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FLUID MECHANICS

EXPERIMENTAL ANALYSIS OF HYDRAULIC JUMP LENGTH IN ROUGH-BEDDED COMPOUND CHANNELS

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ABSTRACT: This study explores how bed roughness affects the length of hydraulic jumps in a rectangular compound channel under zero slope. Experiments were done in a 10 m flume with a compound cross-section (minor bed: 14.4 cm, major bed: 25 cm), using plastic roughness elements (ε = 6–12 mm). Different flow rates and upstream depths were tested. Results show that increased roughness shortens jump length (L_j) by enhancing turbulence and momentum transfer. The minor bed's relative roughness (ε/b) had the strongest effect. Dimensionless equations were developed linking L_j/h_1 with the Froude number (F_1) and roughness. Findings underline the role of bed roughness in managing jumps, with implications for energy dissipation and flood control systems.

KEY WORDS: Hydraulic jump, bed roughness, energy dissipation.

1 INTRODUCTION

The hydraulic jump, a fundamental phenomenon in open channel flow, represents a rapid transition from supercritical to subcritical conditions, commonly occurring in natural and engineered environments such as rivers, spillways, and stilling basins. Characterized by significant energy dissipation, its behavior has been extensively studied since the foundational work of Bélanger, with subsequent research providing valuable insights into its complex dynamics [1, 2]. Moreover, researchers have explored various aspects of hydraulic jumps, including their characteristics under different flow conditions and channel geometries [1–3]. However, despite considerable progress, the influence of bed roughness, particularly in compound channels, remains

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an area requiring further investigation, especially given its practical implications for hydraulic structure design [4].

Compound channels, frequently employed for flood conveyance and water resource management, introduce complexities to hydraulic jump behavior due to the interaction between the main channel and floodplain flows [5, 6]. While previous studies have explored various aspects of hydraulic jumps in compound channels, including numerical modeling, geometric variations such as contractions and expansions [7], and the application of machine learning techniques [8, 9], research on stepped structures has provided additional insights. Notably, the use of stepped gabion weirs has been investigated for its role in energy dissipation and jump stabilization, highlighting its relevance to flow regulation strategies [10]. The specific impact of minor bed roughness on jump characteristics and energy dissipation remains not fully elucidated [11, 12].

Recent laboratory investigations, such as those by Gupta and Dwivedi on rough sloping surfaces, have advanced understanding of roughness effects in simplified configurations, yet gaps persist in compound channel environments where interactions between main channel and floodplain flows dominate. This knowledge gap is particularly relevant for optimizing stilling basin design and ensuring effective energy dissipation [13–15].

This study investigates the influence of bed roughness on the length of the hydraulic jump in a rectangular compound channel consisting of a minor bed (14.4 cm width) and a major bed (25 cm width). The minor bed refers to the narrower, typically deeper section of the compound channel, representing the main flow path under normal conditions. The major bed refers to the wider, shallower sections adjacent to the minor bed, simulating flood terraces or floodplains that become active during higher flow conditions. Building on a substantial body of previous research, this work addresses a key gap by systematically analyzing roughness effects using uniformly distributed plastic elements. Unlike prior studies that examined varied rough surfaces, this approach ensures controlled and consistent roughness conditions. Laboratory experiments were conducted in a flume using five different roughness values ($\varepsilon = 6$, 8, 10, and 12 mm) to develop accurate, dimensionless empirical equations. The results demonstrate that increased roughness significantly shortens the hydraulic jump length due to enhanced momentum transfer and energy dissipation, which restrict the longitudinal extent of the roller region. This effect is particularly pronounced in the minor bed, where relative roughness plays a dominant role. Derived mathematical equations establish a clear relationship between hydraulic jump length, Froude number, and roughness parameters, offering a practical tool for hydraulic structure design. Additionally, the findings highlight the potential of rough beds in optimizing energy dissipation, making them valuable for erosion control and downstream infrastructure protection.

