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Articles

Experimental analysis of hydraulic jump roller length in compound rectangular channels with uniform bed roughness under zero slope conditions

Análisis experimental de la longitud del rodillo de un resalto hidráulico en canales rectangulares compuestos con rugosidad uniforme del lecho en condiciones de pendiente cero

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Abstract

This study investigates the behavior of hydraulic jumps in compound rectangular channels with uniformly roughened beds, a configuration common in natural and engineered open-channel systems but underexplored in existing literature. While traditional research has focused on smooth or partially rough beds in prismatic channels, this work addresses the gap by experimentally analyzing roller length variations in channels featuring both major and minor flow sections roughened with consistent plastic elements. Conducted in a horizontal, closed-circuit flume, the experiments varied bed roughness (ε = 0–12 mm) and Froude numbers ($F_1 \approx 2$–9) to replicate realistic flow conditions. Dimensionless parameters were used to derive empirical correlations between roller length and relative bed roughness, showing a consistent inverse relationship. Statistical regression confirmed strong linear trends between relative roughness and derived model coefficients for both bed types, with high determination coefficients ($R^2 > 0.97$). The findings demonstrate that full-bed roughness significantly enhances energy dissipation by reducing roller length, offering practical design implications for more compact and efficient stilling basins in compound channels.

Keywords: Hydrodynamics, fluid mechanics, hydraulic engineering, hydraulic structures, canals, equations, mathematical models.

Resumen

Este estudio investiga el comportamiento de los resaltos hidráulicos en canales rectangulares compuestos con lechos uniformemente rugosos, una configuración común en sistemas de flujo a cielo abierto tanto naturales como artificiales, pero poco explorada en la literatura existente. Mientras que la investigación tradicional se ha centrado en lechos lisos o parcialmente rugosos en canales prismáticos, este trabajo aborda dicha laguna mediante el análisis experimental de las variaciones en la longitud del rodillo en canales con secciones de flujo mayor y menor rugosificadas con elementos plásticos consistentes. Los experimentos se realizaron en un canal cerrado y horizontal, variando la rugosidad del lecho (ε = 0-12 mm) y los números de Froude ($F_1 \approx 2\text{-}9$) para simular condiciones de flujo realistas. Se utilizaron parámetros adimensionales para derivar correlaciones empíricas entre la longitud del rodillo y la rugosidad relativa del lecho, mostrando una relación inversa consistente. La regresión estadística confirmó fuertes tendencias lineales entre la rugosidad relativa y los coeficientes del modelo derivados para ambos tipos de lecho, con altos coeficientes de determinación ($R^2 > 0.97$). Los hallazgos demuestran que la rugosidad total del lecho mejora de forma significativa la disipación de energía al reducir la longitud del rodillo, lo que ofrece implicaciones prácticas para el diseño de cuencas de disipación más compactas y eficientes en canales compuestos.

Palabras clave: Hidrodinámica, mecánica de fluidos, ingeniería hidráulica, estructura hidráulica, canal, ecuación, modelo matemático.

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Introduction

Hydraulic jumps are a well-established phenomenon in open channel hydraulics, characterized by an abrupt transition from supercritical to subcritical flow, typically marked by a sudden rise in water surface elevation and high turbulence intensity. These jumps serve as crucial energy dissipator in hydraulic engineering applications, including downstream of spillways and sluice gates, where they help to prevent structural damage caused by erosive high-velocity flows (Chanson, 2011; De-Leo, Rinaldi, Comiti, & Nardi, 2020; Leutheusser & Schiller, 1975). A key design parameter in managing such flows is the roller length —the surface recirculating region of the hydraulic jump— which directly influences the required size and cost of stilling basins (Mohamed-Ali, 1991).

Numerous studies have investigated the characteristics of hydraulic jumps on smooth beds, establishing empirical relationships between roller length, sequent depth, and upstream Froude number (Chanson, 2011; Djamaa & Ghomri, 2020). To enhance energy dissipation and reduce basin length, modifications such as roughened beds or the inclusion of appurtenances have been widely employed. Experimental evidence confirms that roughness elements significantly influence jump behavior by increasing turbulence and momentum exchange, resulting in shorter roller lengths and lower downstream depths (Abbaspour, Hosseinzadeh-Dalir, Farsadizadeh, & Sadraddini, 2009; Carollo, Ferro, & Pampalone, 2007; Ead & Rajaratnam, 2002; Mohamed-Ali, 1991; Djamaa, Ghomri, & Khechana, 2021). Carollo *et al*. (2007), and Ead and Rajaratnam (2002) demonstrated that uniformly rough or corrugated beds contract the roller length through enhanced energy loss. Similarly, Mohamed-Ali (1991) found that roughened-bed stilling basins substantially reduce required jump length, allowing for more compact and economical designs.

Despite extensive research on smooth and rough beds in prismatic channels, real-world applications often involve compound channels-geometries comprising a deeper main channel and shallower floodplains. These configurations introduce additional complexity due to differential momentum exchange and flow redistribution between the channel compartments (Djamaa & Ghomri, 2020). Existing research on hydraulic jumps in compound channels remains limited (Benabdesselam, 2020; Khattaoui & Achour, 2012; Riguet, Debabeche, & Ghomri, 2020), with studies by Khattaoui and Achour (2012), and Benabdesselam (2020) highlighting how compound geometry alters sequent depth and energy dissipation. Riguet *et al*. (2020) further explored depth ratio characteristics, yet most available studies focus on smooth or partially roughened beds, overlooking the roller length as a key parameter.

Recent investigations have begun to address this gap. Djamaa and Ghomri (2020) examined roller length in compound channels with rough bottoms and found a measurable influence of roughness, though their focus was exploratory. In a follow-up study, Djamaa *et al*. (2021) demonstrated that roughness in the minor bed reduces the threshold Froude number for jump formation, underscoring the role of roughness in compound cross-sections. However, both studies applied roughness to only part of the compound channel, typically the floodplain, while the main bed remained smooth.

