promising configuration capable of providing an optimal compromise between energy dissipation and hydraulic stability.

The objective of this study is to analyze the hydraulic behavior of a hydraulic jump controlled by a square perforated weir and to compare it with that controlled by a solid weir. The analysis focuses on the conjugate depth ratio $Y = h_2/h_1$, the relative jump length L_j/h_1 , the roller length L_r/h_1 , and the energy efficiency η , whose principal parameters are illustrated in Figure 1.

This study therefore aims to highlight the contribution of square perforation to improving the performance of energy dissipators and to propose suitable analysis and modeling tools for high-energy flow conditions.

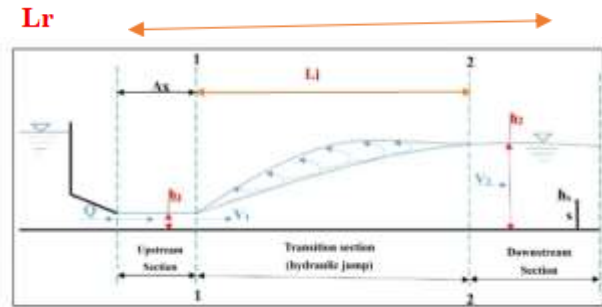


Figure 1: Schematic representation of a hydraulic jump controlled by a weir in a rectangular channel

2. Materials and Methods

2.1 Experimental Setup

The experiments were conducted in a rectangular channel 10 m long, 0.25 m wide, and 0.50 m deep operating in a closed-circuit system. The flow was supplied by an axial pump connected to a 5000 L main reservoir, with a maximum discharge of 44 L/s. A metallic convergent section was installed to ensure a uniform velocity profile at the channel entrance, while a downstream gate was used to control the upstream depth h_1 . All experiments were performed under zero longitudinal slope conditions to guarantee uniform flow.

2.2 Investigated Weirs

Two configurations were considered:

1. A solid weir used as a reference,
2. A square perforated weir.

The weirs were installed 4 m downstream of the gate in order to allow complete development of the hydraulic jump. The tested weir heights ranged from 4 to 12 cm, while the perforation ratio was varied over a wide range.

This approach made it possible to evaluate the effect of square perforation on the hydraulic performance of the jump.

The perforation ratio (TP) varied from 10% to 90%.

2.3 Experimental Measurements

Hydraulic parameters were measured using devices suitable for free-surface flows, including point gauges and calibrated weirs.

The measured quantities included upstream and downstream water depths, characteristic jump lengths (L_j and L_r), and discharge.

2.4 Dimensionless Parameters

The results were analyzed using conventional dimensionless parameters:

Upstream Froude number:

$$Fr_1 = \frac{V_1}{\sqrt{gh_1}}$$

Conjugate depth ratio:

$$Y = \frac{h_2}{h_1}$$

Relative jump length:

$$\frac{L_j}{h_1}$$

Relative roller length:

$$\frac{L_r}{h_1}$$

Energy efficiency:

$$\eta = \frac{E_1 - E_2}{E_1} \times 100$$

with:

$$E = h + \frac{V^2}{2g}$$

3. Results and Discussion

3.1 Effect on the Conjugate Depth Ratio Y

Experimental results show that the square perforated weir causes a significant reduction in the conjugate depth ratio $Y = h_2/h_1$ compared with the solid weir. For the solid weir, the corrected Bélanger relation indicates a gradual decrease in Y with increasing relative weir height S/h_1 , as illustrated in **Figure 6**, which presents the variation of Y_{exp} and Y_{th} as a function of Fr_1 for the solid weir.