2 MATERIALS AND METHODS

The experimental methodology of this study was meticulously designed to investigate the length of hydraulic jumps (L_j) within a controlled laboratory environment at the University of Ouargla. A 10 m long, 0.5 m deep hydraulic channel with a compound rectangular cross-section was employed, featuring a horizontal orientation with zero slope to ensure consistent flow conditions. The channel included a 4 m experimental section equipped with transparent Plexiglas walls, facilitating clear observation of the flow phenomena and precise measurement of key hydraulic parameters.

The compound cross-section was specifically configured to replicate natural riverbed conditions, consisting of a rough minor bed (14.4 cm wide) and a rough major bed (25 cm wide). These distinct sections allowed for the investigation of hydraulic jump characteristics under varying bed roughness conditions, mimicking the complexities of natural channels with flood terraces. Water was supplied to the channel by a pump with a maximum capacity of 55.55 liters per second. The flow was delivered through a 150 mm diameter pipe into a closed metal box fitted with a flat orifice plate. This setup was crucial for initiating a supercritical, torrential flow, which is a prerequisite for the formation of a stable hydraulic jump within the experimental section.

To enhance the clarity of the experimental setup and the parameters measured, we have supplemented Fig. 1 with a detailed schematic drawing of the working section. This schematic clearly illustrates the hydraulic jump and precisely marks the critical flow depths and jump length used in our dimensionless equations:

h_1 (upstream flow depth): This represents the initial flow depth in the supercritical flow region, measured immediately upstream of the hydraulic jump. This parameter is crucial for calculating the initial Froude number (F_1), which characterizes the flow conditions before the jump;

h_2 (sequent depth): This denotes the flow depth in the subcritical flow region, measured downstream of the hydraulic jump, where the flow has stabilized after the energy dissipation process;

L_j (hydraulic jump length): This is defined as the longitudinal distance from the toe (beginning) of the hydraulic jump to the point where the water surface becomes essentially horizontal and parallel to the channel bed, indicating the practical end of the turbulent roller. This length is a primary focus of our study, as it directly reflects the efficiency of energy dissipation.

These parameters (h_1, h_2, and L_j) are fundamental to the dimensionless equations derived in this study, which correlate the Froude number and bed roughness with the hydraulic jump length.

