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Three-Dimensional porous media as a novel approach for stilling basin optimization: An experimental comparison with solid elements

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ABSTRACT

Objective: The purpose of this research is to experimentally investigate and compare the effects of solid and porous baffle blocks and roughness elements on hydraulic jump characteristics downstream of an ogee spillway, aiming to optimize stilling basin design for reduced length and enhanced energy dissipation.

Method: Experiments were conducted in a 10 m horizontal flume with an ogee spillway, testing various arrangements of solid (impermeable) and porous (permeable, Φ=0.25) cubic blocks (2.1 cm) as baffle blocks and bed roughness. Five discharges (5–17 L/s) corresponding to Froude numbers (Fr_1=4.58–5.75) were used, measuring sequent depths (y_1, y_2) and jump length (L_j) with a point gauge and visual grid. A total of 157 runs compared configurations against a smooth-bed control. Baffle Block Configurations: Single-Row (full-width bar, double-block with central gap, triple-block with two gaps); Double-Row (two rows spaced 2.1 cm apart); Stepped Co-Flow (downstream row twice the height of upstream); Stepped Opposing-Flow (upstream row twice the height of downstream). Bed Roughness Configurations: Row-wise (transverse rows spaced 2.1 cm or 6 cm); Staggered (checkerboard/offset pattern); Zigzag (dense interlocking pattern); Combined Roughness (alternating rows of solid and porous cubes).

Results: All configurations reduced sequent depth ratio (y_2/y_1) and jump length (L_j) compared to the classical jump. Porous elements outperformed solid ones: porous baffle blocks achieved 16–43% L_j reduction (vs. 12–29% for solid), and porous roughness 7–47% (vs. 5–35% for solid). Optimal setups included double-row porous baffles, zigzag porous roughness, and row-wise (6 cm spacing) porous/combined roughness. Porous media enhanced energy dissipation via internal shear, jet interactions, and turbulence, leading to up to 36% shorter relative jump length (L_j/y_2) than USBR standards.

Conclusions: Porous appurtenances provide a superior, novel approach for stilling basin optimization, enabling more compact, cost-effective designs through volumetric energy dissipation mechanisms beyond form drag.

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Introduction

The longevity and structural integrity of major hydraulic structures such as dams, spillways, and barrages are critically dependent on the effective management and dissipation of the immense kinetic energy of downstream flows. Failure to control this energy can lead to severe engineering challenges, including catastrophic bed scour, tailwater degradation, and compromised structural stability. A stark real-world example is the Taunsa Barrage, where, soon after its 1958 operation, a cascade of problems emerged, including the uprooting of impact baffle blocks, damage to the basin floor, and significant bed retrogression. Despite numerous repair efforts and expert committees, these issues persisted, highlighting the profound limitations of traditional design approaches (Zulfiqar & Kaleem, 2015).

To mitigate such risks, the hydraulic jump serves as the primary energy dissipation mechanism. This phenomenon, characterized by the abrupt transition of a high-velocity supercritical flow to a low-velocity subcritical flow, is fundamental to protecting the channel bed from erosion (Bélanger, 1841). The performance and safety of a hydraulic structure are thus intrinsically linked to the design of its stilling basin, which is engineered to contain the highly turbulent jump and dissipate residual energy within a protected, often concrete-lined, area (Peterka, 1984). The complex nature of the hydraulic jump, with its wall jet-like velocity profiles and high turbulence intensities, has been the subject of extensive investigation, focusing on free surface fluctuations and internal bubbly flow structures across a wide range of Froude numbers (Chachereau & Chanson, 2011; Wang & Chanson, 2015; Murzyn & Chanson, 2009).

To enhance dissipation efficiency and forcibly shorten the required basin length, stilling basins are almost universally equipped with appurtenances. The engineering community has explored a vast array of solid, impermeable elements to optimize this process. These include standard baffle blocks (Habibzadeh et al., 2012), friction blocks (Chaudary & Sarwar, 2014), and various forms of terminal sills (Mansour et al., 2004; Alikhani et al., 2010). Research has pushed the boundaries of geometric innovation, examining splitter blocks (Verma & Goel, 2003), curved blocks (Eloubaidy et al., 1999), T-shaped and triangular blocks (Tiwari & Goel, 2016), and the effect of negative steps on the basin floor, which have been shown to increase energy dissipation by up to 11% (Sayyadi et al., 2022). Among these, Wedge-Shaped Baffle Blocks (WSBBs) have received considerable attention, with studies demonstrating their ability to reduce basin length by 15–25% by creating more extensive wake regions and promoting efficient lateral flow spreading compared to traditional impact blocks (Pillai et al., 1989; Goel, 2008). In parallel, the influence of bed roughness has been identified as a key factor, with studies developing semi-empirical methods to correlate jump characteristics with roughness parameters (Maleki & Fiorotto, 2021) and employing numerical models to show how roughness height and spacing affect jump length (Nikmehr & Aminpour, 2020).

Despite these advancements, conventional solid elements primarily rely on form drag for energy loss and are not without their own challenges. As observed at the Taunsa Barrage, vertical-faced blocks are susceptible to uprooting under intense, fluctuating hydrodynamic pressures. Furthermore, traditional impact blocks can suffer from flow reattachment on their sides, a phenomenon that diminishes their effective drag force and overall efficiency (Frizell & Svoboda, 2012). While modern numerical tools like FLOW-3D have proven invaluable for investigating and optimizing these traditional designs with high accuracy (Macián-Pérez et al., 2020b; Zaffar & Hassan, 2023b), the fundamental dissipation mechanism remains surface-based. A promising but less explored paradigm is the use of porous media for energy dissipation. Unlike their solid counterparts, porous elements introduce additional, highly effective energy dissipation mechanisms. As flow penetrates the porous structure, energy is dissipated not only by form drag but also through a volumetric process involving internal shear stresses, complex jet interactions, and intense turbulence generation within the interconnected pore network. This process can be theoretically described using Darcy's law for low-velocity flows, which relates flow rate to permeability and pressure gradient, and the Forchheimer equation for high-velocity, non-Darcy flows where inertial effects dominate: $\Delta P/L = (\mu/k)\, v + \rho\, \beta\, v^2$, where k is permeability, β is the Forchheimer coefficient, v is velocity, μ is viscosity, and ρ is density. These theories highlight how porous media enhance dissipation via quadratic inertial terms, suggesting higher efficiency in turbulent hydraulic jumps (e.g., Sajjadi et al., 2025; Tahmasbipour et al., 2024; Ahadiyan et al., 2024). Dimensionless parameters such as permeability (k/y_1^2) and tortuosity (path complexity) further justify their use by quantifying internal flow resistance (Salahi et al., 2024; Ahadiyan et al., 2024a). This suggests that porous elements could achieve a higher rate of energy dissipation within a more compact volume, leading to significant reductions in stilling basin length and associated construction costs.

Although recent numerical investigations have begun to explore the potential of porous baffles (Zaffar & Hassan, 2023a), a critical research gap remains. There is a lack of systematic, direct experimental comparison of 3D porous versus solid elements of identical geometry, particularly when applied as both baffle blocks and bed roughness elements downstream of an ogee spillway. Therefore, the present study aims to provide a comprehensive experimental investigation to address this gap. Through detailed physical modeling, this research seeks to: (1) systematically quantify the reduction in sequent depth and jump length for various arrangements of solid and porous elements compared to the classical jump; (2) identify the most effective configuration in terms of energy dissipation and basin compactness by directly comparing solid versus porous elements and different spatial layouts; and (3) develop practical insights for the optimal design of stilling basins using porous media, contributing to more efficient, economical, and sustainable hydraulic structures.