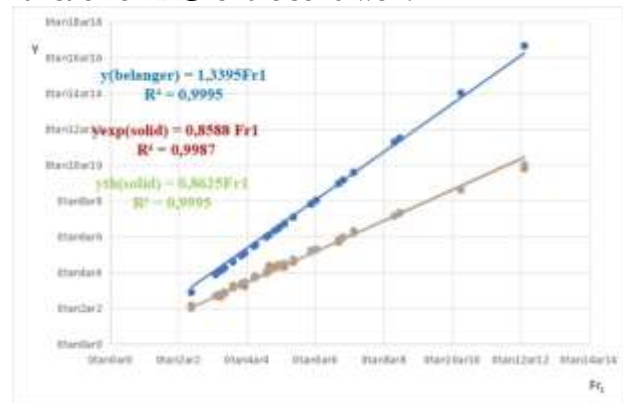


Figure 2. Variation of Y_{exp} and Y_{th} as a function of Fr_1 for the solid weir

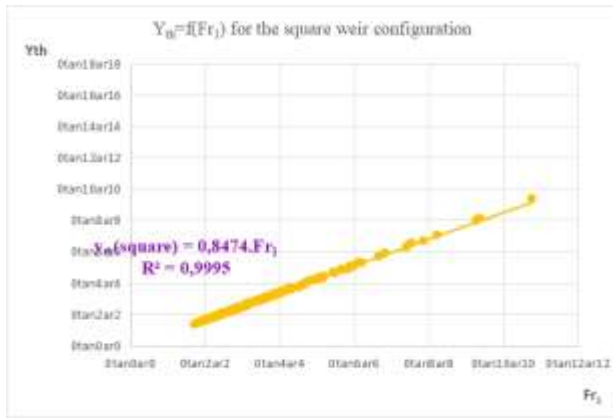


Figure 3. Variation of Y_{th} as a function of Fr_1 for the square weir configuration

Similarly, Figure 7 shows the variation of Y_{th} with Fr_1 for the square perforated weir configuration, highlighting the hydraulic response of this geometry. For the solid weir, the corrected Bélanger

formulation also shows this decreasing trend of Y with increasing S/h_1 , as further illustrated in Figure 8, which presents the variation of the correction coefficient K with the relative weir height.

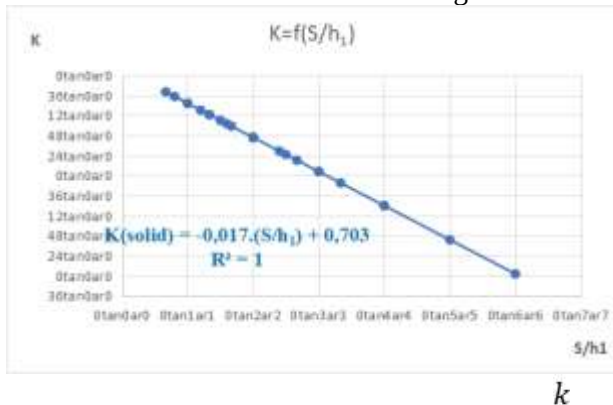


Figure 4. Variation of the correction coefficient K as a function of the relative weir height (S/h_1) for the solid weir

In the case of the square perforated weir, this reduction becomes more pronounced due to the influence of the perforation ratio TP , which allows partial flow passage through the weir and modifies

the hydraulic jump structure, as clearly shown in Figure 7.

This behavior reflects a reduction in downstream depth and an intensification of dissipative mechanisms, leading to a more compact hydraulic jump compared with the solid weir.

Finally, experimental validation confirms excellent agreement between theoretical and experimental values, as illustrated in Figure 9, with a high coefficient of determination ($R^2 = 0.9987$).

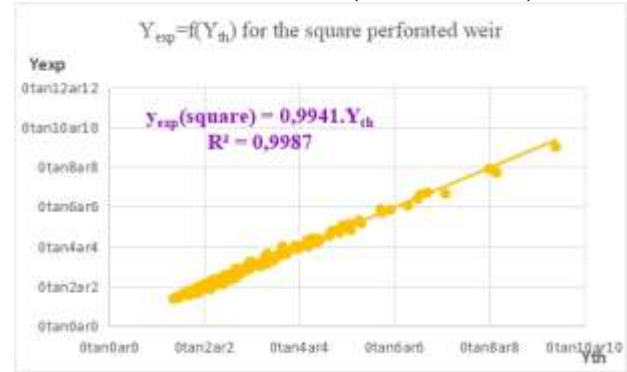


Figure 5. Correlation between Y_{exp} and Y_{th} for the square perforated weir

3.2 Effect on L_j/h_1

The variation of the relative hydraulic jump length L_j/h_1 as a function of the upstream Froude number Fr_1 is presented for both the solid weir and the square perforated weir.