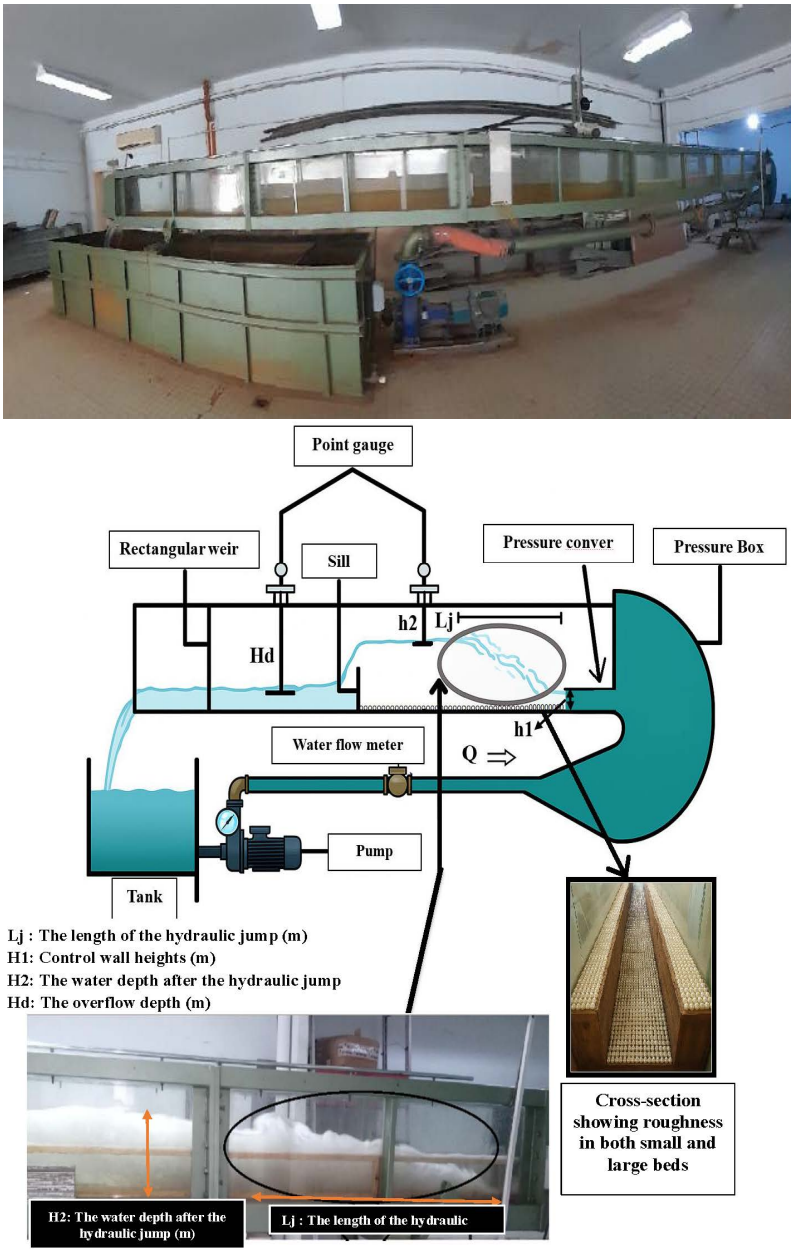

Fig. 1. The experimental channel used to study the hydraulic jump.

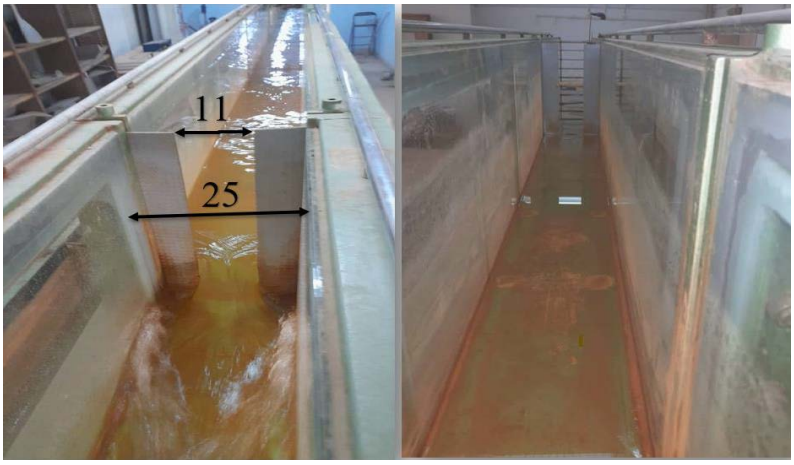

Fig. 2. Rectangular spillway with lateral narrowing for flow measurement.

To systematically study the hydraulic jump length (L_j), thin control walls of varying heights (ranging from 2.5 cm to 21 cm) were installed within the channel to stabilize and control the jump's formation. Five distinct roughness mats were prepared with equivalent roughness values of $\varepsilon = 6$ mm, 8 mm, 10 mm, and 12 mm (see Fig. 3), using uniformly distributed plastic granules adhered to the mats. The roughness configuration included a 4 m $\times$ 14.4 cm mat for the minor bed and two 4 m $\times$ 5.3 cm mats for the major bed's upper sections. The upstream flow depth (h_1) was adjusted across four distinct configurations 2.5 cm, 3.0 cm, 3.5 cm, and 4.0 cm to examine the jump length under diverse flow conditions. The flow rate (Q) was