Recent studies have further advanced understanding of energy dissipation in complex flows, including numerical analyses of roughness in expansions (Sajjadi et al., 2025), stabilization of T-jumps with jets and corrugated beds (Tahmasbipour et al., 2024), CFD modeling of lateral intakes (Ahadiyan et al., 2024), effects of particle and vegetation roughness on drag (Salahi et al., 2024), submerged jets in wavy beds (Ahadiyan et al., 2024a), turbulence in dissipators with cross beams (Hajialigol et al., 2024; Hajialigol et al., 2021), hydraulic jumps in expanding channels with jets (Sharoonizadeh et al., 2022), two-phase flows in vegetated jumps (Adeli et al., 2021), and effects of floating or anchored dissipators (Ahadian & Varshosaz, 2018; Khedri Mirghaed et al., 2018). These works provide a foundation for our comparison of porous media.

Methods

Dimensional Analysis

The characteristics of a hydraulic jump formed downstream of an ogee spillway and forced by bed appurtenances depend on fluid properties, flow characteristics, and geometric parameters. The primary dependent variables are the sequent depth (y_2) and the jump length (L_j). The independent variables are:

- Fluid properties: density (ρ), dynamic viscosity (μ), and gravitational acceleration (g).
- Flow characteristics: initial jump depth (y_1) and velocity (V_1).

- Geometric properties: spillway width (B), appurtenance height (h), and appurtenance porosity (Φ).

The functional relationship can be expressed as:

$$f(y_2, L_j, y_1, V_1, B, h, \Phi, \rho, \mu, g) = 0 \quad (1)$$

Using the Buckingham Π theorem with ρ, V_1, and y_1 as repeating variables, the following dimensionless groups are derived:

$$f(y_2/y_1, L_j/y_1, B/y_1, h/y_1, \Phi, \rho V_1 y_1/\mu, V_1/\sqrt{(g y_1)}) = 0 \quad (2)$$

The dimensionless parameters are the sequent depth ratio (y_2/y_1), relative jump length (L_j/y_1), geometric ratios (B/y_1, h/y_1), porosity (Φ), Reynolds number ($Re = \rho V_1 y_1/\mu$), and Froude number ($Fr_1 = V_1/\sqrt{(g y_1)}$). For the highly turbulent flow in a hydraulic jump, viscous effects are negligible compared to inertial and gravitational forces, so the Reynolds number is typically omitted from the analysis. The physical dimensions of the flume width (B) and appurtenance height (h) were kept constant throughout the experiments, while the dimensionless ratios B/y_1 and h/y_1 naturally varied with the upstream Froude number. The geometric ratios were kept constant. Thus, the relationship simplifies to:

$$y_2/y_1, L_j/y_1 = F(Fr_1, h/y_1, \Phi) \quad (3)$$

In porous media contexts, additional parameters like permeability (k) and the Forchheimer coefficient (β) could refine this analysis, as they quantify internal resistance and non-linear effects (Sajjadi et al., 2025). However, due to experimental constraints, these were not varied independently.

Experimental Setup

The experiments were conducted in a 10 m long, 0.3 m wide, and 0.45 m high horizontal flume with glass walls and a Plexiglas bed at the Hydraulic Laboratory of Khatam Alanbia University of Technology, Behbahan. Water was supplied by a 10-kW pump, and the discharge was measured using a digital flow meter with an accuracy of ±0.1 L/s.

An ogee spillway, designed according to USBR standards, was installed in the flume to generate the supercritical flow. The spillway had a height (P) of 29.5 cm and a crest length of 30 cm. A movable sluice gate at the downstream end of the flume was used to adjust the tailwater depth, ensuring the hydraulic jump formed at the toe of the spillway for all test conditions. The experimental setup is illustrated in Fig. 1.

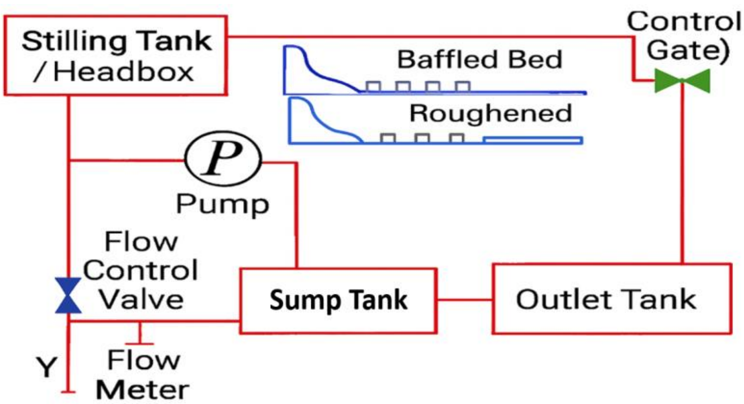

Figure 1. Schematic of the experimental setup showing the ogee spillway and the stilling basin with appurtenances

Due to laboratory limitations, advanced measurements such as velocity profiles via PIV or ADV were not feasible. Instead, we relied on visual observations and point-gauge measurements, which introduce some subjectivity but were calibrated for consistency (estimated uncertainty: ±0.1 mm for depths, ±5 cm for L_j). Future studies should incorporate these tools for quantitative flow structure analysis.

Model Appurtenances

The experimental program was designed to investigate the effects of two distinct types of stilling basin appurtenances: baffle blocks and bed roughness elements. A key innovation of this study was the systematic comparison of conventional solid (impermeable) elements with novel three-dimensional porous (permeable) elements.

The solid elements were fabricated from wood, with all components treated with oil and coated with waterproof paint to prevent water absorption. The porous elements were custom-fabricated from interlocking, three-dimensional plastic lattice cubes. Both solid and porous elemental cubes had identical dimensions of 2.1 cm × 2.1 cm × 2.1 cm. The porous cubes had a uniform volumetric porosity of $\Phi = 0.25$.

This porosity value was selected based on material availability and preliminary tests showing effective penetration without structural failure. A range of porosities was not tested due to resource constraints, but we recommend varying Φ (e.g., 0.1–0.5) in future work to establish its functional relationship with performance (e.g., via Forchheimer parameters).

A critical methodological distinction was made in the installation of the two types of appurtenances (Fig. 2). For the baffle block configurations (Fig. 2a), elements were placed directly onto the flume bed, acting as protruding obstacles. For the bed roughness configurations (Fig. 2b), the flume bed was recessed by 2.1 cm, allowing the roughness cubes to be installed flush with the primary stilling basin floor.

To systematically investigate the effect of spatial arrangement, these appurtenances were configured in various layouts, which are described below and illustrated in Fig. 3:

- **Baffle Block Configurations:**
  - Single-Row: A single transverse row of elements. Configurations included a full-width bar (one continuous block), a double-block arrangement (two blocks with a central gap), and a triple-block arrangement (three blocks with two gaps).
  - Double-Row: Two transverse rows of elements spaced 2.1 cm apart.
  - Stepped Co-Flow: A double-row configuration where the downstream row was twice the height of the upstream row (Fig. 3c).
  - Stepped Opposing-Flow: A double-row configuration where the upstream row was twice the height of the downstream row (Fig. 3d).
- **Bed Roughness Configurations:**
  - Row-wise: Elements arranged in transverse rows. The longitudinal spacing between rows was tested at both 2.1 cm and 6 cm.
  - Staggered: Elements arranged in a checkerboard or offset pattern.
  - Zigzag: Elements arranged in a dense, interlocking zigzag pattern (Fig. 3f).
  - Combined Roughness: A third material category was tested for bed roughness, consisting of alternating transverse rows of solid and porous cubes to evaluate intermediate performance (Fig. 3g, 3j).

Fig. 3 provides photographic examples of several key experimental setups.