In practice, both the main and minor beds may possess significant roughness —e.g., coarse gravel beds in channels and vegetated floodplains— necessitating a more comprehensive understanding of how full-bed roughness affects hydraulic jump dynamics. Furthermore, most existing work has not isolated the influence of roughness under horizontal (zero slope) conditions, which are representative of engineered structures like stilling basins. While some prior work has explored adverse slope scenarios (Esfahani, 2017; Pourabdollah, Heidarpour, & Koupai, 2019), the behavior of jumps in compound channels with entirely rough beds under zero slope remains underexplored.

This study advances previous research by specifically investigating hydraulic jumps in rectangular compound channels with uniformly distributed plastic roughness applied to both the main and minor channel beds. Unlike earlier investigations that explored the effects of varied roughness geometries —such as those by Ghomri and Riguet (2012) and Debabeche *et al*. (2006)— this study employs consistent artificial roughness elements across five discrete roughness values (ε = 6, 8, 10 and 12 mm). The primary objective is to develop concise, dimensionless empirical equations derived from an extensive experimental dataset to describe the relationship between roller length and roughness parameters. These formulations aim to provide a practical and predictive tool for hydraulic design on rough compound beds. Furthermore, the study highlights the potential of rough beds to enhance energy dissipation efficiency, offering viable design strategies for stilling basins intended to reduce downstream erosion and structural damage.

Materials and methods

The experimental setup for investigating the roller length of hydraulic jumps was meticulously established within a closed-circuit hydraulic flume system located at the Laboratory for Exploitation and Valorization of Natural Resources in Arid Zones, University of Ouargla, Algeria. The primary apparatus consisted of a rectangular channel measuring 10 meters in length and 0.5 meters in height, constructed with transparent Plexiglas sidewalls to facilitate direct and clear observation of the flow characteristics and the hydraulic jump formation. The channel was precisely oriented horizontally with zero slope to ensure accurate isolation of the hydraulic jump phenomena from gravitational influences (Figure 1).

Figure 1. The channel used for the experiment.

The test section within the channel extended 4 meters and was designed with a compound cross-section, comprising two clearly defined sections: a narrower minor bed with a width of 14.4 cm, and a wider major bed measuring 25 cm in width. Both beds were consistently constructed at a uniform height of 15.5 cm. The beds' surfaces were roughened using carefully selected uniform plastic pellets with roughness heights (ε) of 6 mm, 8 mm, 10 mm, and 12 mm. These pellets, chosen to simulate realistic conditions in industrial and natural environments such as concrete-lined channels and rocky streams, were secured using robust adhesive and rigid fishing lines. This careful attachment ensured durability and prevented erosion or displacement under torrential flow conditions, thus providing repeatable experimental conditions (Figure 2).

Figure 2. Compound cross-section in the experimental channel with roughened main and minor beds using uniformly arranged plastic spheres for studying hydraulic jump characteristics.

Water supply for the experiment was meticulously managed through a circular pipe with a diameter of 150 mm, connected to an axial pump capable of delivering precise flow rates up to 55.55 liters per second. Upstream, the setup featured a closed metal box containing a precisely adjustable flat plate orifice, whose main function was to generate controlled torrential flows. This orifice allowed fine adjustment of the initial hydraulic jump height (h_1), specifically tested at heights of 2.5, 3, 3.5 and 4 cm. These values were strategically selected to yield practical Froude numbers (approximately ranging from 2 to 9), which are typical of real-world scenarios encountered in hydraulic structures such as spillways and stilling basins.

A downstream sluice gate was employed to further control and stabilize the flow conditions, while a rectangular sharp-crested weir installed at the downstream end of the channel provided accurate and direct measurement of flow rates.

To systematically study the effects of downstream conditions on the hydraulic jump, 26 thin metal plate thresholds, each precisely constructed with thicknesses ranging from 1 to 2 mm, were securely anchored to the channel bed. These thresholds were adjustable in height at fine increments of 1 cm, covering an extensive range from 2.5 to 21 cm. This range facilitated detailed exploration of tail water level variations, allowing for controlled transitions between subcritical and supercritical flows, critical for analyzing stable jump formation and accurately determining roller lengths (Figure 3).