The results show that, for the solid weir, the jump length increases almost linearly with Fr_1 , as illustrated in Figure 10. In contrast, for the square perforated weir, a significant reduction in L_j/h_1 is observed, particularly with increasing perforation ratio TP , as shown in Figure 11.

This reduction reflects faster energy dissipation and hydraulic jump compaction, which leads to a decrease in the longitudinal extent of the flow compared with the solid weir.

The empirical relationships proposed for predicting L_j/h_1 are presented in Table 1, where good agreement is observed between theoretical and experimental values.

Table 1. Validation of the models for the relative hydraulic jump length (L_j/h_1) for different weir configurations

Weir type	Predictive relationship L_j/h_1	Experimental validation $(L_j/h_1)_{exp} = f((L_j/h_1)_{th})$	R^2
Solid (reference)	$L_j/h_1 = 2.627 + 7.461 Fr_1$	$(L_j/h_1)_{exp} = 1.000 (L_j/h_1)_{th}$	0.9917
Square	$L_j/h_1 = (10.704 - 0.098 TP + 0.248 (S/h_1)) + (4.425 - 0.027 TP + 0.396 (S/h_1)) Fr_1$	$(L_j/h_1)_{exp} = 1.0016 (L_j/h_1)_{th}$	0.9756

Table 2. Validation of the relative hydraulic jump roller length (L_r/h_1) models for the solid and square perforated weirs

Weir type	Predictive equation (L_r/h_1)	Experimental validation	R^2
solid weir (réf.)	$(L_r/h_1) = 1.1894 + 3.7115 Fr_1$	$(L_r/h_1)_{exp} = 1.0001 (L_r/h_1)_{th}$	0.9934

square weir	$(L_r/h_1) = 1.099 - 0.035 TP + 3.43 (S/h_1) + (3.212 - 0.027 TP - 0.247 (S/h_1)) Fr_1$	$(L_r/h_1)_{exp} = 0.9988 (L_r/h_1)_{th}$	0.9946
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Table 3. Physical interpretation of the coefficients of the empirical relation for the relative hydraulic jump roller length (L_r/h_1)

Weir type	coefficient Fr_1 (energy sensitivity)	Influence of TP	Influence of S/h_1	R^2	Physical interpretation
square weir	+3.212	-0.027	+0.247	0,9647	Good energy dissipation, stable structure, and a moderate and regular development of the hydraulic jump roller.

Table 4. Validation of the energy efficiency (η) models for the solid and square perforated weirs

Weir type	Predictive equation η_{th}	Experimental validation	R^2
solid weirs	$\eta_{th} = -16.611 - 6.619 (S/h_1) + (57.6 - 0.131 (S/h_1)) \ln(Fr_1)$	$\eta_{exp} = 1.000 \eta_{th}$	0.9999
square weirs	$\eta_{th} = -14.067 - 0.095 TP + 0.189 (S/h_1) + (50.4 + 0.154 TP - 1.795 (S/h_1)) \ln(Fr_1)$	$\eta_{exp} = 0.9996 \eta_{th}$	0.9998

Table 5. Physical interpretation of the coefficients of the empirical relation for energy efficiency (η)

Weir type	Influence of TP	Influence of S/h_1	R^2	Physical interpretation
square weirs	-0.095	+0.189	0,9817	Very strong energy dissipation, high hydraulic efficiency, and stable flow.
solid weirs (réf.)	—	-6.619 (strong negative effect of the weir elevation)	0,9687	Dissipation is ensured mainly by the main roller, with stable but lower efficiency.

