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Research Article

Evaluation of hydraulic jump characteristics in rough sloping surfaces for sustainable environment: A laboratory investigation

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ABSTRACT

Hydraulic jumps occur in various hydraulic structures such as stilling basin and energy dissipaters. By studying the effect of gravel bed material size on hydraulic jump characteristics, researchers can gain insights into how to enhance energy dissipation and reduce the impact of hydraulic jumps on channel stability, erosion, and sediment transport. This research can contribute to more environmentally friendly and sustainable hydraulic designs. In this research experiment was performed on rapidly varied flow test setup for four different channel slopes varied from 0° to 6° and three different gravel bed material sizes (10 mm, 20 mm and 30 mm). Over the course of experiment, the Reynolds number varied from 5500 to 26500 and the Froude number varied from 2.45 to 8.75. Using a novel intuitive technique, correlations were created for various hydraulic jump characteristics in rough sloping channels by first accounting for the inflow Reynolds number. A rise in roughness height results in an average drop of relative jump height of about 16.21%, while the average reduction when compared to a classical jump is approximately 67.25%. For gravel bed material sizes of 10 mm, 20 mm, and 30 mm, respectively, the average increase in relative energy dissipation was determined to be about 32.47%, 48.32%, and 58.02% for the rise in slope of channel from 0° to 6°.

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INTRODUCTION

Hydraulic jumps play a significant role in various hydraulic engineering applications, including spillways, energy dissipators, and stilling basins. Understanding the characteristics and behavior of hydraulic jumps is crucial for designing efficient and stable hydraulic structures [1-3]. Hydraulic jumps are encountered in various applications; including irrigation systems, open channels, and wastewater treatment plants. Hydraulic jumps occur when high-velocity, torrential flow transitions to low-velocity, tranquil flow. The sudden and abrupt energy dissipation in hydraulic jumps is crucial for preventing downstream flooding, reducing erosion, and maintaining channel stability [4-5]. Understanding the impact of gravel bed material size on the hydraulic jump can aid in optimizing the performance and efficiency of these systems. By manipulating the gravel bed material size, engineers can potentially enhance

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energy dissipation, reduce turbulence, and minimize maintenance requirements, leading to cost savings and improved system operation. Gravel bed materials, such as rocks and sediments, can significantly affect the hydraulic jump's behavior due to their ability to dissipate energy and modify flow patterns. The size and arrangement of the gravel bed materials are key factors that influence the hydraulic jump's efficiency and stability [6-8]. Many researchers have performed experimental [9-13] and numerical simulation [14-16] to predict hydraulic jump characteristics in rough surfaces.