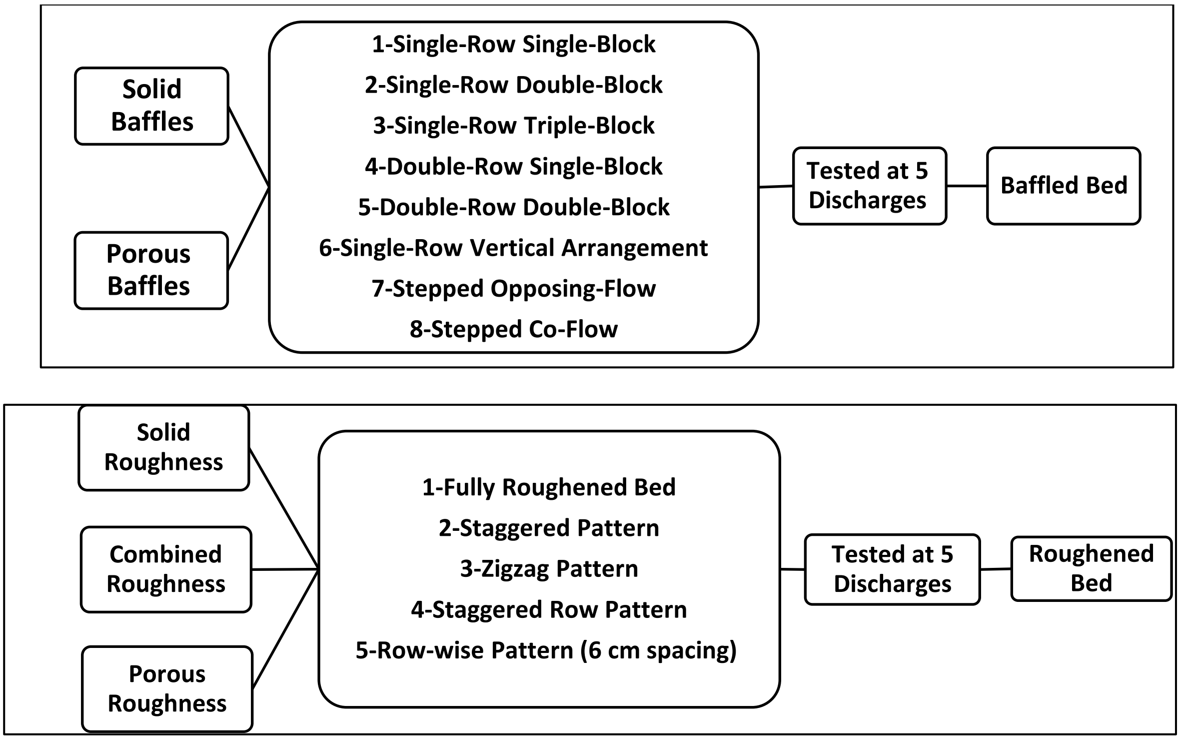

Figure 2. Examples of tested appurtenance configurations: (a) Baffled Bed, (b) Roughened Bed

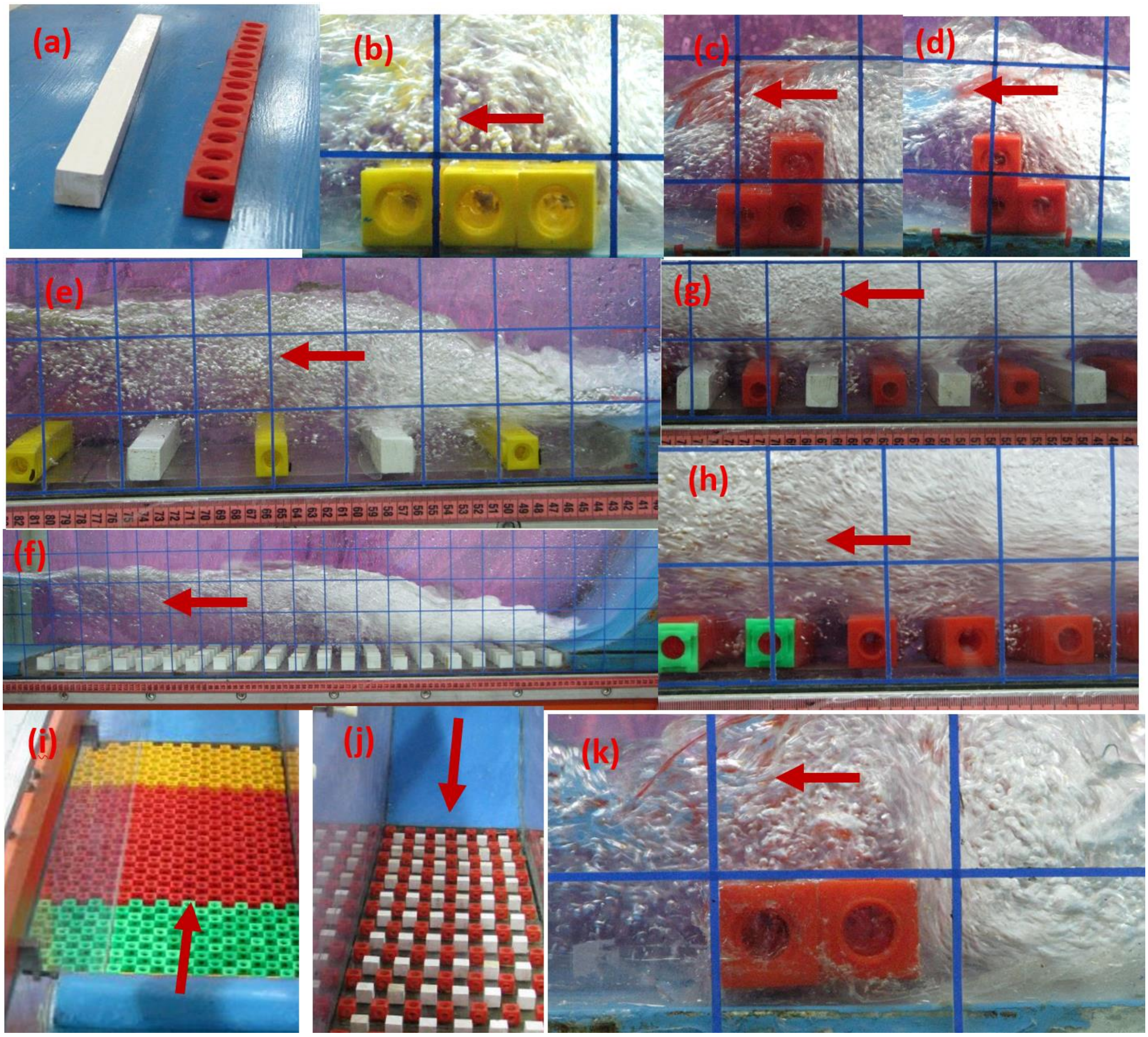

Figure 3. Photographic examples of selected experimental arrangements in the flume. (a) Solid and porous baffle blocks in a one-row configuration. (b) Porous baffle in Single-Row Triple-Block. (c) Porous baffle Stepped Co-Flow pattern. (d) Porous baffle in Stepped Opposing-Flow pattern. (e) Combined Roughness in Row-wise Pattern (6 cm spacing). (f) Solid Roughness in Zigzag Pattern. (g) Combined Roughness in Staggered Row Pattern. (h) Porous Roughness in Staggered Row Pattern. (i) Porous Roughness in Staggered Pattern. (j) Combined Roughness in Zigzag Pattern. (k) Porous baffle blocks in a Single-Row Double-Block

Experimental Procedure and Measurements

A total of 157 experimental runs were performed. This included a control case (smooth bed) and various configurations with baffle blocks (80 runs) and roughness elements (65 runs). Five different discharges (Q = 5, 8, 11, 14, and 17 L/s) were tested, corresponding to a Froude number range of 4.58 to 5.75.

For each run, the discharge was set, and the downstream gate was adjusted to stabilize the hydraulic jump at the spillway toe. After the flow reached a steady state, the following parameters were measured:

- **Sequent depths (y_1 and y_2):** Measured using a point gauge with an accuracy of ±0.1 mm.

- **Jump length (L_j):** Measured visually using a grid on the flume wall. The end of the jump was defined as the point where the high-velocity forward flow near the bed ceased and the water surface became approximately horizontal.

Measurements were repeated three times per run to estimate uncertainty (standard deviation: ±0.2 mm for depths, ±3-5 cm for L_j, depending on flow rate). Visual methods, while subjective, were necessary due to equipment limitations.