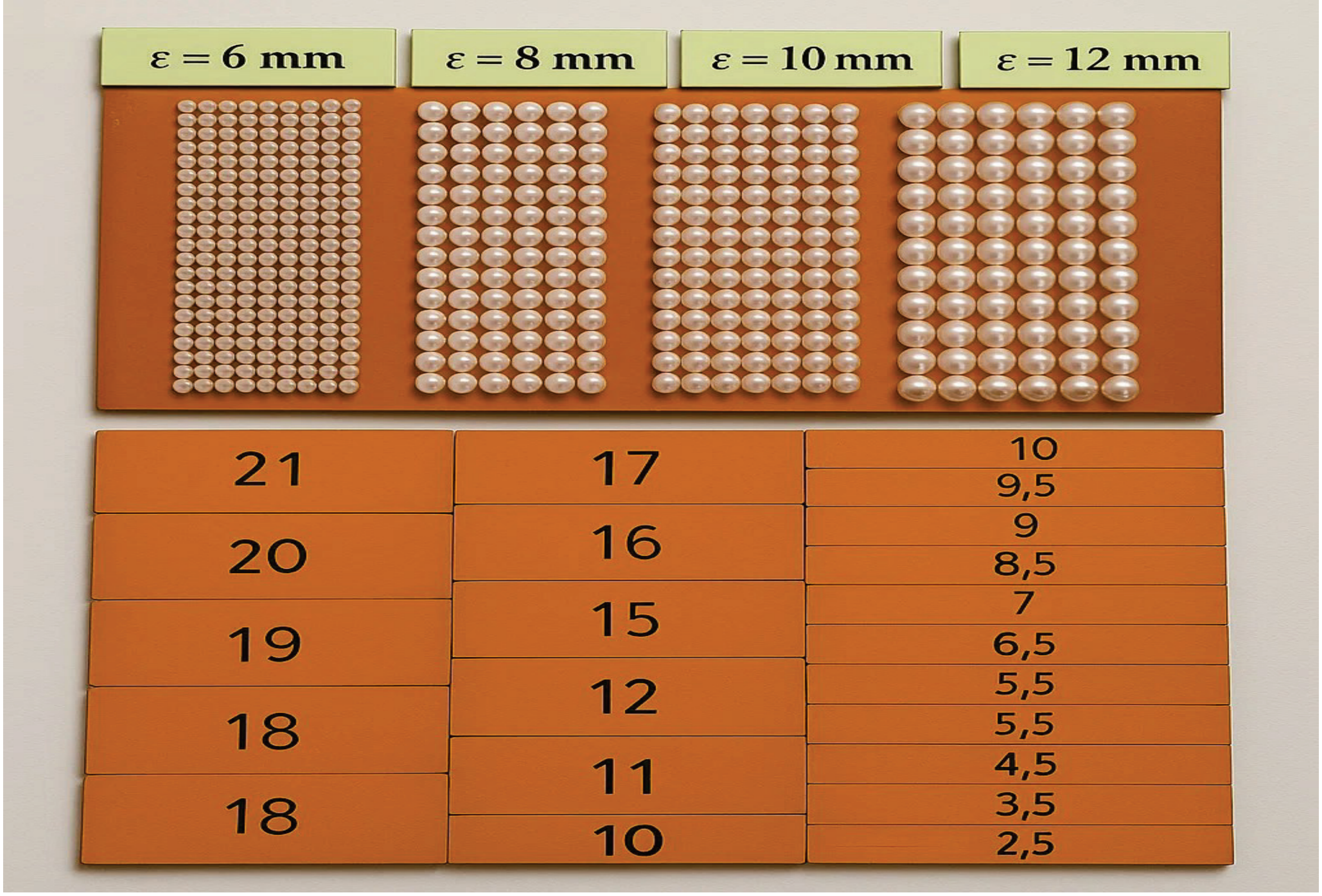

Figure 3. Roughness elements and threshold heights in the experimental study of hydraulic jumps.

All experimental parameters were converted into dimensionless ratios (ε/B, and ε/b, Lr/h1). This dimensionless analysis permitted straightforward extrapolation of experimental findings to larger-scale prototype channels, significantly enhancing the practical applicability and relevance of the experimental results to real-world hydraulic engineering scenarios.

Results and discussion

Figure 4 and Figure 5 presents Variation of the roller length Lr as a function of the upstream Froude number F1 for five absolute bed roughness values (ε = 0, 6, 8, 10,12 mm), applied respectively to the minor bed (0 < h2 < 15.5 cm) (Figure 4) and the major bed (15.5 < h2 < 28 cm) (Figure 5). Distinct clusters of data points appear for each roughness level. The results show that, for a given Froude number, increasing the imposed bed roughness leads to a consistent reduction in roller length. This indicates that bed roughness plays a key role in enhancing energy dissipation and shortening the hydraulic jump within the compound channel.