Nikmehr et al. [17] performed experimentation with both smooth as well as rough bed on adverse slope to predict the jump length and loss of energy due to formation of subcritical flow. Experimentation was performed on four different channel slopes for both cases. The findings demonstrated that for the identical slopes and Froude numbers, the length of jump and the depth ratio were higher on a smooth bed than they were on a rough bed. However, compared to smooth beds, rough beds lost more energy. Kumar et al. [18] performed experimentation of sloping rough surfaces at three different slopes and five different roughness heights. The data analysis showed that the properties of a hydraulic jump in sloping channels were not considerably impacted by bed roughness heights. However, the parameters were greatly impacted by the channel's slope. In a hydraulic jump on a rocky bed, air-water flow was examined by Bahmanpouri et al. [19]. The discharge during experimentation was varied between 0.06 m^3/s to 0.1 m^3/s. The void proportion and bubble measure rate, among other fundamental two-phase flow metrics, are presented. The mean void percent on the roughen bed was larger than on uniform bed near to the toe of the jump, despite the fact that larger magnitudes were found on the smoother bed further downstream. Ahmed et al. [20] performed experimentation on corrugated bed to predict the different parameters of submerged jump. Experimental research has been done to determine how a spaced triangular segment corrugated bed affects submerged jump behaviours. A broad range of Froude numbers fluctuated from 1.68 to 9.29 was taken into account in thirty experimental runs. The results show that, in comparison to a classical jump, at the ideal spacing roughness, subsequent depth and length of jump were decreased on average by 15% and 21%, while efficiency of jump raised by 50.31%. Felder et al. [21] performed experimentation on macroroughness with uniform bed to predict the air-water flow pattern jump phenomenon. Hydraulic jumps on rougher beds differed noticeably from jumps on smoother beds in a number of ways, including a clean hydro-flow zone beneath the jump and an upward movement of the roller of the jump. A phase-detection probe was used to test the air-water flow, and the results showed that the parameters of the air-water flow were distributed similarly for the smooth and rough bed jumps. The inclusion of macroroughness may be a practical method to enhance flow aeration and bubble break-up in industrial applications where air-water transfer of mass operations and mixing techniques are critical. According to research on depth ratio correlations, adding macroroughness that is uniformly distributed may have additional benefits, such as reducing flow energy. Pourabdollah et al. [22] evaluated various jump qualities on three beds with varying levels of roughness and slope. Based on the result, the subsequent depth ratio decreased and the relative energy loss increased, respectively, by 33% and 27.41% more in comparison to the conventional jump. For calculating the depth ratio, two novel analytical methods were created applying the momentum formula linked to other fundamental fluid mechanics equations. As a consequence of the experimental conditions, a novel analytical method was also developed to determine the relative energy loss. The outcomes also showed that the two analytical methods for calculating the depth ratio had maximum errors of 15 and 20 percent, respectively. Again Pourabdollah et al. [23] performed investigation on step with adverse slope using stilling basin to control the hydraulic jump. Four negative slope and three favourable steps were utilized during the experimentation. For estimating the depth, an analytical method based on the momentum principle was created, and its predictions were contrasted with the experimental observations. The effects of both the negative slope and the favourable step diminished the depth ratio, length of jump, and length of rollers more than the traditional jump, but the adverse slope's effect was more than the favourable step's. Energy loss was larger than in the standard conditions when there was an unfavourable slope and a positive step. Palermo et al. [24] investigated the energy dissipation in rough surfaces and developed semi analytical method for dissipation of energy in sloped channel rough bed. Two standard models were developed to assess the relative dissipation of energy under various geometric conditions and hydraulic parameters. The suggested standard equations were analytically developed, and they are unaffected by the method used to determine the depth ratio. Yonesi et al. [25] experimented on vertical drop having horizontal screen to predict the energy loss on both smooth and rough bed. Two porosity distributions of screens were used in the experiments, with aggregates having an average size of 1.9 cm, and a relative critical depth of 0.13 to 0.39. The findings demonstrate that the relative flooded length of screens rises as supercritical Froude number and screen porosity decrease. Daneshfaraz et al. [26] looked into the hysteretic action of torrential flow in channel laboratory on smooth and rough bed in horizontal channel. According to the findings, various flow behaviours can be seen for the same laboratory conditions by initially raising the rate of flow and then reducing it. With enhancing flow situation, the relative jump depth reveals tranquil flow regime, while reducing the flow reveals torrential behaviour for the same situations. Additionally, the material's average diameter increase causes the flow's hysteretic behaviour to become more pronounced. Bejestan et al. [27] investigated various jump characteristics with dune bed arrangement on horizontal channel. They considered dune bed as similar to roughen bed. The findings indicate that, in general, dune-covered beds have smaller relative jump length (38.4%) and depth ratio (26.5%) also. Gupta et al. [28] developed empirical correlations for different jump characteristics in rough sloping surfaces. Their findings indicated that energy loss rises by approximately 29.67% on average with the rise in roughness height and by approximately 78.66% on average when compared to a conventional jump. Simsek et al. [29] experimentally analyzed high Froude number hydraulic jump with sill arrangement. The relative height of sill varied from 4 to 13. Their findings demonstrated that as the sill height decreases, the hydraulic jump's length grows. An increase in sill height reduces the energy dissipation in the stilling basin.