Table 6. Comparative synthesis of the hydraulic performance of the solid weir and the square perforated weir

Weir type	Y (dissipation)	L_j/h_1	L_r/h_1	η	Stability	Overall ranking
Square perforated weir	High	Medium	Short	Very high	Very stable	1
Solid weir	Low	Long	Long	Low	Very stable	2

The experimental validation of these models is illustrated in Figure 12, which shows an almost perfect correlation between experimental and theoretical values, with a high coefficient of determination ($R^2 = 0.9756$), confirming the reliability of the proposed relationships.

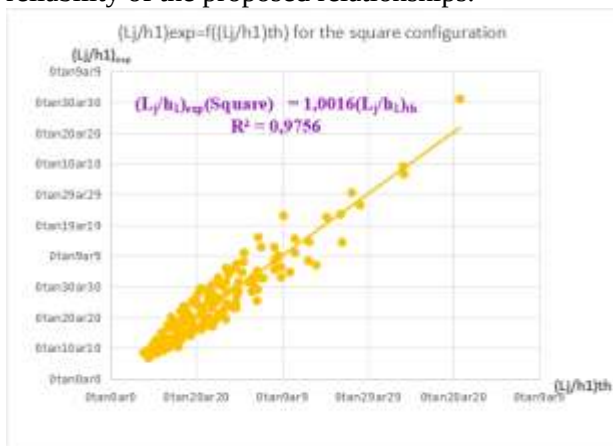


Figure 6. Correlation between $(L_r/h_1)_{exp}$ and $(L_r/h_1)_{th}$ for the square configuration

3.3 Effect on L_r/h_1

The variations of the relative roller length L_r/h_1 as a function of the upstream Froude number Fr_1 are presented for both the solid weir and the square perforated weir.

The results show that, for the solid weir, the roller length increases with Fr_1 , indicating significant development of the recirculation zone. In contrast, in the case of the square perforated weir, a noticeable reduction in L_r/h_1 is observed, as illustrated in Figures 13 and 14.

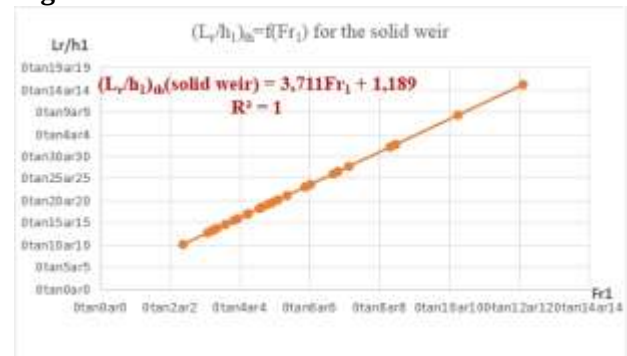


Figure 7. Variation of the relative hydraulic jump roller length (L_r/h_1) as a function of Fr_1 for the solid weir

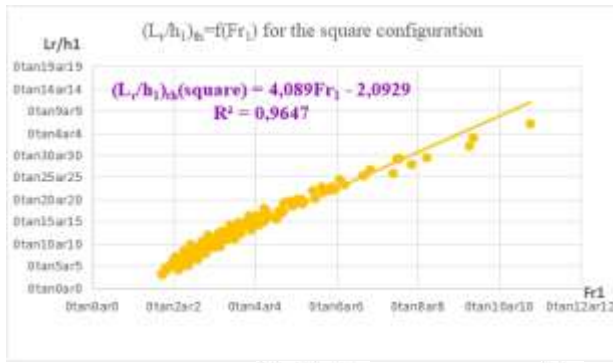


Figure 8. Variation of $(L_r/h_1)_{th}$ as a function of Fr_1 for the square configuration

This reduction reflects a decrease in the recirculation zone and a compaction of the hydraulic jump roller, resulting from faster and better distributed energy dissipation compared with the solid weir.