Results

Control Case and Validation

The experiments on a smooth, flatbed served as the control case. The measured sequent depth ratio (y_2/y_1) for the classical jump showed excellent agreement with the theoretical Belanger equation, validating the experimental setup and procedures. The baseline data for the control case is presented in Table 1.

Table 1: Hydraulic parameters for the control case (smooth bed)

Discharge (L/s)	Jump Length L_j (cm)	Head on Crest H_e (cm)	Froude Number Fr_1
5	49	4.5	5.75
8	60	5.5	5.14
11	72	6.7	4.85
14	76	7.6	4.73
17	90	8.7	4.58

Effect on Sequent Depth Ratio (y_2/y_1)

The introduction of appurtenances in the stilling basin is a proven method to increase energy dissipation, which manifests as a reduction in the sequent depth ratio (y_2/y_1) compared to a classical jump. This trend was consistently observed across all experimental configurations in this study. The performance of baffle blocks and bed roughness is analyzed separately below, with emphasis on the most effective options.

Baffle Blocks: The performance of various arrangements of solid and porous baffle blocks was evaluated, with the results depicted in Fig. 4. For both solid (Fig. 4a) and porous (Fig. 4b) blocks, the sequent depth ratio increases with discharge, yet remains significantly below the theoretical Belanger curve for all cases. A key finding is the consistent superiority of porous blocks over their solid counterparts. As shown by comparing Fig. 4a and 4b, porous blocks achieve a greater reduction in y_2/y_1 across all tested discharges. This indicates that the flow passing through the pores introduces additional momentum exchange and turbulence, forcing the jump to stabilize at a lower downstream depth. Within the tested arrangements, the stepped opposing-flow and single-row vertical configurations were particularly effective in reducing the sequent depth ratio. This enhanced performance is likely attributable to their greater effective height, which forces a more significant interaction with the high-velocity incoming jet. These reductions (up to 20% for porous blocks) align with Habibzadeh et al. (2012), who reported 10-15% reductions for solid baffles, but our porous elements exceed this due to internal dissipation.

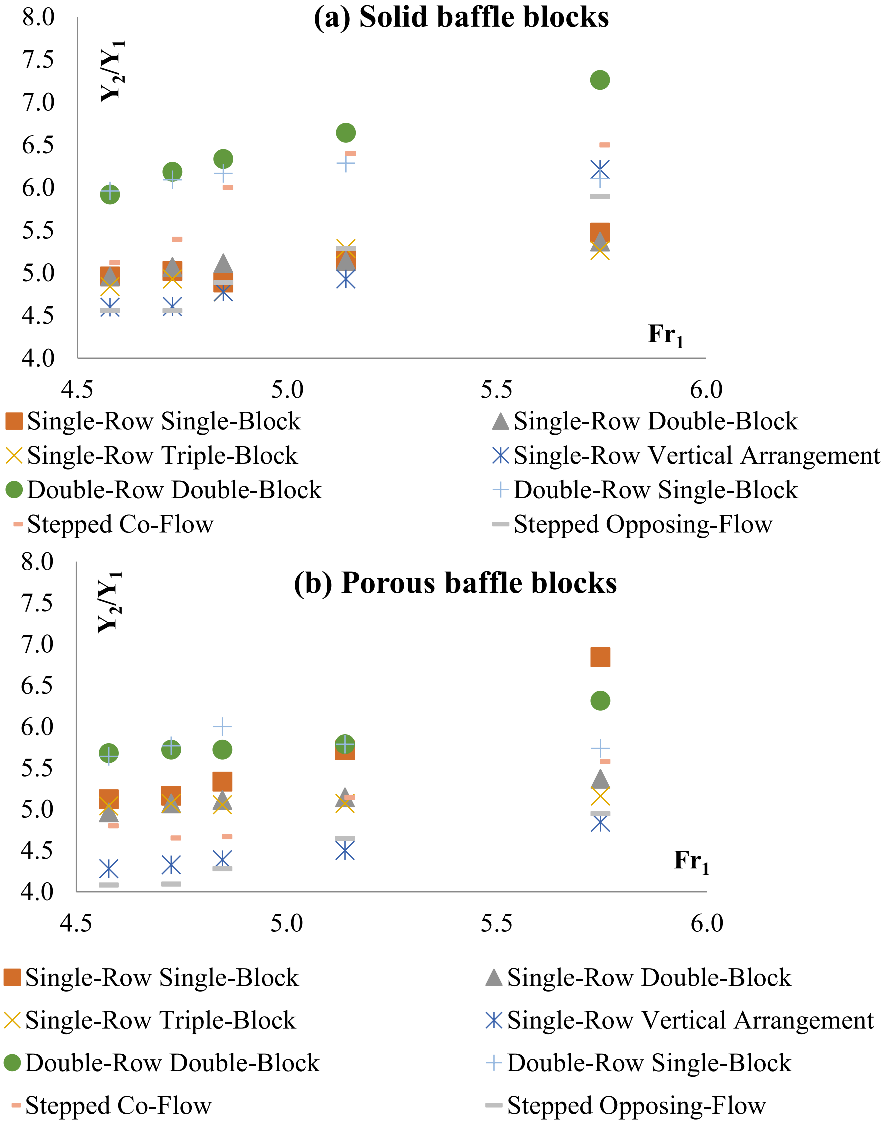

Figure 4. Sequent depth ratio (y_2/y_1) versus discharge (Q) for different arrangements of (a) solid baffle blocks and (b) porous baffle blocks

The effect of bed roughness was investigated using solid, combined (a mix of solid and porous), and fully porous elements. The results, presented in Fig. 5, further underscore the benefits of porosity. As shown across Fig. 5a, 5b, and 5c, all roughness configurations reduce the sequent depth ratio relative to the classical jump. Since the height of the roughness elements (h) was kept constant in all these tests, the observed performance differences are directly attributable to the material (porosity) and the spatial arrangement. The most effective layouts were consistently the zigzag and the row-wise pattern with 6 cm spacing. A comparative analysis of the material types reveals a clear performance hierarchy: porous roughness was more effective than combined roughness, which in turn was more effective than solid roughness. This trend holds true across all arrangements and Froude numbers. The data strongly suggest that increasing the porosity of the bed elements enhances energy dissipation, leading to a more compact and efficient hydraulic jump. This confirms that the internal shear and turbulent interactions within the porous media are primary contributors to the overall performance enhancement. Compared to vegetated roughness in Adeli et al. (2021), which reduced y_2/y_1 by 5-10%, our porous zigzag achieved up to 15%, highlighting volumetric advantages.