In particular, the impact of gravel bed material size on the relative height and energy dissipation of roughen bed sloped channel hydraulic jump remains an important yet underexplored area of research. This study aims to investigate the impact of gravel bed material size on hydraulic jump characteristics, with a focus on relative height and dissipation of energy. Although a great deal of study has been done on hydraulic jumps, there is a lack of comprehensive understanding regarding the specific effects of gravel bed material size on relative height and energy dissipation in sloped channels. Most existing studies have focused on smooth channels without considering the influence of bed materials. However, in practical engineering scenarios, sloped channels often contain gravel bed materials, which can substantially alter the hydraulic jump's characteristics. Former researchers disregarded the impacts of Reynolds number without providing a valid justification, believing hydraulic jump features to be solely dependent on the Froude number. In this paper effects of gravel bed material size on relative height and energy dissipation of hydraulic jump studied experimentally and correlations are developed considering the effects of inflow Reynolds number (Re_1), channel slope (θ), inflow Froude number (Fr_1), and relative roughness height (h/d_1) first time as a novel approach.

The outcomes of this research will have practical implications for hydraulic structure design, energy dissipation optimization, and environmental sustainability. By uncovering the relationships between gravel bed material size, relative height, and energy dissipation, engineers and designers can make informed decisions regarding the selection and arrangement of gravel bed materials to enhance the performance and stability of hydraulic systems.

INVESTIGATION OF HYDRAULIC JUMP IN SLOPING CHANNEL WITH GRAVEL BED MATERIALS

Analytical Analysis

The formation of hydraulic jump in sloping channel with gravel bed materials is shown in Fig. 1. The momentum formula is used to describe the hydraulic jump formation in sloping surfaces with gravel bed materials. A lot of assumptions are required to solve the momentum equation because it has various unknown terms. The term Wsinθ which represents jump water weight can not be obtained analytically. It requires experimentation.

Utilising the momentum concept, the shear force (F_τ) on a sloped channel with gravel bed materials may be calculated. Momentum equation is represented by Eq.1 using the terminologies of Figure1.

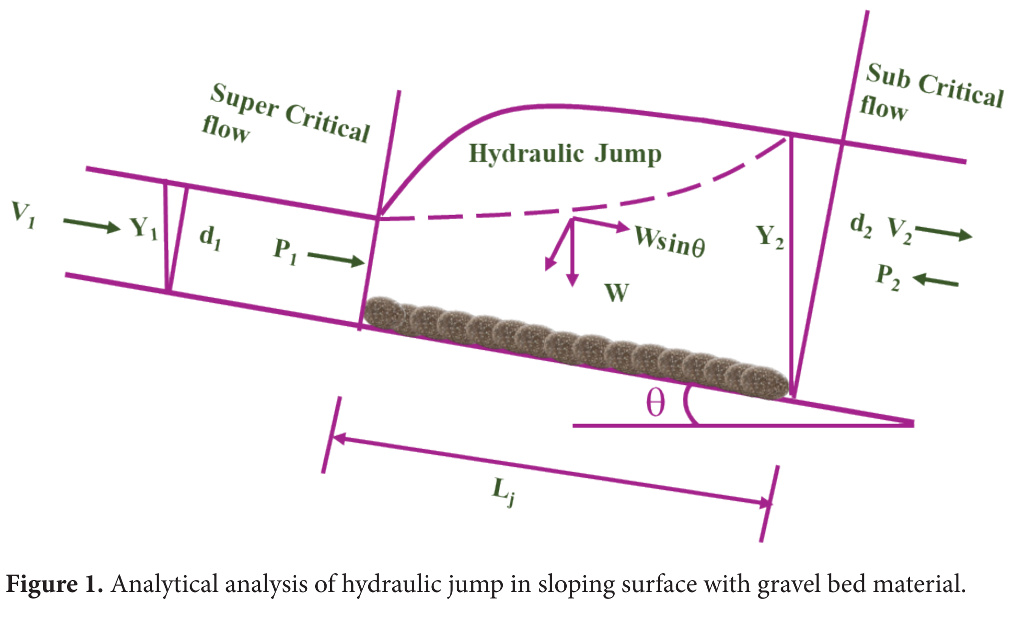

Figure 1. Analytical analysis of hydraulic jump in sloping surface with gravel bed material.