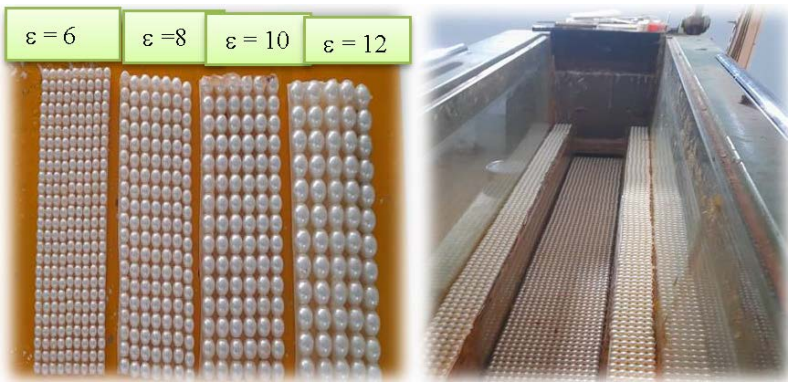

Fig. 3. Rough mat installed in the experimental channel.

measured downstream using a rectangular weir with lateral contraction, where the overflow depth (hd) was recorded with a limnimeter. The flow rate was calculated using the empirical formula by Hachemi Rachadi [16]:

$$Q = 0.3794B\sqrt{2g}\,\beta\left(1 + 0.16496\beta^{2,0716}\right)^{3/2} h_d^{3/2}, \tag{1}$$

where Q is the flow rate (m^3/s), B is the channel width (m), β is the contraction ratio (0.44), h_d is the overflow depth (m), and g is the gravitational acceleration (m/s^2), applicable when $\beta = b/B < 0.45$.

3 Results and Discussions

The experimental investigation sought to measure the hydraulic jump length (L_j) and develop a dimensionless relationship influenced by surface roughness (ε), step height (h_s), flow rate (Q), and control wall heights (h_1), conducted systematically in a laboratory with initial Froude numbers (F_1) ranging from 2.5 to 8. Tests varying (Q) and h_1 showed that higher flow rates shifted the jump downstream and extended L_j, yet roughness in both the minor bed (14.4 cm wide) and major bed (25 cm wide) reduced the L_j/h_1 ratio by increasing turbulence and energy dissipation. While in the large bed ($15.5 < h_2 < 28$ cm), higher roughness markedly reduces L_j, especially at elevated Froude numbers, demonstrating roughness as an effective tool for controlling flow and dissipating energy in hydraulic structures.

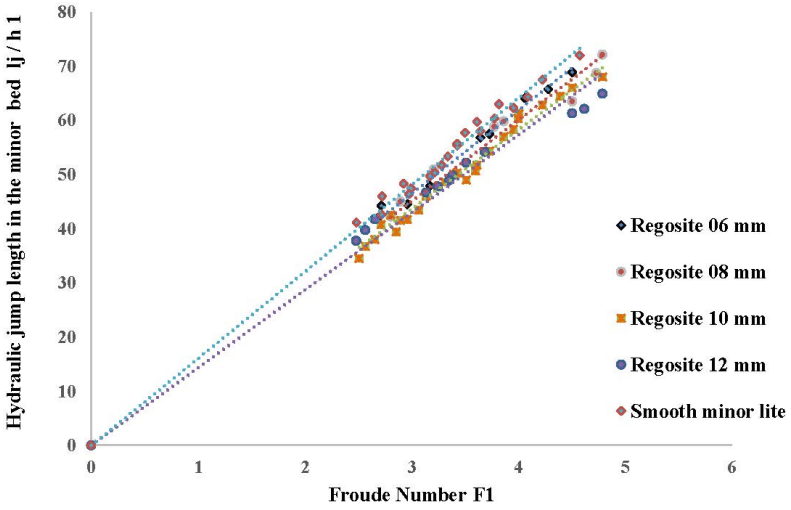

Fig. 4. Variation of hydraulic jump length in the minor bed ($0 < h_2 < 15.5$ cm) as a function of Froude number across different roughness levels.

