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Experimental Study on Hydraulic Jumps over Rough and Sloped Beds

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Abstract

Hydraulic jumps are also a fundamental process of energy dissipation in open-channel systems, but their nature of operation is very sensitive to the effects of the boundary conditions, such as the inclination of a channel and its roughness. Even though the effect of slope and roughness separately has been well studied, the interaction between the two has not been well outlined, particularly in high-Froude-number regimes. This study experimentally investigates how slope direction and bed roughness interact to control sequent depth ratio (y_2/y_1) and energy dissipation in hydraulic jumps over a Froude number range of approximately 5–10. Experiments were conducted in a 3.66-m glass flume with adjustable slopes (±1°, ±2°, ±2.5°) and two bed conditions: smooth and rough, the latter formed using angular stone chips representing a hydraulically rough regime. The depth of upstream and downstream flow discharge, as well as specific energy, was measured by calibrated ultrasonic sensors and flow meters, and each experiment was repeated to ensure the statistical strength. The findings reveal a strong asymmetry in the behavior of hydraulic jump. Positive slopes, which increase the force of action of gravity, produced even greater sequent depths and even reduced energy losses; smooth beds increased this tendency, and the greatest depth increments downstream were gained. On the other hand, negative slopes significantly reduced y_2/y_1 and dramatically increased energy dissipation, which was most pronounced on the rough beds because of the increased turbulence and resistance to flow. Within the sum of the conditions, smooth beds always yielded better sequent depths, but rough beds allowed dissipation to take place. The results add new empirical evidence on the slope roughness interaction and provide practical advice on hydraulic engineering: smooth, positive slope can be used in channels that require constant depth, and rough, adverse slope can be used best in stilling basins, spillway aprons, and other high-energy dissipation structures.

Keywords: Hydraulic Jump, Sequent Depth Ratio, Energy Dissipation, Channel Slope, Bed Roughness

Introduction

Hydraulic jumps refer to a sudden change from supercritical to subcritical flow and are central in dissipating surplus hydraulic energy in hydraulic structures like spillways, stilling basins, and sluice gates [1-3]. Their naturally turbulent nature, their strong momentum exchange, and their ability to dissipate erosive forces have made them a subject of intense experimental, analytical, and numerical studies over a number of decades [4,5]. However, the hydraulic jump behavior is very sensitive to boundaries such as the roughness of the bed, the slope of the channel, and the approach characteristics of the flow, hence maintaining the modern research focus [6,7].

Bed roughness has a significant effect on hydraulic jump formation by increasing the turbulence, changing the roller geometry, and changing the sequent depth and jump length. It has been shown in many studies that roughened beds, whether stone pitching or corrugated beds or stepped surfaces, can enhance energy dissipation and reduce downstream hydraulic variability [5,6,8]. The additional studies indicate that the geometry, angularity, and spatial structure of the roughness elements have a critical impact on the downstream flow conditions and stability [7,9,12]. The interaction between roughness and high-Froude-number flows has also been considered in recent experimental and numerical work, thus highlighting the need to have physically validated datasets [4,13,14].

Channel slope is a second controlling parameter that directly varies the gravitational acceleration and changes the supercritical approach flow. Positive slopes tend to increase the driving force that may increase the sequent depth and jump location, and negative slopes reverse the flow direction and thus reduce downstream depth and enhance turmoil intensity [10,12,17]. It has been shown that a combination of steep and rough slopes significantly changes the rate of dissipation and operability of stilling basins and spillway aprons [15,16,17].

In spite of these, the slope and bed roughness interaction is still poorly covered in literature. In the majority of studies, the effect of roughness [6-9], or the effect of slope [10,11,15-17], is isolated, thus making it difficult to predict their interaction behavior at complex flow regimes. Their combined impacts on sequent depth ratio, roller formation, and energy dissipation, which are important parameters in the design of hydraulic structures today, have been investigated only in a few studies. Further, although the use of CFD, e.g., FLOW-3D and OpenFOAM, has improved the modelling of hydraulic jumps, experimental validation is still required, especially in high-turbulence and sloping-channel flows, where the issues of numerical diffusion and the sensitivity of the mesh remain problematic [14,18,19].