The empirical models proposed for predicting L_r/h_1 are presented in Table 2, which highlights excellent agreement between theoretical and experimental values. The physical interpretation of the coefficients in the empirical relation is given in Table 3, where it is observed that the perforation ratio TP contributes to reducing the roller length, while the Froude number remains the dominant parameter governing the development of the hydraulic jump.

The results obtained are also summarized in Table 2, which confirms good agreement between theoretical and experimental values.

The physical interpretation of the coefficients, presented in Table 3, highlights the role of the perforation ratio in enhancing energy dissipation.

The experimental validation of the models is illustrated in Figure 15, which shows an almost perfect correlation between experimental and theoretical values, with a high coefficient of determination ($R^2 > 0.994$), confirming the robustness of the proposed relationships.

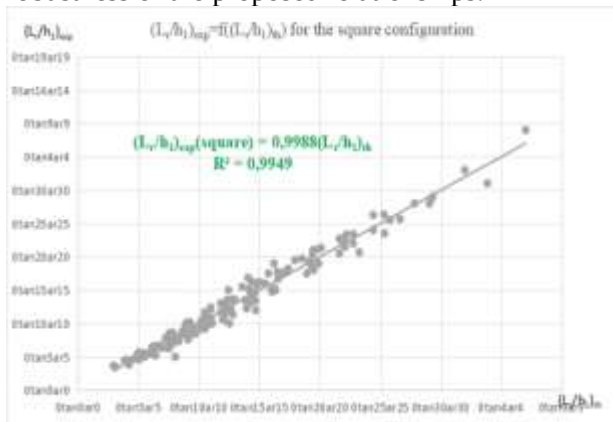


Figure 9. Correlation between $(L_r/h_1)_{exp}$ and $(L_r/h_1)_{th}$ for the square configuration

3.4 Energy Efficiency η

The evolution of the energy efficiency η as a function of the upstream Froude number Fr_1 is analyzed for both the solid weir and the square perforated weir.

The results show that, for the solid weir, the energy efficiency increases gradually with Fr_1 , but remains limited due to energy dissipation being mainly concentrated in the roller region of the hydraulic jump. In contrast, the square perforated weir exhibits a significant improvement in energy efficiency, particularly for intermediate porosity ratios (40–60%), as illustrated in Figures 16 and 17.

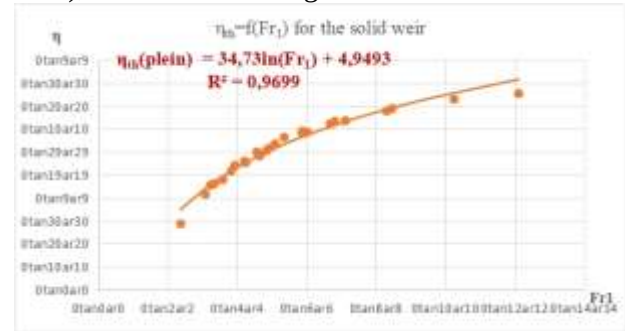


Figure 10. Variation of η_{th} as a function of Fr_1 for the solid weir

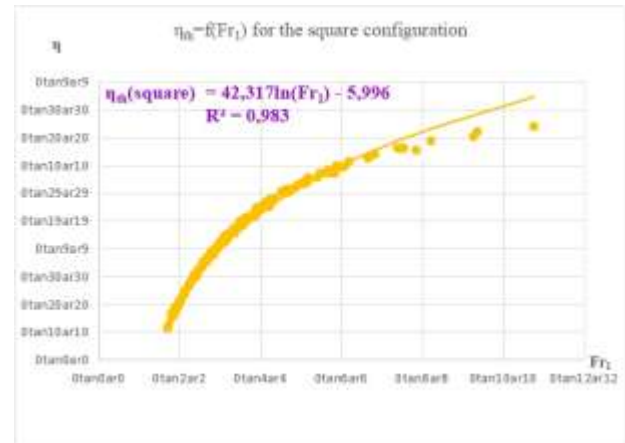


Figure 11. Variation of η_{th} as a function of Fr_1 for the square configuration

This improvement reflects a more efficient dissipation of the incident kinetic energy, associated with the partial passage of the flow through the perforations, the formation of secondary jets, and the intensification of turbulence.