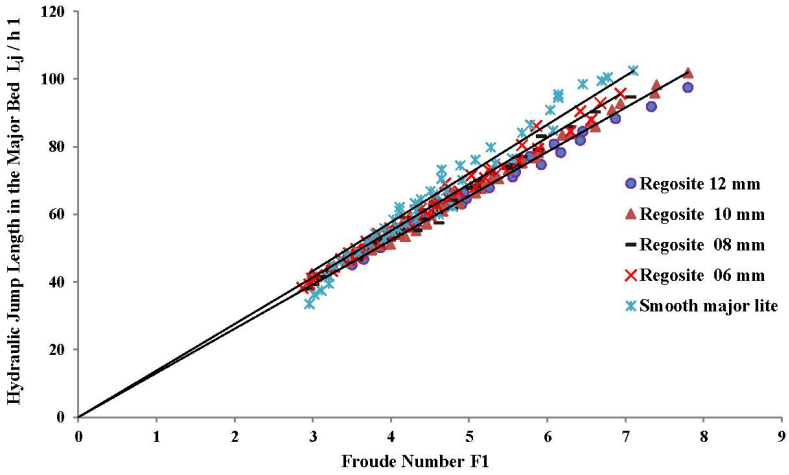

Fig. 5. Variation of hydraulic jump length in the major bed ($15.5 < h_2 < 28$ cm) as a function of Froude number across different roughness levels.

Figures 4 and 5 depict the relationship between the F_1 ratio and the Froude number (L_j/h_1) across five roughness values ($\varepsilon = 0$, 6, 8, 10, 12) for both the minor bed ($0 < h_2 < 15.5$ cm) and the major bed ($15.5 < h_2 < 28$ cm). A statistical analysis of the experimental data was performed using the nonlinear least squares method to examine how the L_j/h_1 ratio of the hydraulic jump relates to the initial Froude number (F_1). The analysis revealed a logarithmic correlation between L_j/h_1 and F_1, which can be expressed by the simplified linear equation:

$$L_j/h_1 = a\,F_1\,. \tag{2}$$

Here, the coefficient (a) varies depending on the bed type: a_1 applies to the minor bed, and a_2 applies to the major bed. The results are presented in Table 1.

Table 1. Relative roughness and regression coefficients for 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	16.019	0.9929	17.294	0.9533
6	0.041666	0.024	15.464	0.9947	16.739	0.9877
8	0.055555	0.032	15.008	0.9907	16.440	0.9889
10	0.069444	0.04	14.548	0.9912	15.916	0.9942
12	0.083333	0.048	14.323	0.9828	15.703	0.9769

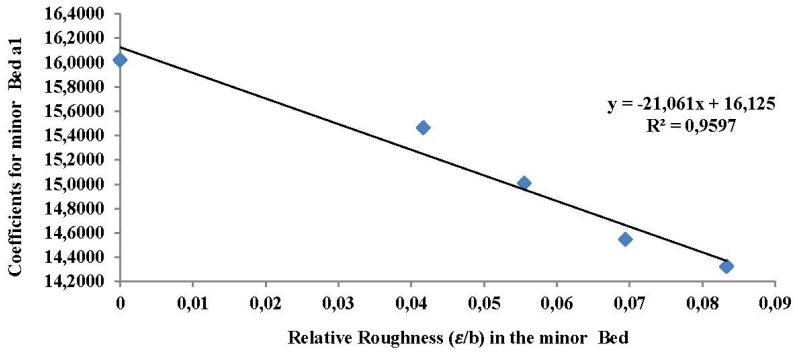

Fig. 6. Variation of the coefficient a_1 with relative roughness (ε/b) in the minor bed.