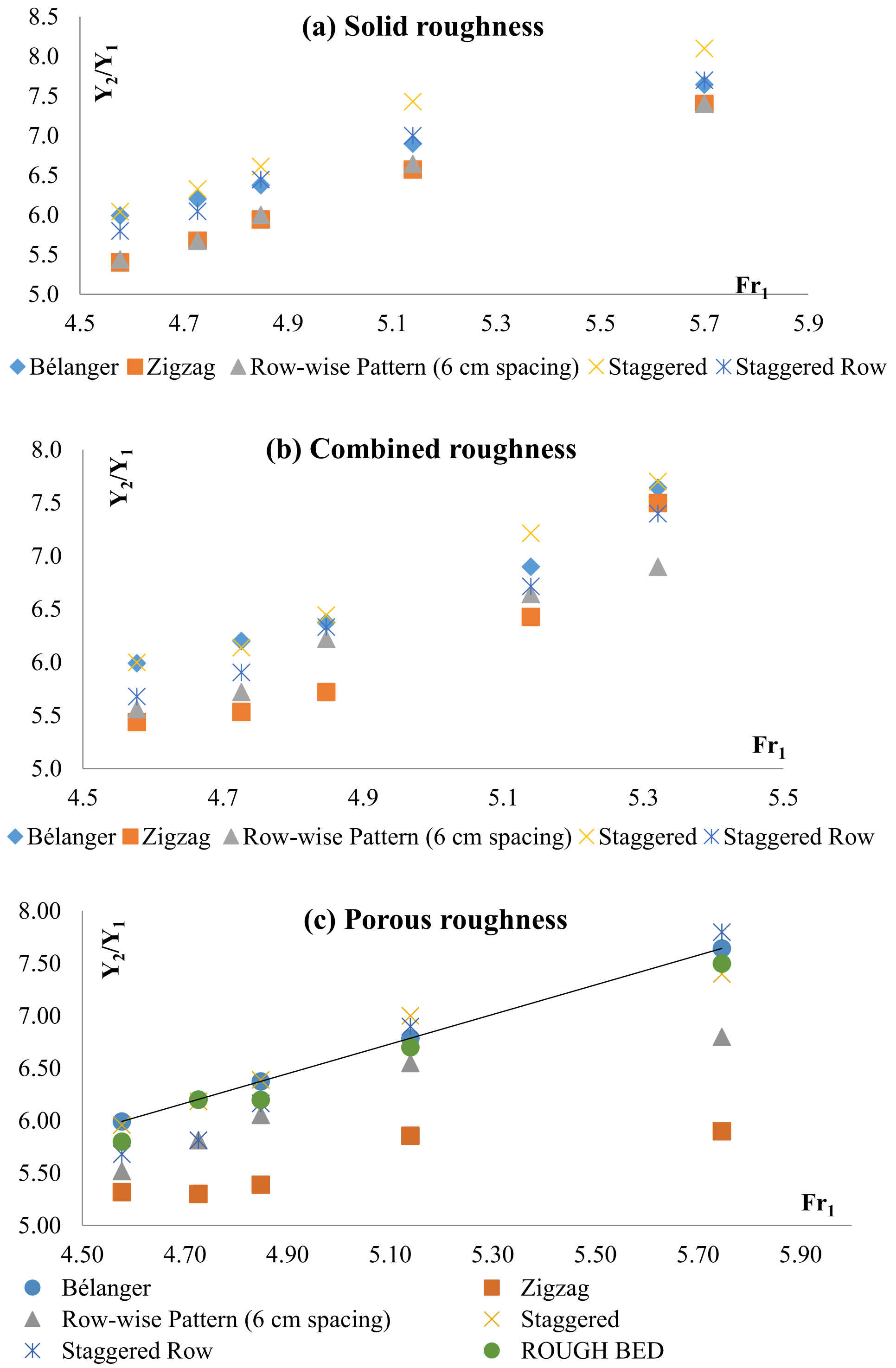

Figure 5. Sequent depth ratio (y_2/y_1) versus Froude number (Fr_1) for different arrangements of (a) solid roughness, (b) combined roughness, and (c) porous roughness

Effect on Hydraulic Jump Length (L_j)

A primary objective of this study was to quantify the reduction in hydraulic jump length (L_j), a critical parameter for the economic design of stilling basins. The percentage reduction in jump length relative to the classical jump (smooth bed) was calculated for each configuration using the following equation:

$$\text{Length Reduction (\%)} = [(L_j\text{classical} - L_j\text{forced}) / L_j\text{classical}] \times 100 \quad (4)$$

Where $L_j$classical is the jump length on a smooth bed and $L_j$forced is the length with appurtenances.

Baffle Blocks: As illustrated in Fig. 6, all baffle block arrangements successfully shortened the hydraulic jump. A general trend observed is that the percentage reduction in length diminishes as the discharge increases. This suggests that at higher flow rates, the incoming jet has sufficient momentum to partially override the obstacles, extending the jump length. Among the solid block configurations (Fig. 6a), the double-row arrangements demonstrated the most consistent and effective performance across all discharges, achieving a length reduction of up to 29%. The performance of porous blocks (Fig. 6b) was notably superior. The same double-row configurations, when porous, achieved a significantly higher length reduction, reaching up to 43%. This highlights the substantial impact of porosity in creating a more compact jump. These results surpass the 20-30% reductions reported for cross-beam baffles in Hajialigol et al. (2021), likely due to porous media's enhanced turbulence generation.

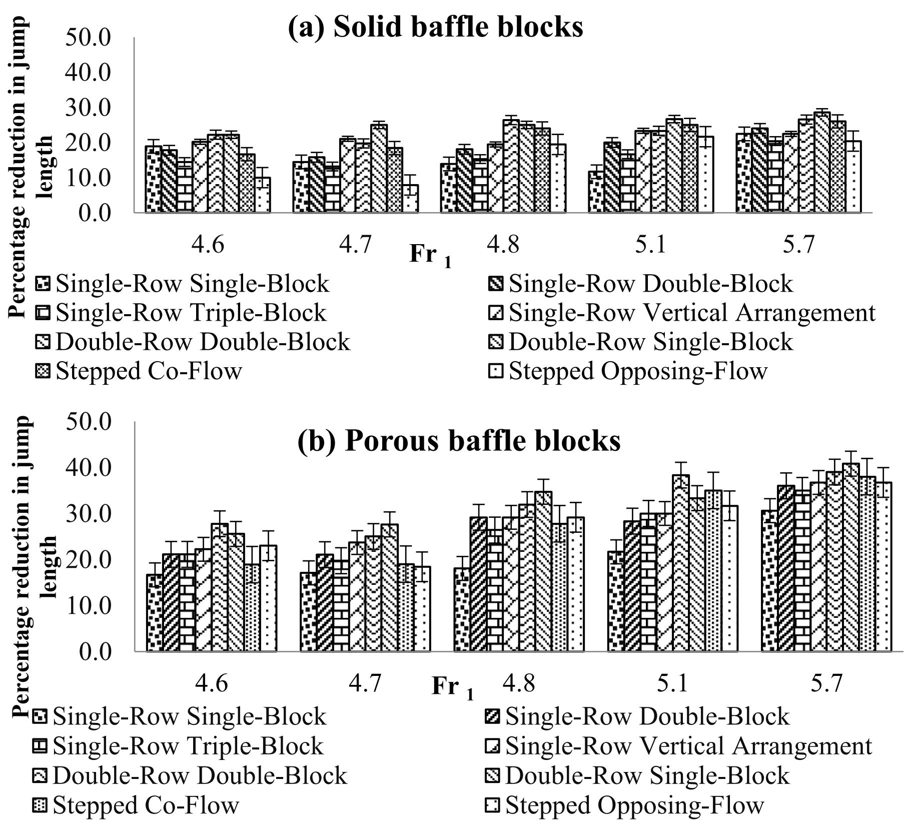

Figure 6. Percentage reduction in jump length vs. discharge for different arrangements of (a) solid baffle blocks and (b) porous baffle blocks

Bed Roughness: The effect of bed roughness on jump length followed a similar pattern, with all configurations yielding a shorter jump than the classical case (Fig. 7). For all material types (solid, combined, and porous), the zigzag arrangement consistently provided the highest length reduction, followed closely by the row-wise pattern with 6 cm spacing. The impact of material porosity was again evident. Solid roughness (Fig. 7a) reduced the jump length by 5–35%. The combined roughness (Fig. 7b), which introduced some porosity, improved this range to 13–45%. The fully porous roughness (Fig. 7c) delivered the best performance, with a length reduction of 7–47%. The superior performance of the porous zigzag layout confirms that the combination of an optimized spatial arrangement and material porosity leads to the most compact stilling basin design. This exceeds the 25-35% reductions in numerical roughness studies by Sajjadi et al. (2025), emphasizing experimental validation of porous effects.