Thus, the square perforation enables a better redistribution of energy and a more homogeneous dissipation compared with the solid weir.

The empirical models proposed for predicting the energy efficiency are presented in Table 4, where excellent agreement is observed between theoretical and experimental values.

The analysis of the coefficients of the empirical relation, presented in Table 5, highlights the significant influence of the perforation ratio TP on improving energy efficiency, confirming the role of perforation in enhancing dissipative mechanisms.

The experimental validation of the models is illustrated in Figure 18, which shows an almost perfect correlation between experimental and theoretical values, with a very high coefficient of determination ($R^2 > 0.998$), confirming the reliability of the proposed relationships.

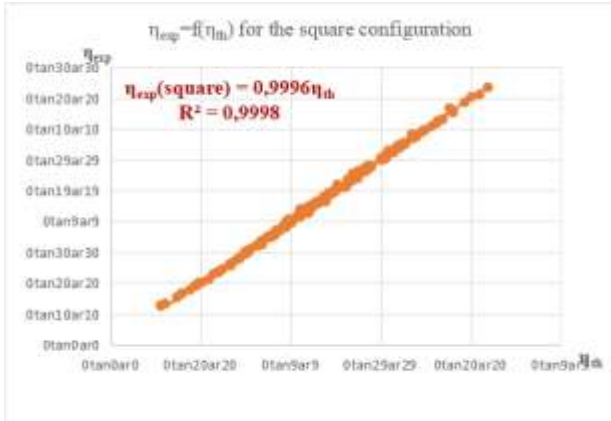


Figure 12: Correlation between η_{exp} and η_{th} for the square configuration

3.5 Overall Comparative Analysis

A global synthesis of the hydraulic performance is presented in order to compare the behavior of the solid (non-perforated) weir and the square perforated weir, taking into account all the studied parameters, namely the conjugate depth ratio Y , the relative hydraulic jump length L_j/h_1 , the roller length L_r/h_1 , and the energy efficiency η .

The results show that the square perforated weir leads to a significant reduction in the ratio Y , as well as in the characteristic lengths L_j/h_1 and L_r/h_1 , indicating an overall compaction of the hydraulic jump. In parallel, a noticeable improvement in energy efficiency η is observed, reflecting a more effective and better distributed energy dissipation.

In comparison, the solid weir exhibits a more classical behavior, characterized by longer hydraulic jump and roller lengths, as well as a lower energy efficiency, with dissipation mainly concentrated in the main recirculation zone.

This overall analysis highlights that the square perforation acts as a complementary dissipative mechanism, promoting energy redistribution and intensifying turbulent phenomena.

The performance synthesis is presented in Table 6, which clearly demonstrates the superiority of the square perforated weir over the solid weir. According to this table, the square perforated weir is characterized by high energy dissipation, reduced hydraulic jump lengths, and excellent hydraulic stability, making it the most efficient configuration for controlling high-energy flows.

In contrast, the solid weir, although ensuring good flow stability, exhibits lower energy dissipation efficiency, resulting in a more extended and less compact hydraulic jump.

Thus, the square perforated weir appears as an optimized solution that simultaneously enhances energy dissipation and the compactness of hydraulic structures.

4. Comparison with Previous Studies

4.1 Comparison with Bélanger's Model

Bélanger's relation (1828) is the classical theoretical reference for free hydraulic jumps. However, it was developed for uncontrolled jumps without additional dissipation devices.

In the present study, deviations from Bélanger's relation were observed even for the solid weir, which justified the introduction of an empirical correction coefficient K .

The deviation becomes more pronounced with the square perforated weir because perforation fundamentally modifies the flow structure by promoting partial flow passage, secondary jet formation, and increased turbulence.