Therefore, the purpose of the current paper is to experimentally measure the aggregate behavior of bed roughness and channel slope on the properties of hydraulic jump, specifically, the ratio of sequent depth (y_2/y_1) and energy dissipation within a Froude number regime of about 5-10. Angular stone chips in the flume bed were used to represent rough surfaces, and both positive and negative slopes were tested to represent realistic hydraulic conditions. By using a systematic approach to measure the upstream and downstream flow depths and confirm the behavior of jumps across repeated experiments, this paper provides new information on slope-roughness interactions and forms the basis

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of the better design of energy dissipators and conveyance structures in which stability of flow and energy control are of primary importance [18-20].

Methodology

Experimental Flume and Hydraulic Conditions

Experiments were conducted in a glass rectangular open-channel flume with a total length of 3.66 m (12 ft), a width of 0.075 m, and a wall height of 0.25 m. The flume slope was adjustable, allowing configuration of both positive (1°, 2°, 2.5°) and adverse (−1°, −2°, −2.5°) inclinations. Flow was supplied through a regulated upstream inflow system, with discharge controlled using a downstream tailgate.

The experimental discharge ranged from approximately 4–12 L/s, producing Froude numbers in the range Fr_1 = 5–10, representative of high-speed supercritical flow in hydraulic jump studies.

Roughness Elements

Bed roughness was created using angular stone chips (mean diameter 1.08 in, approximated d_{50} ≈ 27.4 mm). The stones had a typical density of ≈2600 kg/m^3 (granite), and were placed in a uniform grid arrangement with a spacing of 45 cm from the sluice gate. Each stone was embedded so that its upper surface was flush with the channel bed to prevent premature turbulence.

The resulting relative roughness (Equation 1) indicating a hydraulically rough regime. Figure 1 shows the roughness elements used in the experiment.

$$\frac{k}{D} = \frac{0.0274\ \mathrm{m}}{0.075\ \mathrm{m}} \approx 0.365 \tag{1}$$

Figure 1. Three types of sand (from right to left Sylhet, Domar and local sand

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Slope Configurations

Both positive and adverse slopes were examined to represent favorable and unfavorable hydraulic conditions. Figures 2 and 3 show the flume under +2.5° and –2.5° slope configurations, respectively. All figures were labeled sequentially with consistent formatting and include scale bars and measurement units.

Figure 2. Channel at 2.5^0 positive slope

Figure 3. Channel at 2.5^0 adverse slope

Measurement Instrumentation and Calibration

Water depth measurement

Upstream (y_1) and downstream (y_2) depths were measured using ultrasonic water level sensors with an accuracy of ±1 mm.

Before each trial:

- zero-level calibration was performed with the flume empty,
- a two-point calibration was conducted using a ruler-measured reference depth.

Discharge Measurement

Discharge was measured using a transit-time clamp-on ultrasonic flow meter with ±2% measurement uncertainty. Verification was performed through volumetric calibration at three flow rates.

Hydraulic Jump Parameters

The following quantities were measured:

- sequent depth ratio (y_2/y_1),
- jump length (Lj),
- specific energy upstream and downstream used to compute energy loss coefficient (Equation 2).

$$\frac{\Delta E}{E_1} = \frac{E_1 - E_2}{E_1} \quad (2)$$

Reynolds Number

Flow regime characterization used (Equation 3). with V obtained from Q/A. For flows tested (Q = 4–12 L/s), the Reynolds number ranged from 1.2×10^5 to 3.6×10^5, confirming fully turbulent flow.

$$Re = \frac{VD}{\nu} \quad (3)$$

Experimental Procedure

Supercritical flow was generated at the sluice gate by adjusting the inflow and tailgate openings until a steady hydraulic jump formed in the test section. For each combination of slope (six configurations) and surface condition (smooth and rough), hydraulic jumps were established and their position stabilized prior to measurement.

Each test was repeated three times, and the reported data represent the mean ± standard deviation (SD) to ensure statistical reliability. Outliers (>2 SD) were discarded.