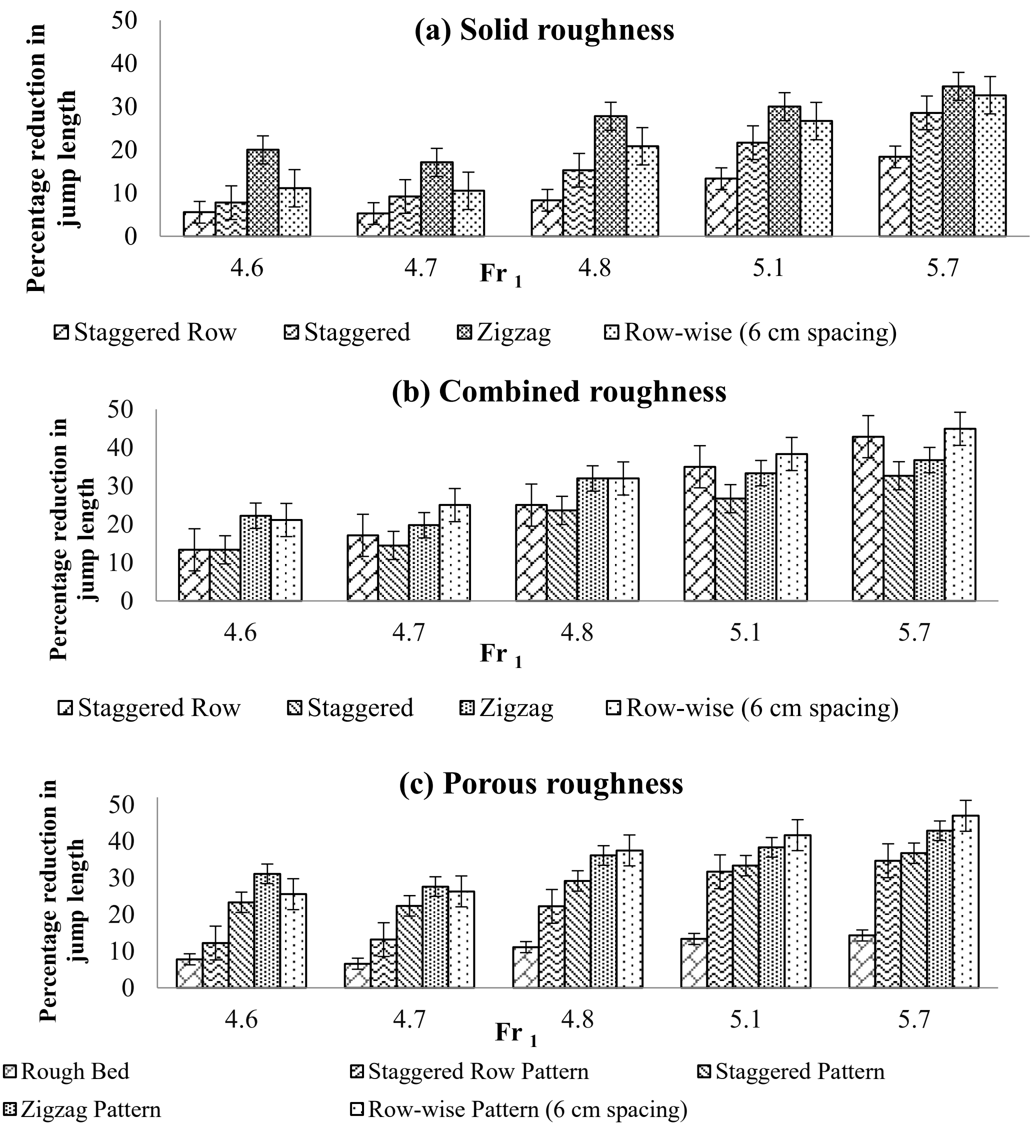

Figure 7. Percentage reduction in jump length vs. discharge for different arrangements of (a) solid roughness, (b) combined roughness, and (c) porous roughness

Analysis of Energy Dissipation

To understand the mechanisms behind the observed reductions in jump length and sequent depth, the energy dissipation was analyzed. The relative energy dissipation of the jump itself ($\Delta Hj/E_1$), was calculated, where ΔHj is the head loss within the jump, determined by $(y_2 - y_1)^2 / (4y_1y_2)$. A lower relative energy dissipation by the jump itself implies that a larger portion of the total energy was dissipated by the appurtenances before the jump could fully form. Note that this formula is an approximation derived for classical jumps and may overestimate dissipation in forced jumps with complex geometries; future CFD could refine this (Sajjadi et al., 2025). To provide a practical tool, we developed an empirical power-law relationship for relative energy loss, similar to those in Sajjadi et al. (2025) for roughness in expansions, based on regression of our experimental data for optimal porous configurations (e.g., Row-wise patterns (6 cm spacing) porous and combined roughness, and zigzag porous bed roughness):

$$\Delta Hj/E_1 = 1.25 * Fr1 -0.35 \quad (R^2 = 0.9) \tag{5}$$

This preliminary equation, valid for $4.5 < Fr_1 < 5.8$, estimates dissipation ranging from approximately 57% to 62%, which is comparable to Peterka's (1984) classical approximations (60-70%) but reflects the enhanced overall efficiency of porous media in forced jumps when considering the total system dissipation. Fig. 8 presents the relative energy dissipation for the baffle block configurations. For the most effective layouts in shortening the jump (e.g., double-row arrangements), the energy dissipated by the jump itself was higher compared to less effective layouts. This might seem counterintuitive, but it indicates that these configurations force a more efficient, albeit shorter, jump. Conversely, taller obstacles (like the stepped opposing flow) dissipated more energy directly through drag and obstruction, leaving less energy for the jump to dissipate, but simultaneously causing more surface instability and a less well-defined jump structure, which did not necessarily translate to the shortest overall jump length. The porous blocks generally resulted in a more efficient overall system, where both the blocks and the resulting forced jump contributed effectively to the total energy loss.

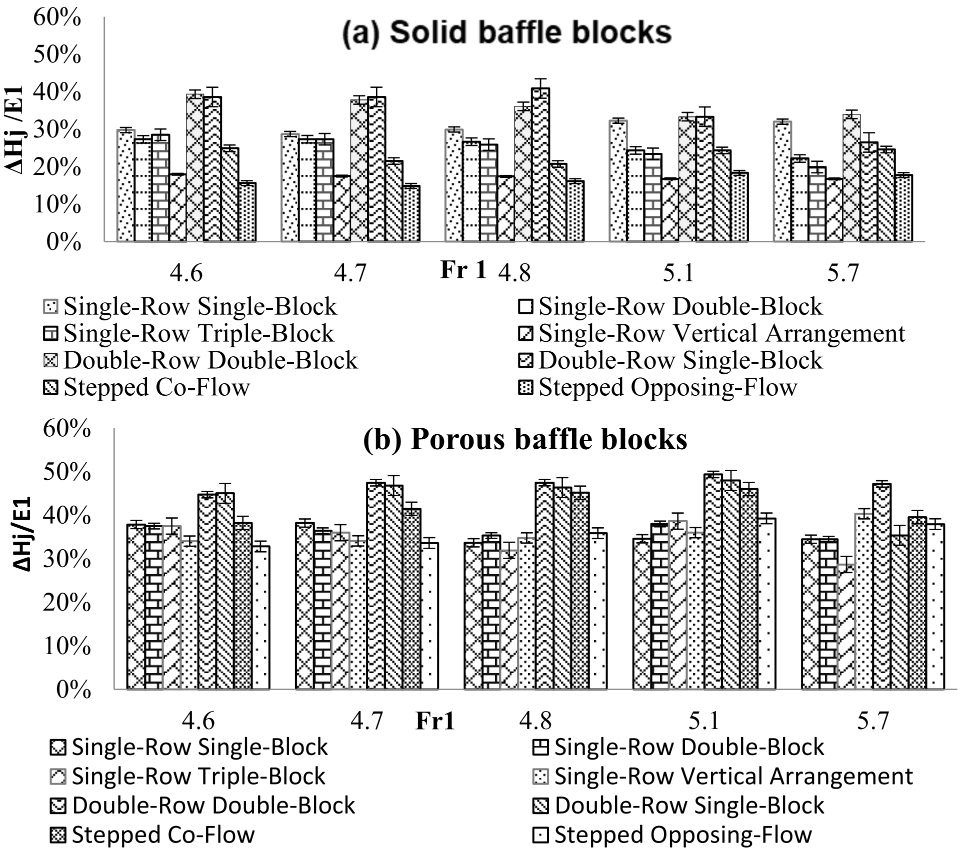

Figure 8. Relative energy dissipation of the hydraulic jump vs. Fr_1 for different arrangements of (a) solid baffle blocks and (b) porous baffle blocks

A similar trend was observed for the bed roughness elements (Fig. 9). The most effective configurations for shortening the jump, namely the zigzag and row-wise (6 cm spacing) patterns, also allowed the jump itself to remain a relatively efficient dissipator. Crucially, the comparison across material types shows that the total energy loss of the system (appurtenances + jump) is highest for porous elements. The flow penetrating the porous media creates significant internal shear and turbulent eddies, which is a highly effective dissipation mechanism. This process extracts a substantial amount of energy from the main flow before it enters the main roller of the jump. As a result, the incoming flow has lower kinetic energy, requiring a shorter distance and a lower sequent depth to transition to subcritical flow. This confirms that the primary advantage of porous media is not just added drag but the introduction of a new, highly efficient volumetric energy dissipation mechanism.