Consequently, the conjugate depth ratio Y becomes lower than that predicted by Bélanger's relation, indicating enhanced energy dissipation.

4.2 Comparison with Rajaratnam's Studies

Rajaratnam (1967) demonstrated that hydraulic jump characteristics strongly depend on the Froude number and turbulence structure.

The present results confirm these general trends for both weir configurations.

However, the square perforated weir significantly reduces the characteristic lengths L_j/h_1 and L_r/h_1 , indicating faster dissipation than that observed for the solid weir.

This difference demonstrates that perforation acts as an additional dissipative mechanism not considered in Rajaratnam's classical formulations.

4.3 Comparison with Previous Experimental Studies

The obtained results are also consistent with previous studies on controlled hydraulic jumps, particularly those conducted by Forster and Skrinde (1950), Achour (2001, 2007), and Debabeche (2006, 2017), who showed that introducing a weir substantially modifies hydraulic jump structure and improves energy dissipation.

The main contribution of the present work lies in highlighting the specific role of square perforation. Unlike broader studies investigating massive weirs or several geometries simultaneously, this analysis demonstrates that the square configuration offers a particularly effective compromise between energy dissipation, jump compactness, and hydraulic stability.

5. Conclusion

This study provided a detailed analysis of the influence of square perforation on hydraulic jump behavior through direct comparison with a solid weir.

The results demonstrate that the square perforated weir significantly improves hydraulic performance by reducing the conjugate depth ratio Y , the relative jump length L_j/h_1 , and the roller length L_r/h_1 . This hydraulic jump compaction reflects faster and better distributed energy dissipation.

Furthermore, analysis of the energy efficiency η revealed a substantial increase in dissipation efficiency in the presence of perforation, particularly for intermediate perforation ratios.

The developed empirical models exhibit high coefficients of determination, confirming their reliability and suitability for predicting hydraulic behavior.

By comparison, the solid weir, although hydraulically stable, shows lower energy dissipation efficiency and less compact hydraulic jumps.

Therefore, the square perforated weir appears to be an optimized solution for controlling high-energy flows by providing an effective compromise between energy dissipation, hydraulic stability, and structural compactness.

6. Perspectives

The results obtained in this study open several interesting research perspectives for further investigation of hydraulic jumps controlled by perforated weirs.

First, it would be relevant to extend this work to three-dimensional configurations in order to more accurately analyze the turbulent flow structure and the interactions between jets issuing from the perforations.

Furthermore, the influence of unsteady flow conditions as well as the presence of sediments could be investigated to evaluate the behavior of perforated weirs under more realistic conditions encountered in river hydraulics.

Another important perspective concerns the geometric optimization of the perforations,

particularly in terms of size, distribution, and porosity ratio, with the aim of further improving energy efficiency and hydraulic stability.

Finally, the integration of advanced numerical models, such as CFD simulations, would complement the experimental approach and provide a deeper understanding of the physical mechanisms responsible for the observed energy dissipation.

Nomenclature

Hydraulic and Geometric Parameters

- h_1 : Upstream water depth [m or cm]
- h_2 : Downstream conjugate depth [m or cm]
- S : Weir height [cm]
- S/h_1 : Relative weir height
- Y : Conjugate depth ratio
- L_j : Hydraulic jump length [m]
- L_j/h_1 : Relative jump length
- L_r : Roller length [m]
- L_r/h_1 : Relative roller length
- V_1 : Upstream mean velocity [m/s]
- V_2 : Downstream mean velocity [m/s]
- Q : Flow rate $\left[\frac{L^3}{s}\right]$
- T_p : Perforation ratio [%]
- F_{r1} : Upstream Froude number
- K : Empirical correction coefficient
- η : Energy efficiency [%]
- exp : Experimental value
- th : Theoretical value
- R^2 : Coefficient of determination
- SPSS: Statistical Package for the Social Sciences
- CFD: Computational Fluid Dynamics

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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