$$P_1 - P_2 + WSin\theta - F_\tau = \rho Q(V_2 - V_1) \quad (1)$$

Where $P_1 = \frac{1}{2}\gamma b d_1^2 \cos\theta,\ P_2 = \frac{1}{2}\gamma b d_2^2 \cos\theta$

Eq. 2 can be used to express the bed shear force (F_τ) [30]

$$F_\tau = \frac{1}{2}\gamma b \varepsilon d_1^2 \cos\theta \quad (2)$$

The weight of water in the jump is represented by Eq. 3 as [31]

$$W = \frac{1}{2}\gamma b L_j (d_1 + d_2) \quad (3)$$

The weight of water (W) involves the longitudinal profile on hydraulic jump since it includes length of the jump. The relative height of jump in sloping surface is represented by Eq. 4 as

$$\frac{H_j}{d_1} = \frac{d_2 - d_1}{d_1} = \frac{d_2}{d_1} - 1 \quad (4)$$

The energy dissipation in sloping surfaces is represented by Eq. 5 as

$$\frac{E_L}{d_1 \cos\theta} = \frac{E_1 - E_2}{d_1 \cos\theta} \quad (5)$$

Where

$$E_1 = d_1 \cos\theta + \frac{V_1^2}{2g} + L_j \sin\theta \quad (6)$$

$$E_2 = d_2 \cos\theta + \frac{V_2^2}{2g} \quad (7)$$

Dimensional Analysis

Dimensional analysis was performed using Buckingham's π theorem [32]. The variables which are affecting jump pattern in sloped channel with gravel bed materials are given as Eq. 8

$$f_1(d_1, d_2, V_1, E_L, h, \rho, g, \mu, \theta) \quad (8)$$

Total number of variable in dimensional analysis is nine and these nine variable contain three fundamental dimensions therefore these nine variables are formed 6 dimensionless group called π terms say π_1, π_2, π_3, π_4, π_5 and π_6 which is represented by Eq. 9. Three variables are repeated in each π term which is d_1, V_1 and ρ.

$$f_2\left(\frac{d_2}{d_1}, \frac{E_L}{d_1\cos\theta}, \frac{V_1^2}{g d_1 \cos\theta}, \frac{\rho V_1 d_1 \cos\theta}{\mu}, \frac{h}{d_1}, \theta\right) = 0 \quad (9)$$

From Eq. 9, it was observed that the relative height and energy dissipation are depends on Fr_1, Re_1, relative height of roughness (h/d_1) and slope of bed (θ) which is represented by Eq. 10 and 11 as

$$\frac{H_j}{d_1} = f_3\left(Fr_1, \mathrm{Re}_1, \frac{h}{d_1}, \theta\right) \quad (10)$$

$$\frac{E_L}{d_1\cos\theta} = f_4\left(Fr_1, \mathrm{Re}_1, \frac{h}{d_1}, \theta\right) \quad (11)$$

EXPERIMENTAL METHODOLOGY

The experimentation was performed in rapidly varied flow test setup at four channel slope (0^0, 2^0, 4^0, 6^0) and four gravel bed material height (0 mm, 10 mm, 20 mm and 30 mm) at Fluid Machinery Laboratory of Institute of Engineering and Technology, GLA University, Mathura, India. A steeper slope increases the likelihood of erosion and sediment transport within the channel. A slope beyond 6° may lead to instability, causing the channel bed to erode more easily and compromising the overall stability of the channel. Because of the limitation of the experimental set-up, it is not possible to perform experimentation beyond 6°. The line diagram of rapidly varied flow test setup is shown in Figure 2.