The correlation between the test measurements of the pair $(\varepsilon/b,\ a_1)$ yields the following explicit approach:

For the minor bed $(0 < h_2 < 15.5$ cm):

As a result, the general dimensionless relationship between the parameter F_1 and the ratio (ε/b) is expressed as follows:

For the minor bed:

$$4L_j/h_1 = (-33.94(\varepsilon/B) + 17.396)F_1\,. \tag{3}$$

A strong correlation appears between the pair $(\varepsilon/B,\ a_2)$ for the major bed, leading to the following equation:

For the major bed $(15.5 < h_2 < 28$ cm):

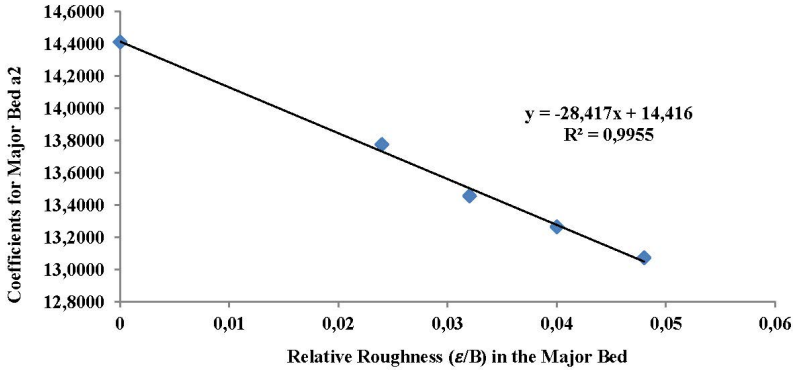

Fig. 7. Variation of the coefficient a_2 with relative roughness (ε/B) in the major bed.

Thus, for the major bed, the general dimensionless relationship between the parameter F_1 and the ratio (ε/B) is given by

$$L_j/h_1 = -28.417(\varepsilon/B) + 14.416(F_1)\,. \tag{4}$$

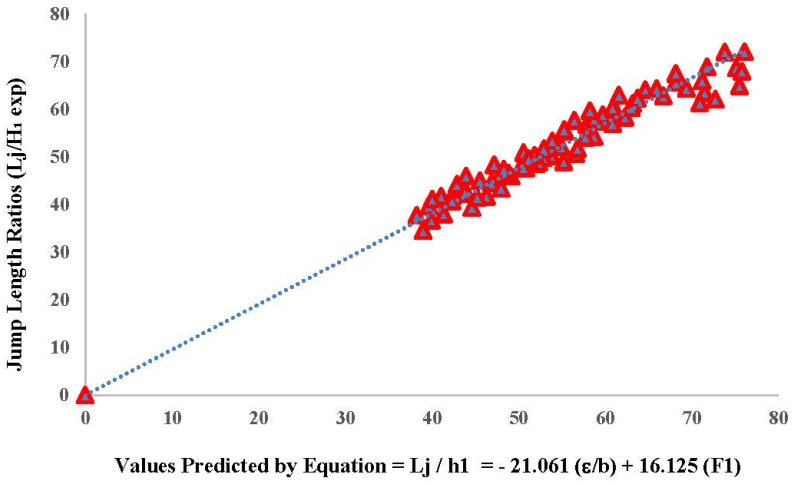

Fig. 8. Graphical illustration of the correlation between experimental jump length values $(L_j/h_1$ exp) and predictions from equation 4.