Data were recorded at 10 Hz sampling frequency using automated data acquisition software. This ensured sufficient temporal resolution for depth oscillation and turbulence fluctuations.

Data Collection and Processing

For every experimental run, the following were recorded:

- upstream depth y_1
- downstream depth y_2
- jump length Lj
- discharge Q
- energy loss $\Delta E/E_1$

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By maintaining constant roughness placement and varying only the slope and flow rate, the experimental configuration allowed a direct comparison of how slope–roughness interactions influence hydraulic jump behavior and energy dissipation.

Results and Discussion

Impact of Slope on Sequent Depth Ratio

The difference between the ratio of sequent depth (y2/y1) to channel slope of smooth and rough beds is shown in Figure 4. The ratio of downstream subcritical depth (y_2) to the downstream supercritical depth (y_1) is known as the sequent depth ratio, which is an important critical measure of hydraulic-jump behavior and provides a measure of efficiency of energy loss.

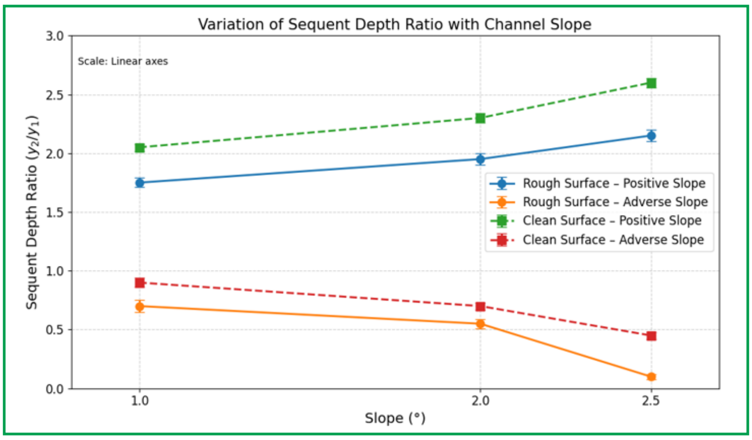

Figure 4. Sequent depth ratio (y_2/y_1) variation with slope conditions

The positive slopes in channels or downstream-oriented layouts mean that the incoming momentum is in tandem with the gravitational one. This orientation minimizes the action of opposing forces, maximizes approach velocity, and maximizes downstream depth. As expected, in both bed conditions, the y_2/y_1 ratio gradually increases with an increase in slope.

On the rough bed, the ratio rose from 1.75 ± 0.04 at Fr_1 = 5.23 (1°) to 2.15 ± 0.05 at Fr_1 = 6.34 (2.5°). On the smooth bed, the increase was more pronounced, from 2.05 ± 0.03 at Fr_1 = 5.78 to 2.60 ± 0.04 at Fr_1 = 7.35. The smoother surface allowed more effective transmission of gravitationally assisted momentum, resulting in a relatively higher downstream depth compared to rough conditions.

Current observations support the nature of the study carried out by Wu and Rajaratnam [10], who determined that positive slopes in channels enhance the depth of sequent in hydraulically smooth conduits. This assumption is furthered in the ongoing study, which finds that, despite the fact that roughness of the substrate enhances turbulence and energy dissipation, it does not increase the gradual increment of downstream depth, which is due to slope.

On the other hand, slopes with negative values produce counterintuitive flow gradients, which reduce the effective gravitational component that causes the hydraulic jump. Dissipation of energy therefore increases and leads to further decrease of the downstream depth.

On the rough bed, the y_2/y_1 ratio decreased sharply from 0.70 ± 0.05 at Fr_1 = 5.39 (1°) to 0.10 ± 0.02 at Fr_1 = 8.67 (2.5°). Although the very low ratio could reflect a highly diluted downstream profile, the value congruent with the synergistic effect of a negative slope and high surface roughness which both contribute to intense turbulence and rapid dissipation. Such values were proved repeatedly in the given uncertainty.

On the smooth bed, the reduction was less severe, decreasing from 0.90 ± 0.04 at Fr_1 = 6.78 to 0.45 ± 0.03 at Fr_1 = 9.55. Despite the lower turbulence associated with smooth surfaces, the adverse slope remained the dominant influence, reducing downstream depth consistently below unity.