To form the requisite roughness, gravels are installed throughout the bed. The supercritical flow ($Fr_1>1$) in flume is created by sluice gate and subcritical flow ($Fr_1<1$) is created by operating the tail gate. Corrugations created turbulent eddy and acted as recesses in the bed, which could have increased the bed shear forces. The main tank receives water from the holding tank through a centrifugal pump. A gravel box in the head tank is used to distribute the flow of water evenly across the flume. A regulating valve is fitted on the main supply pipe line directly prior to the head tank to regulate the water flow rate. Outside walls made of acrylic sheeting are used for picturing the jump's beginning and ending places. The top of the outside walls are where the Ultrasonic US30 data logic sensor, having an operating range of 10-100 cm and an accuracy of 0.1 mm, is mounted. This sensor measured the depth at several locations along the channel's length and width as it glided smoothly down the rails. The discharge in the flume was determined with an ultrasonic discharge measuring instrument, offering an accuracy range of 0.75% to 1.10%. A tail gate regulates the downstream water depth to produce jumps over the rigid bed. The water then flowed to the by-pass channel. For each gate opening, initial depth, depth after the jump,

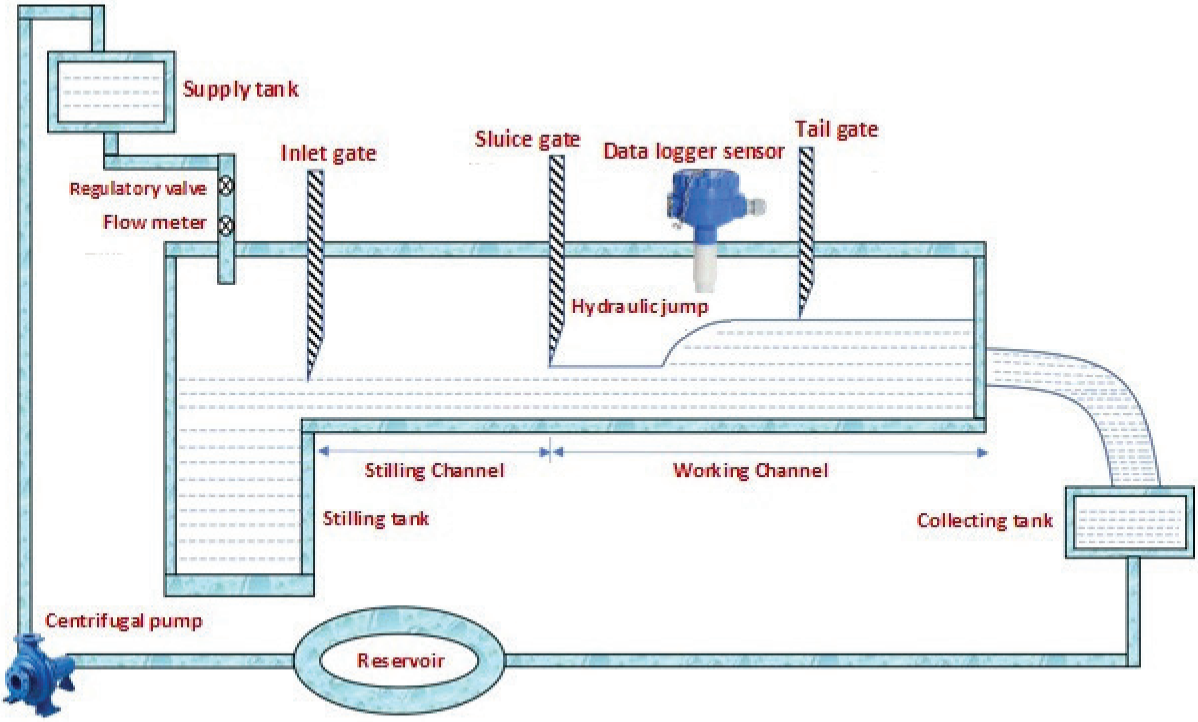

Figure 2. Line diagram of experimental set-up.

Figure 3. Arrangement of gravel bed materials and the formation of hydraulic jumps in the channel.

and jump length are measured at several slope of bed and gravel bed materials height. For each case 35 data are collected. A visual representation of the arrangement of gravel bed materials and the formation of hydraulic jumps in the channel is illustrated in Figure 3. The errors involved in the instrument and measurement of jump characteristics is given in Table 1.