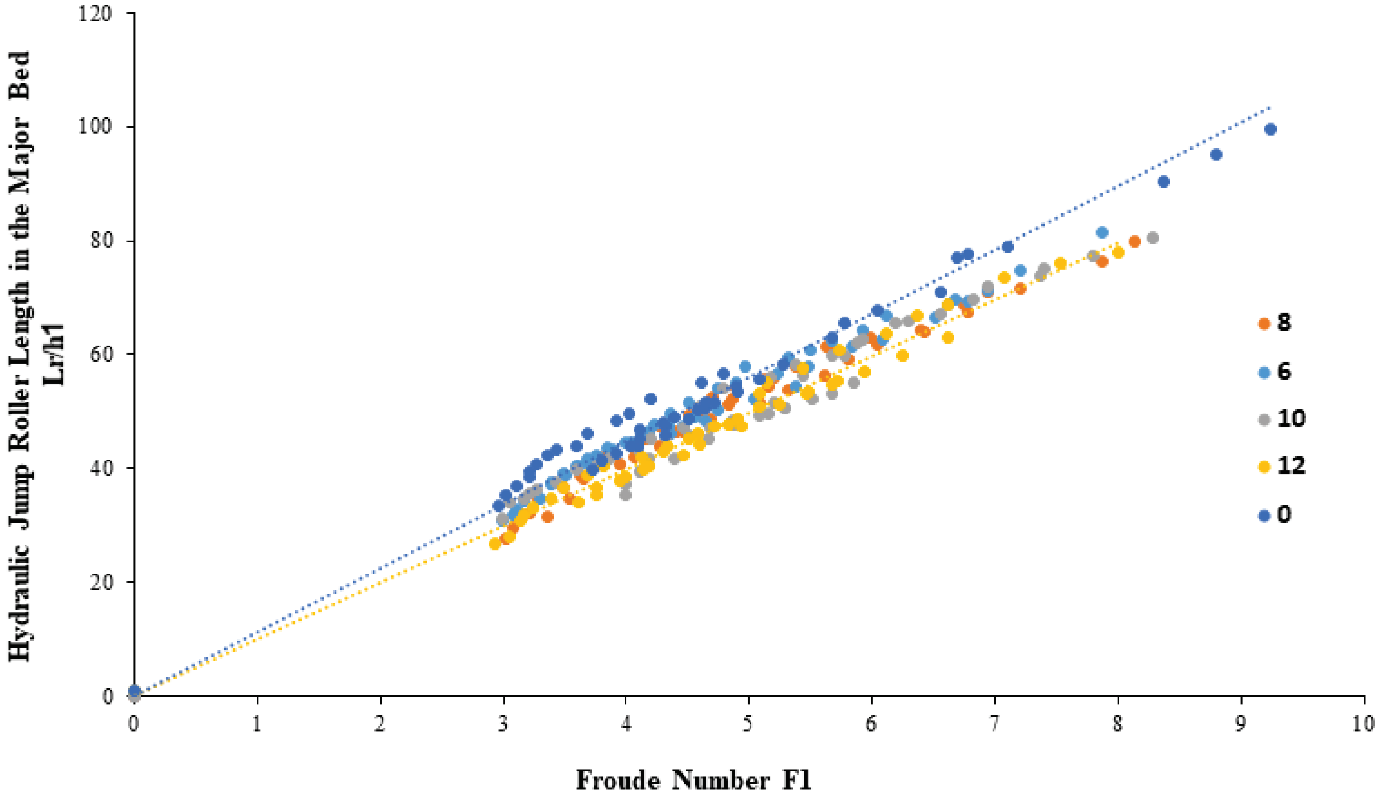

Figure 4. Relationship between the dimensionless hydraulic jump roller length (Lr/h1) and the upstream Froude number (F1) in the minor bed for various bed roughness conditions.

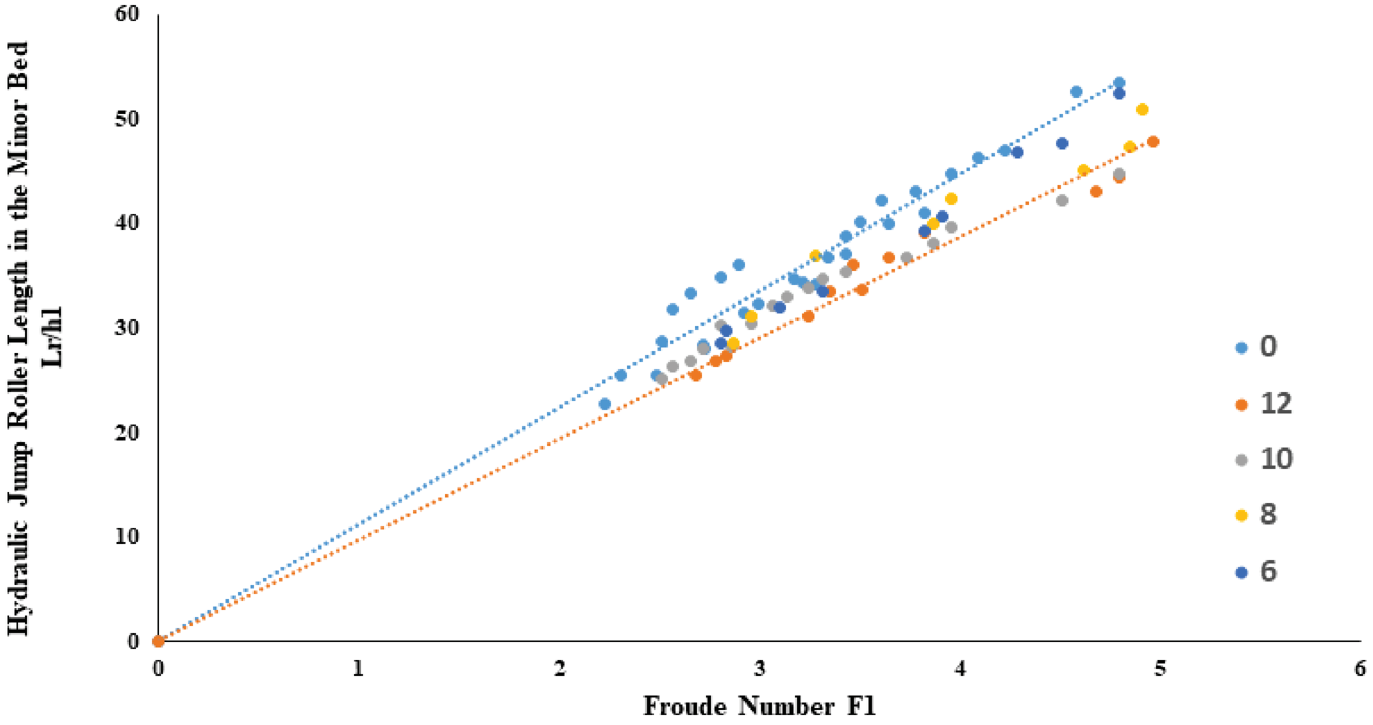

Figure 5. Variation of hydraulic jump roller length (Lr/h1) in the major bed as a function of the upstream Froude number (F1) for different bed roughness conditions.

A statistical analysis was performed on the complete set of experimental data using the nonlinear least squares method. The results indicated that, for each tested equivalent roughness, the incident Froude number (F1) is logarithmically correlated with the dimensionless roller length (Lr/h1) of the hydraulic jump. This relationship is described by the equation:

$$Lr/h1 = a\,(F1) \tag{1}$$

Where the coefficient a varies depending on the bed type: a1 corresponds to the minor bed, while a_2 applies to the major bed. The corresponding values of coefficients a_1 and a_2 for each configuration are presented in Table 1.

Table 1. Regression coefficients (a_1, a_2) and determination coefficients (R^2) for different bed roughness configurations in minor and major beds.