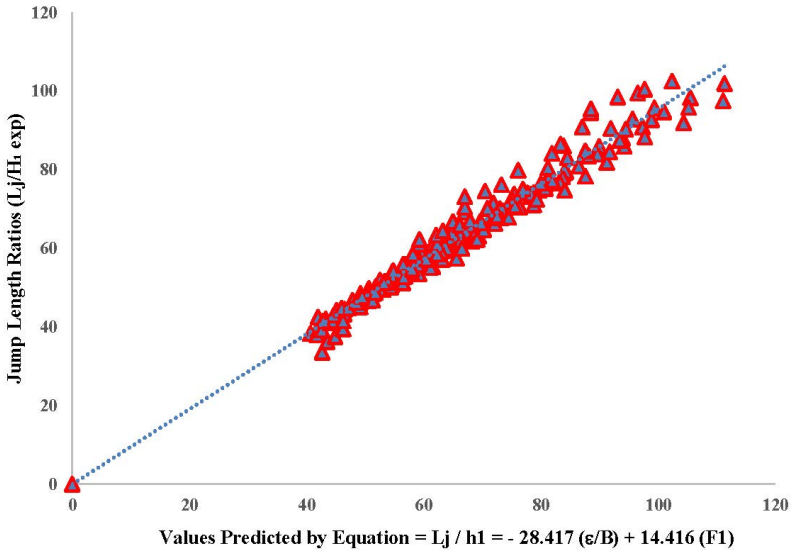

Fig. 9. Visual representation of the relationship between experimental jump length ratios $(L_j/h_1$ exp) and values predicted by equation 2.

Figures 8 and 9 confirm the comparison between the derived global approach and the experimental values. The close alignment along the bisector line in both figures validates the accuracy of the laboratory measurements that led to this dimensionless relationship.

Analysis of Fig. 10 reveals a significant disparity in the jump length ratio, L_j/h_1, between the minor bed (characterized by a narrower and shallower section, where $0 < h_2 < 15.5$ cm) and the major bed (defined by a deeper section, where $15.5 < h_2 < 28$ cm). In the minor bed, the notably lower L_j/h_1 ratio can be attributed to the heightened influence of relative roughness (ε/b). This increased roughness amplifies energy dissipation during the hydraulic jump, consequently shortening the jump length, L_j.

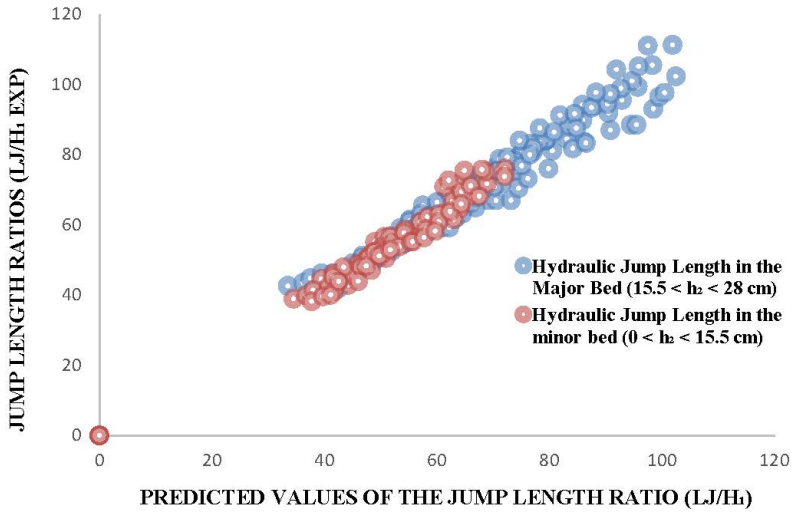

Fig. 10. Graph depicting the correlation between experimental jump length ratios (L_j/h_1 exp) and predictions from the equations for the major and minor beds.

Conversely, in the major bed, the impact of relative roughness is substantially diminished due to the larger cross-sectional area and greater flow volume. These conditions allow a higher proportion of energy to be preserved post-jump, resulting in an extended jump length, L_j.

4 Conclusion

The experimental study confirmed that increasing bed roughness significantly shortens the hydraulic jump length by enhancing turbulence and momentum transfer. This effect was particularly marked in the minor bed where the relative roughness plays a

dominant role, compared to the major bed with a larger cross-sectional area. Dimensionless empirical equations derived from the experiments show a strong correlation between the jump length ratio (L_j/h_1), the initial Froude number, and roughness parameters. These findings offer a practical basis for optimizing energy dissipation and designing efficient hydraulic structures such as stilling basins and flood management systems. Future research should explore additional flow configurations and roughness conditions to further refine these predictive models.

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