Gravel bed material size is chosen after the sieve analysis which was performed in soil testing laboratory. 175 granular samples were used to analyse the grain-size composition for every gravel bed. Examining all three dimensional measurements of every pebble, the diameter functioned as the average value. Grain-size dispersion was defined by d60, the dimension of the bed pebble that is

Table 1. Error involved in the instrument and measurement of jump characteristics

S. No.	Instrument/ Measurement of Jump characteristics	% Error
1	Ultrasonic US30 data logic sensor	0.15%
2	Ultrasonic discharge (flow) meter	0.75% to 1.10%
3	Relative height of jump (H_j/d_1)	±10%
4	Relative energy dissipation (E_L/E_1)	±10%

60% finer than the remainder of the bed grains. The analysis involves passing a sample of the gravel bed material through a series of sieves with different-sized openings. The sieves are stacked with the finest sieve at the bottom and coarser sieves above in ascending order. The material is subjected to mechanical shaking, and particles smaller than the sieve openings fall through while larger particles are retained. D60 sieve analysis allows identifying the median particle size of the gravel bed material, complementing the focus on specific sizes (10 mm, 20 mm, 30 mm). This helps in capturing a more nuanced and inclusive representation of the particle size distribution, including finer and larger particles that may be present in natural settings. It enhances the study's ability to account for the broader spectrum of particle sizes, leading to a more robust and applicable understanding of gravel bed dynamics and sediment transport in natural environments. The gravel size average diameter was used to compute the height of the roughness (h).

In experimentation, a more comprehensive description of air entrainment is necessary due to its sensitive nature caused by scale effects. Hydraulic jump research usually employ the Froude similitude, which results in emulate Reynolds estimates that are lower than actual structure. Therefore, the dual-phase flow properties may be affected by scale effects [33-34]. Chanson conducted a comprehensive experimental analysis of the topic, looking at the scale implications of turbulence in air-water entrapment in hydraulic systems [35]. A comprehensive experiment was conducted by Wang and Chanson to ascertain the scale effect [36]. According to the laboratory investigation, if $b/d_1 > 10$, there is little scale effect on the air-water flow properties. For most of the tests conducted in this research, this constraint is applicable. Thus, the present laboratory findings do not show the scale effect.

RESULTS AND DISCUSSION

Relative Height of Jump

From π- theorem, it was observed that the Froude number (Fr_1), Reynolds number (Re_1), relative height of roughness (h/d_1) and slope of bed (θ) all influence the relative height of jump (H_j/d_1). Figure 4 represents the variation of H_j/d_1 with Fr_1, h and θ. The average value of relative height (H_j/d_1) of jump at different roughness height and bed slope is shown in Table 2. It was observed from Figure 4 that H_j/d_1 increases with increase in Fr_1 and θ while it decreases with increase in h. As the Froude number increases, it indicates a higher velocity of the flow relative to the depth. A higher Froude number suggests that the flow is more energetic and has a larger amount of kinetic energy. When the Froude number increases, the hydraulic jump becomes stronger. The higher kinetic energy of the flow requires more energy dissipation, leading to a larger rise in water level downstream of the jump. Consequently, the relative height of the hydraulic jump increases as the Froude number increases. The flow velocity increases as the channel slope increases. As previously mentioned, this increase in velocity leads to a greater Froude number. As the Froude number increases due to the steeper channel slope, the energy dissipation requirements also increase. Therefore, the hydraulic jump becomes more pronounced, resulting in a higher relative height.

The empirical correlation of relative height (H_j/d_1) was created taking the effects of Fr_1, Re_1, relative height of roughness (h/d_1) and slope of bed (θ) and could be represented by Eq. 12 having determination coefficient (R^2) equal to 0.99.

$$\frac{H_j}{d_1} = 1.12\left(\frac{Fr_1^{\,1.2}}{\mathrm{Re}_1^{\,0.001}}\right) + 24\tan\theta - 1.48\left(\frac{h}{d_1}\right) - 0.65 \quad (12)$$