Roughness (mm)	**Relative roughness (ε/b) in the minor bed**	**Relative roughness (ε/B) in the major bed**	**a_1**	**R^2**	**a_2**	**R^2**
0	0	0	11.172	0.9977	**12.167**	0.9978
6	0.041666	0.024	10.538	0.9976	**11.751**	0.9985
8	0.055555	0.032	10.235	0.9974	**11.303**	0.9983
10	0.069444	0.04	10.008	0.9977	**11.1**	0.9975
12	0.083333	0.048	9.6693	0.9983	**10.941**	0.9985

The experimental results revealed a strong correlation between relative roughness (ε/b and ε/B) and the regression coefficients (a_1 and a_2) in both the minor and major beds. In the case of the minor bed ($0 < h_2 < 15.5$ cm), the coefficient a_1 was found to decrease linearly with increasing relative roughness (ε/b), following the relationship:

$$\mathrm{Lr/h1} = (-17.764\,(\varepsilon/\mathrm{b}) + 11.213)\,(\mathrm{F1}) \qquad (2)$$

With a determination coefficient of $R^2 = 0.9917$, indicating a high level of model accuracy.

Similarly, for the major bed ($15.5 < h_2 < 28$ cm), the coefficient a_2 showed a linear decrease with increasing (ε/B), as expressed by:

$$Lr/h1 = (-26.594\,(\varepsilon/B) + 12.222)\,(F1) \tag{3}$$

This relation yielded an even higher determination coefficient of $R^2 = 0.9755$, reflecting a very strong alignment ((Figure 6 and (Figure 7).

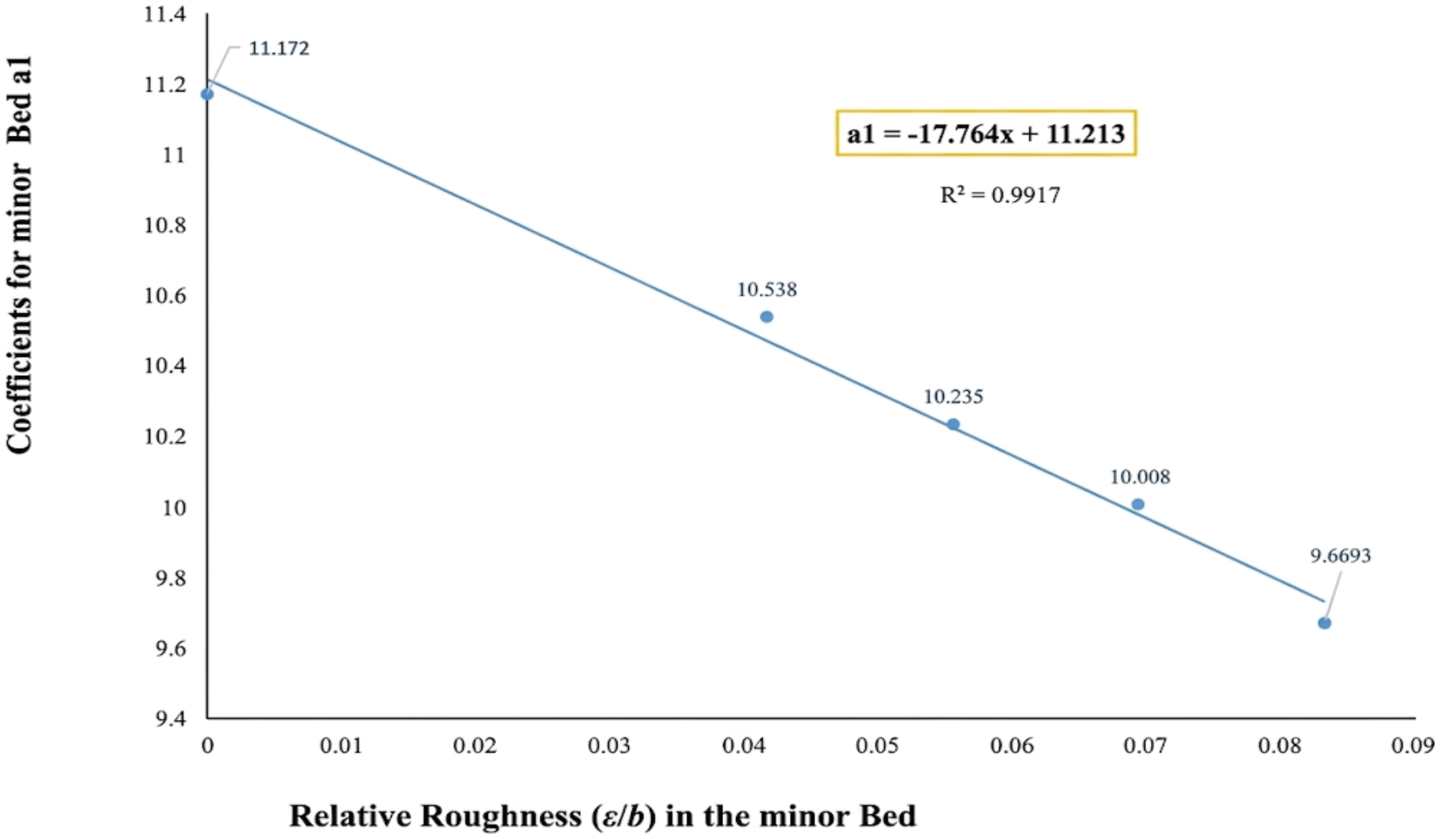

Figure 6. Linear relationship between relative roughness (ε/b) and coefficient a_1 in the minor bed.