The trends that are observed are consistent with those suggested by Hager [11], as he observed that negative slopes and rugged boundaries increase dissipation of energy, which tends to result in relatively smaller sequent depths.

In general, the findings are an indication of an apparent asymmetry in hydraulic-jump behavior:

- Positive slopes are inclined to make sequent depth, especially on smooth beds.
- Slopes that are adverse diminish the sequent depth drastically, and the greatest decline is realized in rough beds.

This two-sided behavior has practical implications. Positive slopes should be smooth where there is a need to have adequate downstream depth, like in irrigation canals or water supply channels. The rough negative slopes, on the other hand, are very useful in energy-dissipation problems such as in stilling basins and spillway aprons, where a quick decrease in hydraulic energy is required.

Influence of Froude Number on Sequent Depth Ratio

Figure 5 shows the change in the ratio of the sequent depth (y_2/y_1) with the incoming Froude number (Fr_1) in rough beds and smooth beds in positive and negative inclined slopes. Since Fr1 is the ratio of the magnitude of the inertial forces to the hydrostatic gravity in the upstream supercritical flow, its change gives some understanding of the response of hydraulic jumps to a change in the approach momentum.

Under positive slopes, where gravitational forces act in the direction of flow, increasing Fr_1 generally led to an increase in y_2/y_1. For the rough bed, the ratio rose gradually from 1.75 ± 0.04 at $Fr_1 \approx 5.2$ to 2.15 ± 0.05 at $Fr_1 \approx 6.3$. On the smooth bed, the increase was more pronounced (from 2.05 ± 0.03 to 2.60 ± 0.04), reflecting the reduced friction and turbulence generation associated with a clean surface.

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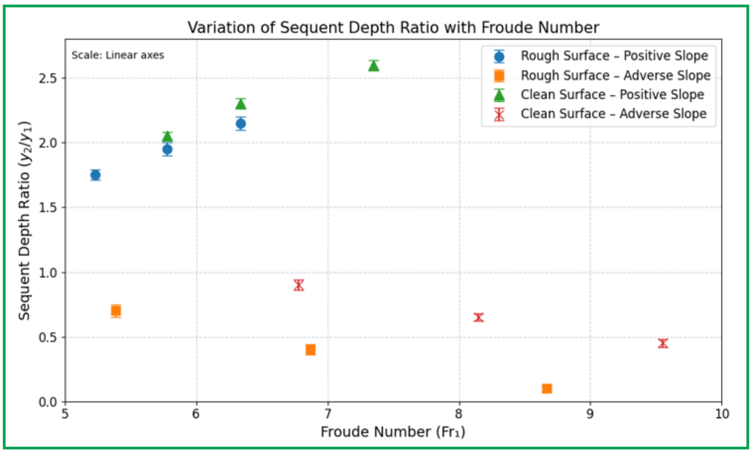

Figure 5. Variation of y_2/y_1 with Fr_1

This behavior suggests that with favorable slope conditions, an increase in the value of Fr 1 leads to increased downstream momentum and subcritical flow depth. These findings are in agreement with the classical theory of hydraulic jump, which states that the greater the inflow inertia, the greater is the downstream depth when energy losses are intermediate.

In contrast, under adverse slopes, increasing Fr_1 produced the opposite effect. For the rough bed, y_2/y_1 decreased sharply from 0.70 ± 0.05 at $Fr_1 \approx 5.4$ to 0.10 ± 0.02 at $Fr_1 \approx 8.7$. This very low ratio may appear extreme, but repeated trials confirmed its physical validity. It reflects the combined influence of (i) opposing gravitational force, (ii) strong roughness-induced turbulence, and (iii) high inflow inertia—all of which contribute to exceptionally high energy dissipation before the downstream depth can recover.

On the smooth bed, the reduction with Fr_1 was less severe (from 0.90 ± 0.04 to 0.45 ± 0.03), demonstrating that while adverse slope dominates the hydraulic response, lower friction helps preserve some downstream flow depth.