It is clear from Eq. 12 that relative jump height reduces with an increment in Reynolds number and roughness height and increases with a rise in Froude number and channel slope. Low Reynolds numbers usually result in laminar flow, which is characterised by the fluid moving in smooth, parallel layers. In this case, the relative height of the jump can be relatively high because the viscous forces dominate. As the fluid approaches the jump, it experiences a slowing down due to the viscous forces, allowing it to build up potential energy and resulting in a higher jump. However, as the Reynolds number increases, the flow becomes more turbulent. Turbulence is characterized by chaotic, swirling motion and the mixing of fluid elements. In turbulent flow, the inertial forces become more significant, and the flow tends to be less affected by viscous forces. In a turbulent flow regime, the fluid particles near the surface of the jump experience more mixing and turbulent energy dissipation. This causes a reduction in the

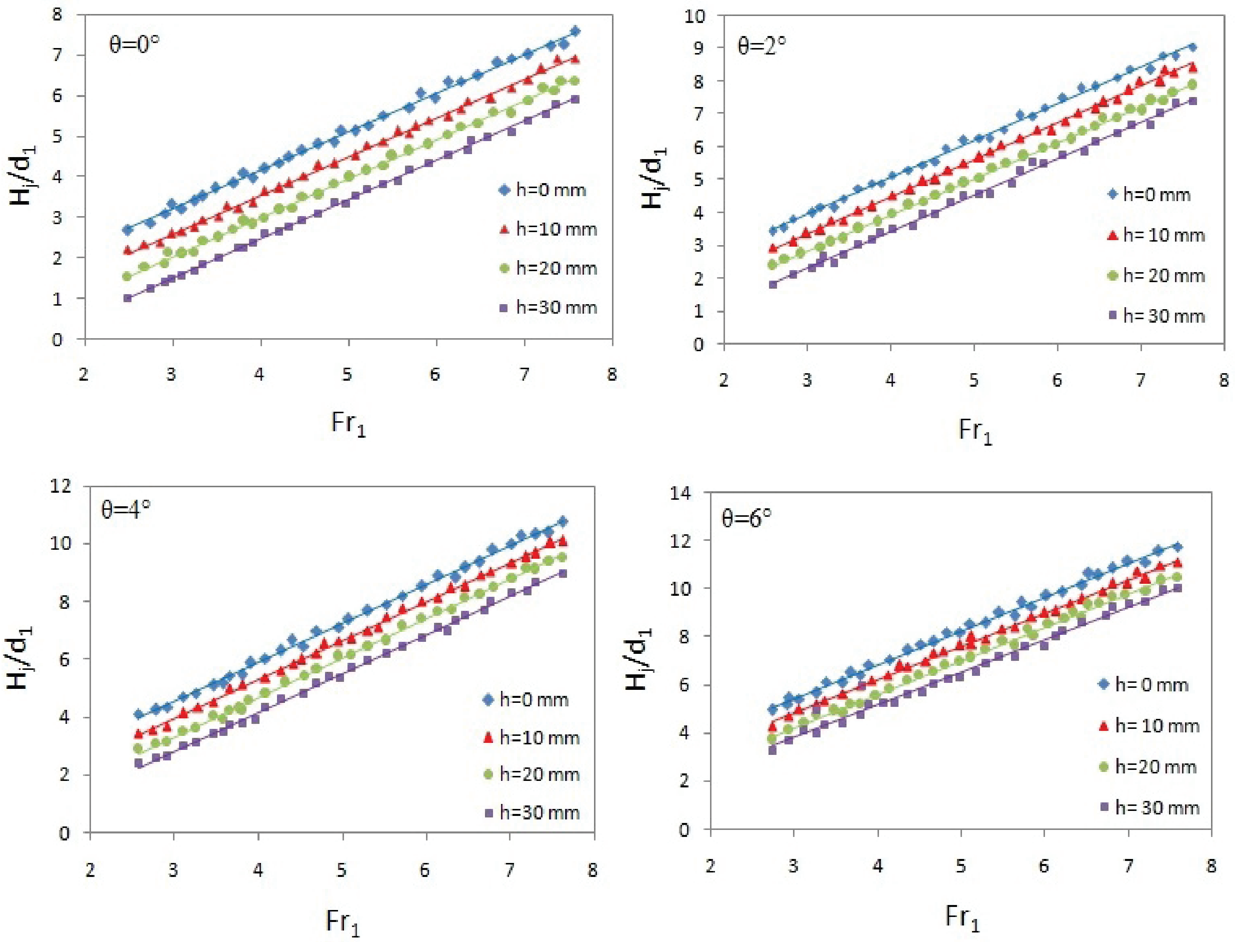

Figure 4. Relative height of jump (H_j/d_1) variation with inflow Froude number (Fr_1) at different gravel bed material size (h) and channel slope (θ).