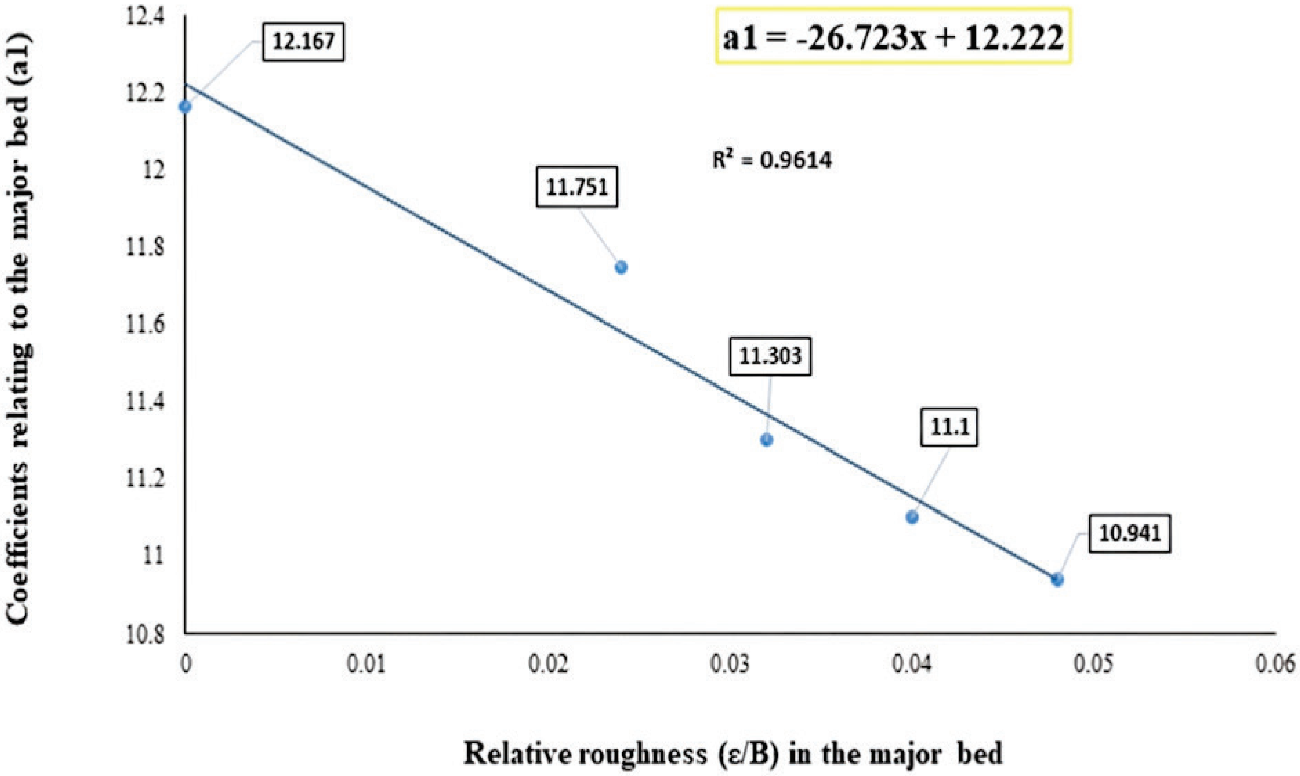

Figure 7. Variation of the regression coefficient a_2 with relative roughness (ε/B) for the major bed.

Figure 8 and Figure 9 collectively demonstrate that the relationship Lr/h1 = f ((ε /b), F1) for the minor bed and Lr/h1 = f ((ε /B), F1) for the major bed exhibit strong correlations across both flow domains. In each case, the majority of the experimental data points closely align with the first bisector, confirming the reliability of the regression models and the accuracy of the experimental measurements. Further, validate the robustness of the proposed dimensionless relationships.