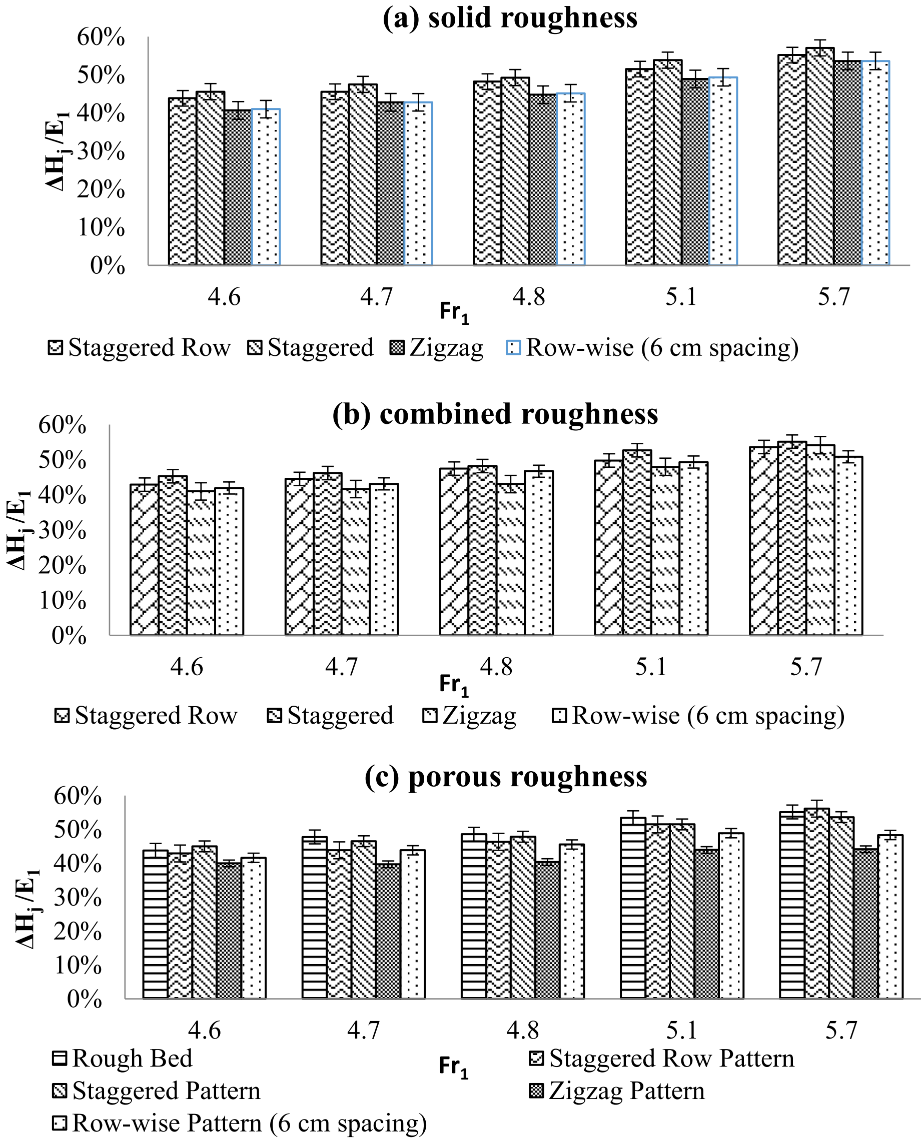

Figure 9. Relative energy dissipation of the hydraulic jump vs. Fr_1 for different arrangements of (a) solid roughness, (b) combined roughness, and (c) porous roughness

Comparative Analysis and Discussion

The experimental results demonstrate a substantial improvement in stilling basin performance through the use of porous appurtenances. To contextualize these findings, the performance of the optimal configurations from this study the porous zigzag roughness and the double-row porous baffle blocks is compared with established design standards.

Fig. 10 presents the relative jump length (L_j/y_2) as a function of the incoming Froude number (Fr_1). The data from our control case (smooth bed) align well with the USBR design curve for classical jumps, which suggests $L_j/y_2 \approx 6.1$ for $Fr_1 > 4.5$ (Peterka, 1984), validating our experimental methodology. As shown, our optimal porous configurations achieve a significantly shorter relative jump length than the classical jump. Specifically, the porous zigzag roughness resulted in an average reduction of 36% in relative jump length compared to the USBR standard for the tested Froude number range. This performance is comparable to empirical relations for forced jumps, such as those by Rajaratnam (e.g., Habibzadeh et al., 2012), where roughness reduces L_j by 20-30%; our porous elements exceed this, likely due to Forchheimer-type inertial dissipation. Compared to cross-beam dissipators (Hajialigol et al., 2024; Hajialigol et al., 2021) or vegetated beds (Adeli et al., 2021), porous media offer volumetric advantages. Further, our porous baffles outperform numerical models of abrupt expansions in Sajjadi et al. (2025) by 10-15% in length reduction, while aligning with turbulence measurements in Hajialigol et al. (2024), where cross-beams reduced L_j by 25-35% but lacked porosity's internal effects.

The superior performance of porous media, as observed in this study, can be explained by comparing their dissipation mechanisms to those of traditional solid elements. Solid appurtenances dissipate energy primarily through form drag and the generation of large-scale vortex shedding in their wake (e.g., Habibzadeh et al., 2012; Peterka, 1984). In contrast, porous elements introduce more complex and efficient dissipation mechanisms. As the high-velocity jet impinges on the porous blocks, a portion of the flow penetrates the internal structure. This process induces:

1. Internal Shear and Turbulence: The intricate flow paths within the porous matrix generate significant shear stress and small-scale turbulence, effectively dissipating energy volumetrically.
2. Jet Splitting and Interaction: The main jet is split into multiple smaller jets that interact with each other and the solid matrix, further enhancing turbulent mixing and momentum exchange.
3. Pressure Drag and Wake Modification: The flow passing through the pores alters the pressure distribution around the block and modifies the structure of the downstream wake, leading to a more stable and compact jump.
4. Upward Jet Interaction: As observed in our experiments, the flow exiting the top of the porous blocks creates upward-directed jets. These jets penetrate the overlying roller region of the hydraulic jump, disrupting its structure and enhancing the momentum transfer from the main flow to the recirculation zone. This interaction is a key mechanism that contributes to the significant reduction in jump length and is less pronounced with solid blocks.

This study builds upon the established literature on solid appurtenances by providing a systematic comparison with porous media. Our findings not only confirm the effectiveness of porous elements but also demonstrate that the spatial arrangement (e.g., a zigzag pattern for roughness) is as crucial as the material's porosity. The combination of an optimized layout and porosity maximizes the interaction between the flow and the appurtenances, leading to the most efficient energy dissipation and the most compact stilling basin design.