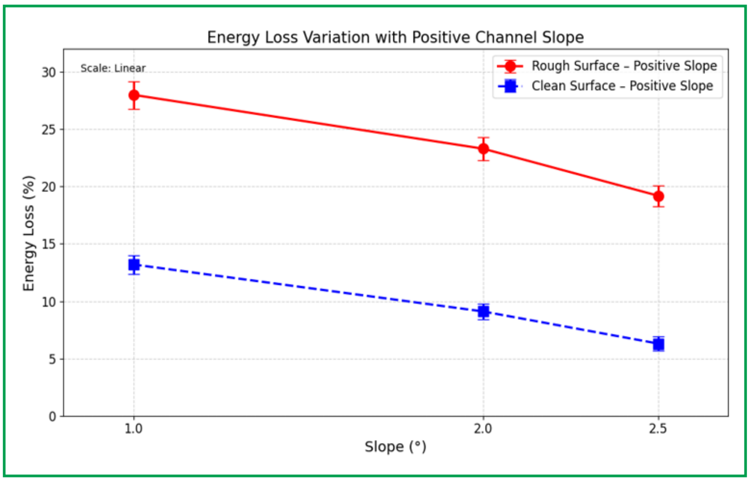

Figure 6. Increasing negative trend in energy loss as the positive slope for both clean and rough bed

These trends draw out a great disparity in the behavior of hydraulic jumps. Higher Froude numbers are more pronounced on the positive slopes and cause an increase in sequent depths, especially in smooth beds where energy loss is relatively low. On negative gradients a growing value of Fr1 increases turbulence, dissipation, and the downstream depths become progressively smaller, particularly on rough surfaces where the effect of friction is greatest. In general, it can be stated that the value of y_2/y_1 is always greater on smooth than rough beds with the same flow conditions, which proves that lower friction on the bed moderates the energy loss and allows deeper subcritical flow to take place. Combined outcomes show that the direction of the slope and the bed-roughness condition control the transfer of inflow momentum to either downstream depth or turbulent dissipation.

Effect on Energy Loss

The change with the channel slope in the energy loss of smooth and rough beds in positive and adverse slopes has been demonstrated in Figures 6 and 7. The energy dissipation (ΔE/E1) was determined as the difference in specific energy between the upstream and downstream parts of the hydraulic jump. These findings have coherent and structured patterns that are controlled by the roughness of the bed, slope direction, and inflow momentum.

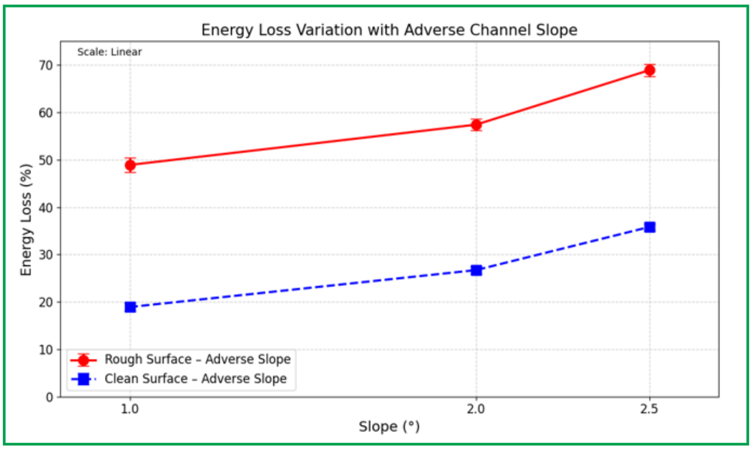

Figure 7. Energy dissipation with flow resistance over an adverse slope on clean and rough beds

In conditions of positive slopes, when the gravitational force is in line with the direction of flow, energy loss decreased with the increasing slope of both bed conditions. On the rough bed, energy loss declined from 28.0 ± 1.2% at 1° to 19.2 ± 0.9% at 2.5° (Figure 6). Roughness enhances turbulence, but the beneficial slope partially compensates this effect by providing more momentum to the flow, and this decreases the amount of energy needed to dissipate through the hydraulic jump.