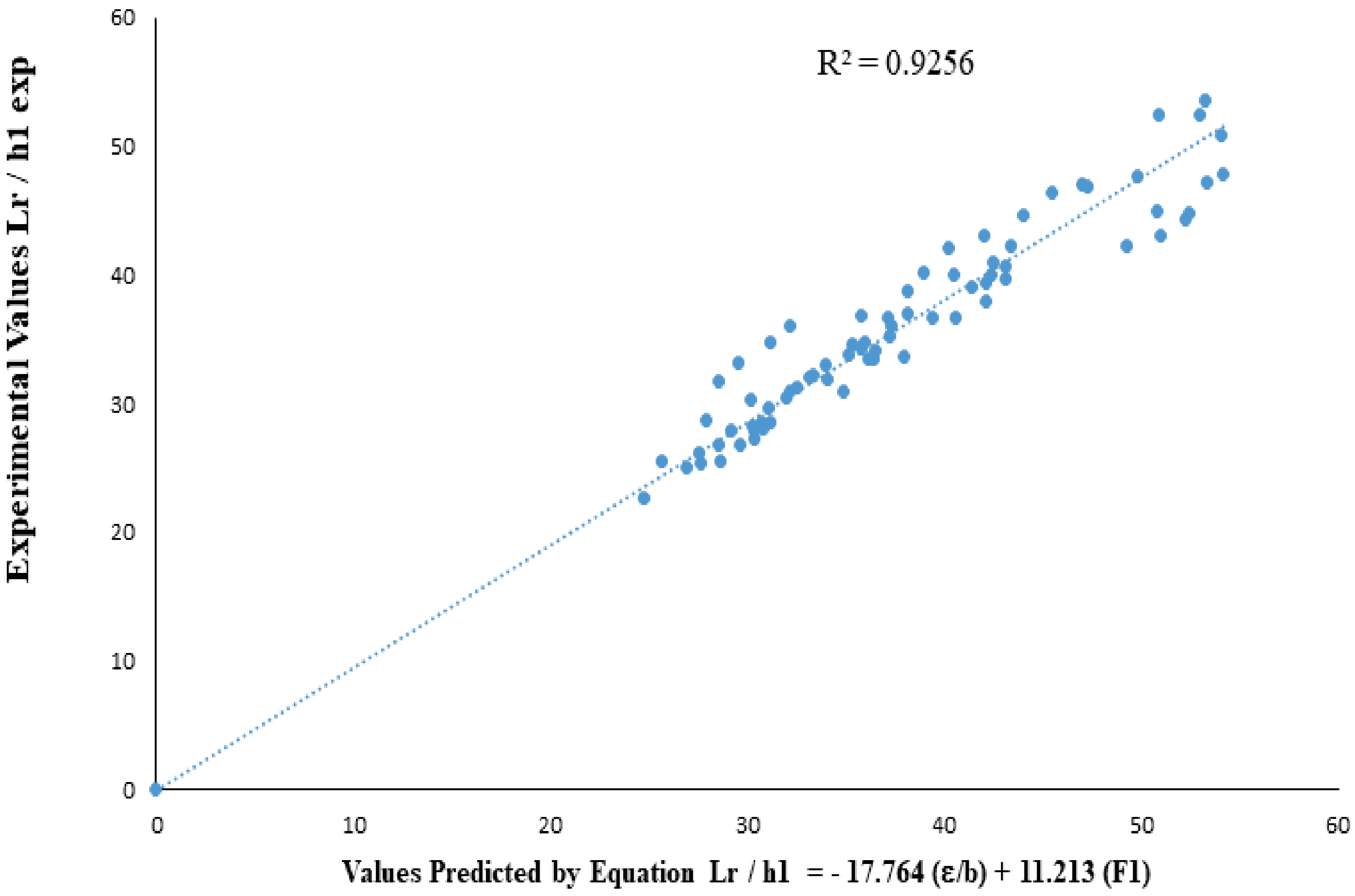

Figure 8. Comparison between experimental and predicted values of Lr / h1.

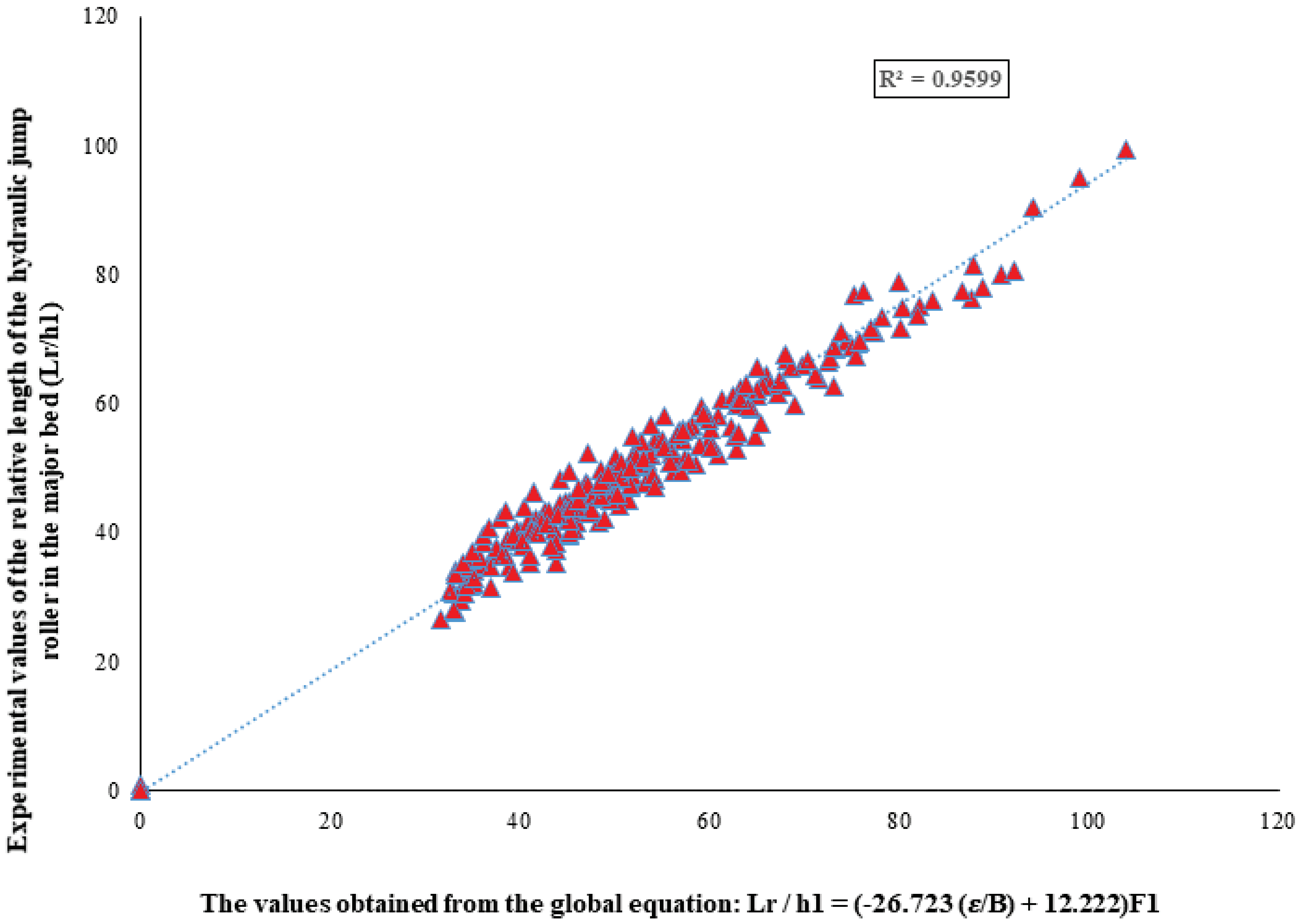

Figure 9. Agreement between experimental data and predicted values of Lr/h1 based on the equation for the major bed.