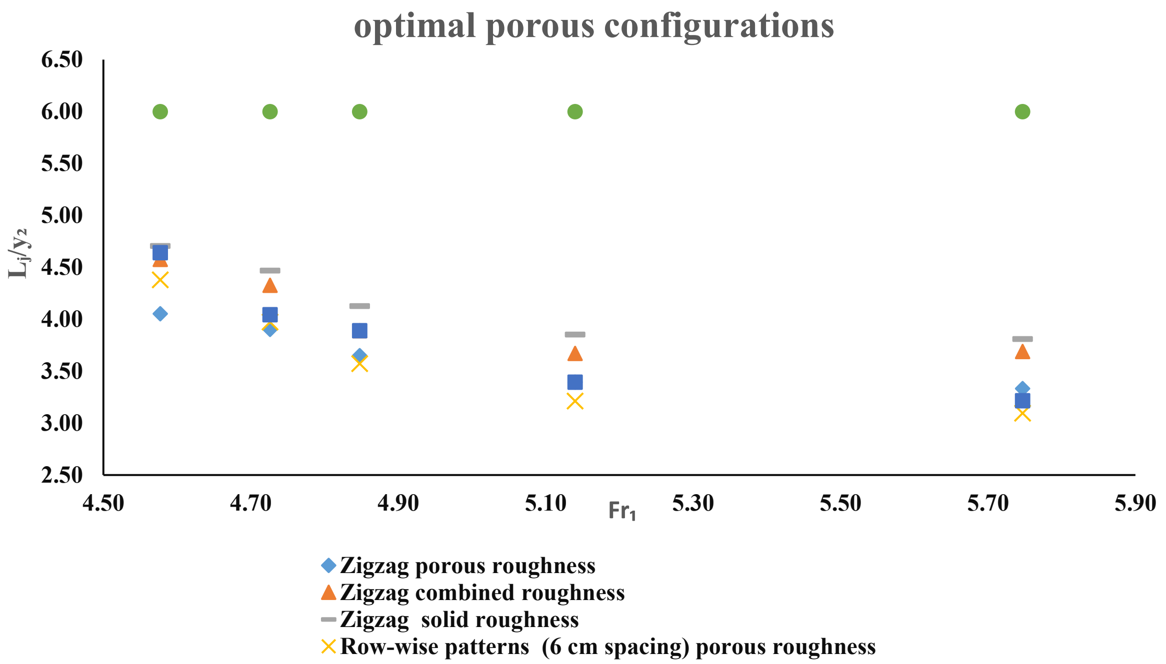

Figure 10. Comparison of relative jump length (L_j/y_2) vs. Fr_1 for the optimal porous configurations from this study, the classical USBR curve

Predictive Empirical Relationships

To facilitate the practical application of these findings, empirical relationships for predicting the relative jump length (L_j/y_2) were developed based on regression analysis of the experimental data. The power-law form, which is common for such phenomena, was found to provide the best fit. These relations are preliminary and correlative, grounded in Fr_1 scaling from dimensional analysis (Eq. 3), but may not generalize beyond our conditions (e.g., fixed Φ=0.25). They compare favorably to Peterka's (1984) classical form. Note that parameters like h/y_1 and Φ are not explicitly included due to their fixed values in experiments; future studies should incorporate them for more comprehensive models. For the zigzag porous bed roughness, the proposed relationship is:

$L_j / y_2 = 14.59 * Fr_1^{-}0.86$ ($R^2 = 0.83$) (6)

For the Row-wise patterns (6 cm spacing) porous roughness, the relationship is:

$L_j / y_2 = 37.67 * Fr_1$-1.46 ($R^2 = 0.82$) (7)

Where L_j is the length of the forced jump over the appurtenances. These equations are valid for the tested Froude number range of $4.5 < Fr_1 < 5.8$. Fig. 11 plots the experimental data and fitted curves for Equations 6 and 7.

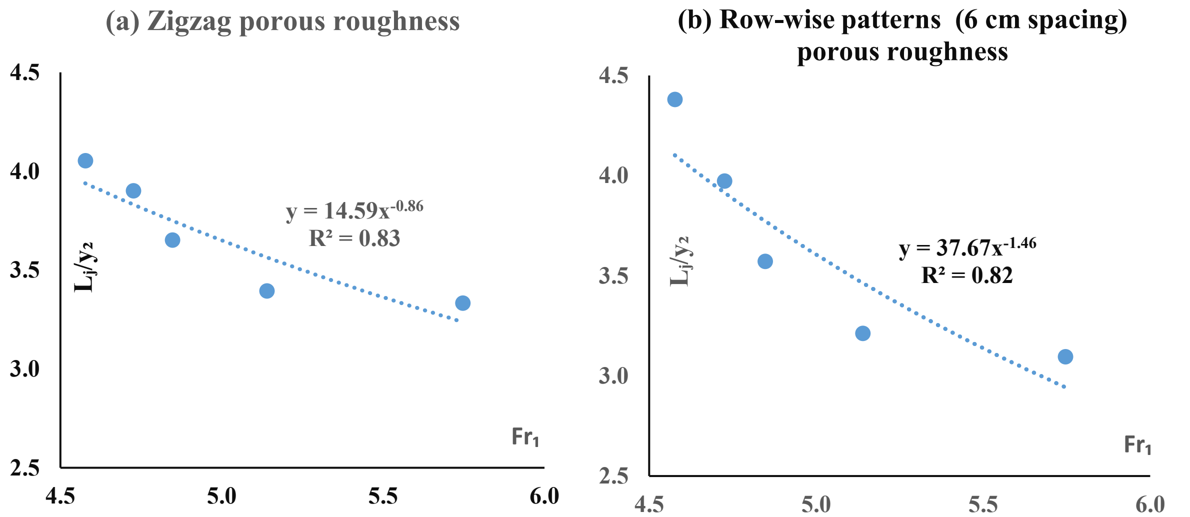

Figure 11. Plots of relative jump length (L_j/y_2) vs. Fr_1 for (a) porous zigzag roughness (Equation 6) and (b) Row-wise patterns (6 cm spacing) porous roughness (Equation 7), showing data points and fitted lines

Conclusions

This experimental study systematically investigated the influence of solid and porous baffle blocks and bed roughness on the characteristics of a hydraulic jump. Based on the results, the following conclusions are drawn:

1. Universal Effectiveness: All tested appurtenances, whether solid or porous, effectively reduced the sequent depth ratio and jump length compared to a classical hydraulic jump on a smooth bed.
2. Superiority of Porous Media: Porous elements consistently demonstrated superior performance over their solid counterparts. The maximum jump length reduction of 47% was achieved using a zigzag arrangement of porous roughness elements, highlighting the significant benefit of incorporating porosity.
3. Optimal Configurations: For baffle blocks, a double-row arrangement proved most effective. For bed roughness, the zigzag porous pattern and Row-wise patterns (6 cm spacing) porous and combined roughness yielded the best results in terms of shortening the jump length and reducing the sequent depth.
4. Dissipation Mechanism: The enhanced efficiency of porous media is attributed to additional energy dissipation mechanisms, including internal flow shear, jet interactions within the porous structure, and increased turbulence from the interaction of penetrating flow with the main jump roller.
5. Practical Implications: The use of porous appurtenances offers a viable and highly effective method for designing more compact, economical, and sustainable stilling basins. The findings provide valuable data and empirical relationships that can aid engineers in the design of energy dissipators, particularly where spatial constraints are a concern.

Future work should explore the effect of varying porosity levels (e.g., Φ=0.1–0.5), investigate a wider range of Froude numbers, and use advanced numerical models (e.g., CFD as in Sajjadi et al., 2025; Ahadiyan et al., 2024) to further elucidate the complex 3D turbulent structures responsible for the enhanced dissipation. Incorporating velocity measurements

(PIV/ADV) would provide quantitative evidence for mechanisms like internal shear and jet splitting, addressing current limitations. Additionally, expand empirical relationships to include parameters like h/y_1 and Φ for broader applicability.

Author Contributions

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the authors.

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Ethical Considerations

The authors avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of Interest

The authors declare no conflict of interest.

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