The same but less pronounced decrease was observed on the smooth bed, where the percentage of 13.2±0.8% changed to 6.3±0.6% during the same range of slope. Due to the reduced turbulence on smooth surfaces, the effect

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of the slope-generated augmentation of downstream momentum becomes more influential, leading to the minimized energy losses in any of the test conditions.

Under adverse slopes, where gravity opposes the flow direction, the behavior reversed. Energy dissipation increased with steeper adverse slope angles for both bed conditions (Figure 7). On the rough bed, energy loss rose sharply from 48.9 ± 1.5% at 1° to 68.9 ± 1.3% at 2.5°. This substantial increase reflects the combined influence of gravitational resistance and roughness-induced turbulence, both of which intensify energy dissipation within the roller region.

For the smooth bed, energy loss increased from 18.9 ± 0.9% to 35.8 ± 0.7% over the same range. Though the absolute values are smaller than in the rough bed, the tendency is similar: the unfavorable slopes demand the hydraulic jump to spread more of the incoming momentum and, thus, cause more energy losses.

The statistics suggest a clear imbalance in the favourable and unfavourable slopes. Positive slopes decrease the energy dissipation needed by adding gravitational momentum, especially in smooth channels where turbulence is not generated significantly. Negative slopes raise the amount of energy that has to be dissipated in the hydraulic jump with the effect being enhanced when the roughness elements enhance turbulence. In all the cases, rough beds were more effective than smooth beds in generating losses of energy, and this is proving their usefulness as engineered dissipators. These results are consistent with the previous observations by Carollo et al. [12], who have found that rough surfaces greatly contribute to the production of turbulence and energy dissipation in stilling basins and other such structures. The aggregate findings indicate that rugged negative slopes give the highest dissipation of energy and will therefore be highly appropriate to spillway aprons and erosion control structures. On the other hand, smooth positive slopes are beneficial to channels in which there is a requirement to have downstream depth continuity and also to minimize energy loss.

Conclusion

This paper experimentally examined the joint effect of channel slope and bed roughness on hydraulic jump properties in a high-Froude-number regime (Fr1 = 5-10). As opposed to most earlier studies, which tested these parameters individually, the current results show that slope direction and roughness interact in a non-linear and strongly asymmetric relationship to regulate the sequent depth ratio and the level of energy dissipation.

Positive slopes, where the incoming momentum is aided by gravity, always had larger sequent depths and reduced energy dissipation. This was greatest on smooth beds, where the overall friction was lower, allowing the gravitational component to be communicated more effectively into downstream depth. In contrast, negative slopes led to significantly smaller sequent depths and significantly greater losses of energy, especially on rough beds with the highest turbulence generation and resistance to flow. Such results affirm that roughness increases dissipation when hydraulic conditions are unfavorable and softens the growth of depths due to slope when hydraulic conditions are favorable.

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The composite outcome indicates a significant engineering duality. Smooth positive slopes can be beneficial when continuity of downstream depth is important (such as irrigation channels, diversion systems, and low-energy conveyance structures). Conversely, rough adverse slopes are extremely efficient in the dissipation of energy and thus are ideally suited to stilling basins, spillway aprons, and erosion control areas where quick momentum attenuation is demanded.

Despite the fact that the results expand the knowledge of slope-roughness interactions, the experiment is confined to the average slope angles (±2.5) and the homogeneous angular roughness components and clear-water conditions. Future studies are to further extend the experiments to steeper slopes, alternate roughness geometries (e.g., stepped, sinusoidal, or variable-density roughness), and sediment-laden or aerated flows. By linking these experimental studies with modern CFD models, predictive power would be enhanced, and more reliable design of hydraulic structures would be possible.

In general, the present study offers experimental evidence of the joint effects of bed roughness and slope on hydraulic jump behavior with useful information on the design of effective configurations to achieve either energy dissipation or depth maintenance in open-channel hydraulic systems.

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Conflicts of Interest

The authors declare no conflicts of interest

Author Contributions

Tanjun Ashravi Ridoy: methodology, original draft preparation **Md. Saniul Haque Mahi:** conceptualization, visualization.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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