Figure 10 presents a comparative analysis of the predicted and observed values for the roller length ratio (Lr/H_1) across both minor and major bed configurations. The data reveal a distinct separation between the two setups. For the major bed (depicted in blue), which corresponds to the deeper flow region (15.5 cm < h_2 < 28 cm), the Lr/H_1 values are notably higher. This reflects longer roller lengths, likely resulting from increased energy conservation due to the reduced impact of relative roughness (ε/B). The larger flow cross-section and volume lessen frictional resistance and energy loss. In contrast, the minor bed (shown in orange), associated with a shallower depth range (0 cm < h_2 < 15.5 cm), consistently yields lower Lr/H_1 values. These indicate shorter roller lengths, attributed to enhanced energy dissipation caused by a stronger influence of relative roughness (ε/b). Notwithstanding these contrasts, both datasets exhibit a strong linear relationship with the identity line, thereby affirming the predictive model's reliability across diverse bed geometries. The clear data separation further underscores the significance of bed structure and surface roughness in governing hydraulic jump dynamics.

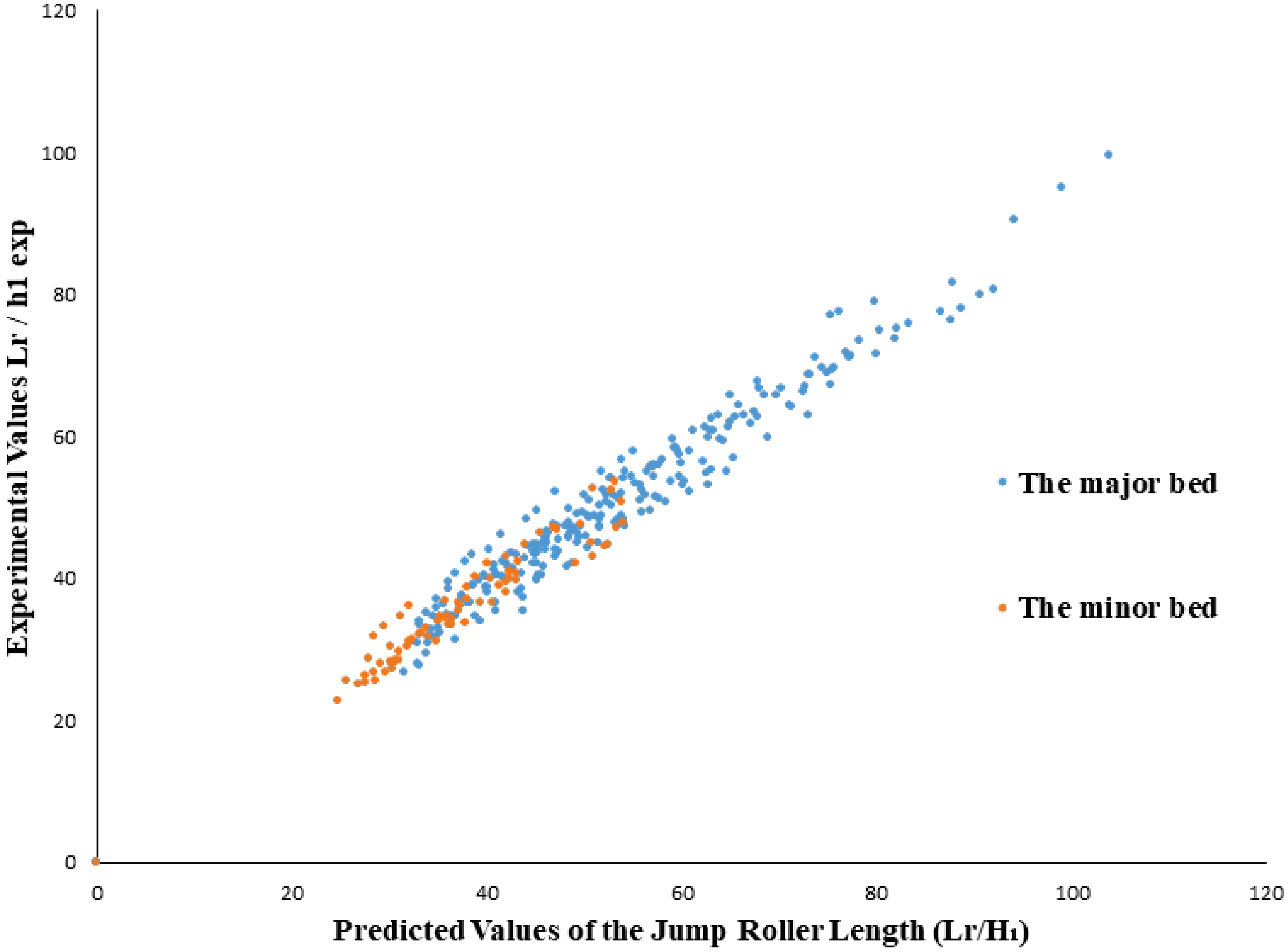

Figure 10. Comparison between predicted and experimental values of jump roller length (Lr/H1) for major and minor beds.

Conclusions

This experimental investigation has advanced the understanding of hydraulic jump dynamics in compound channels by demonstrating the critical influence of uniform bed roughness across both the major and minor beds. The results confirm that increasing bed roughness leads to a consistent decrease in roller length, with distinct behaviors observed between the deeper major bed and the shallower minor bed due to differences in relative roughness impact. The relationships between the Froude number and the dimensionless roller length were validated with high statistical reliability, supporting their utility in predictive modeling. These findings offer valuable insights for hydraulic engineers seeking to optimize stilling basin design in compound channels, particularly in environments with natural or engineered roughness. Future research may explore the combined effects of slope variations, roughness distribution patterns, and flow turbulence metrics to further refine hydraulic jump modeling under complex boundary conditions.

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