Table 2. Average value of relative jump height (H_j/d_1) at different roughness height and bed slope

θ	h = 0 (mm)	h =10 (mm)	h = 20 (mm)	h = 30 (mm)
0°	5.017503	4.405455	3.907879	3.332121
2°	6.127305	5.801753	5.228317	4.495394
4°	7.305605	6.827687	6.088716	5.543493
6°	8.327992	7.859706	7.257609	6.564021

potential energy buildup and subsequently decreases the relative height of the jump. The turbulent motion of the fluid leads to more energy losses, which are not converted into upward motion as effectively as in laminar flow. The increase in gravel bed material size introduces greater resistance to flow, enhances energy dissipation, and disrupts flow patterns. These factors collectively contribute to a decrease in the relative height of a jump. Smaller bed material sizes, on the other hand, allow for smoother flow, less resistance, and less energy dissipation, enabling the formation of higher jumps.

Figure 5 compares the measured value of current experimental observation to the value calculated by the correlation of relative height of jump (H_j/d_1) by Eq. 12 using Bhutto [37] data for validation of present finding. The results indicated that the matched measured data and the computed data, which had an R^2 value of 0.99 and were close to regression agreement line, varied by roughly ±10%. The results demonstrated that applying Eq. 12 to calculate the relative jump height produced high agreement and efficacy which validate the correlation developed by predicting relative height of jump (H_j/d_1) and present finding.

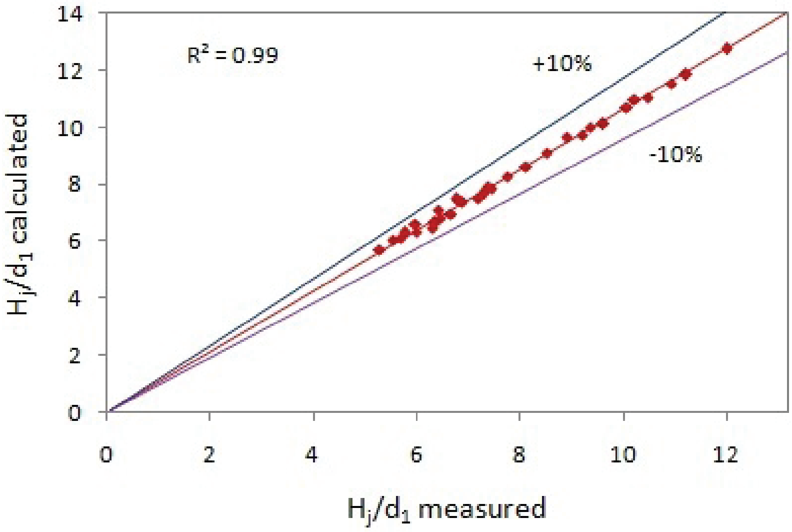

Figure 5. Comparison of the relative height of jump's (H_j/d_1) calculated by correlation and experimental measured values.

Relative Energy Dissipation

It is important to remember that the dissipation of energy in a hydraulic jump is directly related to the system's overall energy loss [38-39]. The total energy comprises both the kinetic energy and the potential energy of the flow. The decrease in total energy is reflected in a decrease in flow velocity and a rise in water surface elevation after the hydraulic jump. The specific amount of energy dissipated depends on various factors, including the flow rate, channel geometry, and roughness of the channel walls [40].

From Buckingham's π theorem observation, it was observed that the relative energy dissipation depends upon Fr_1, Re_1, relative height of roughness (h/d_1) and channel slope (θ). Figure 6 represents the polynomial

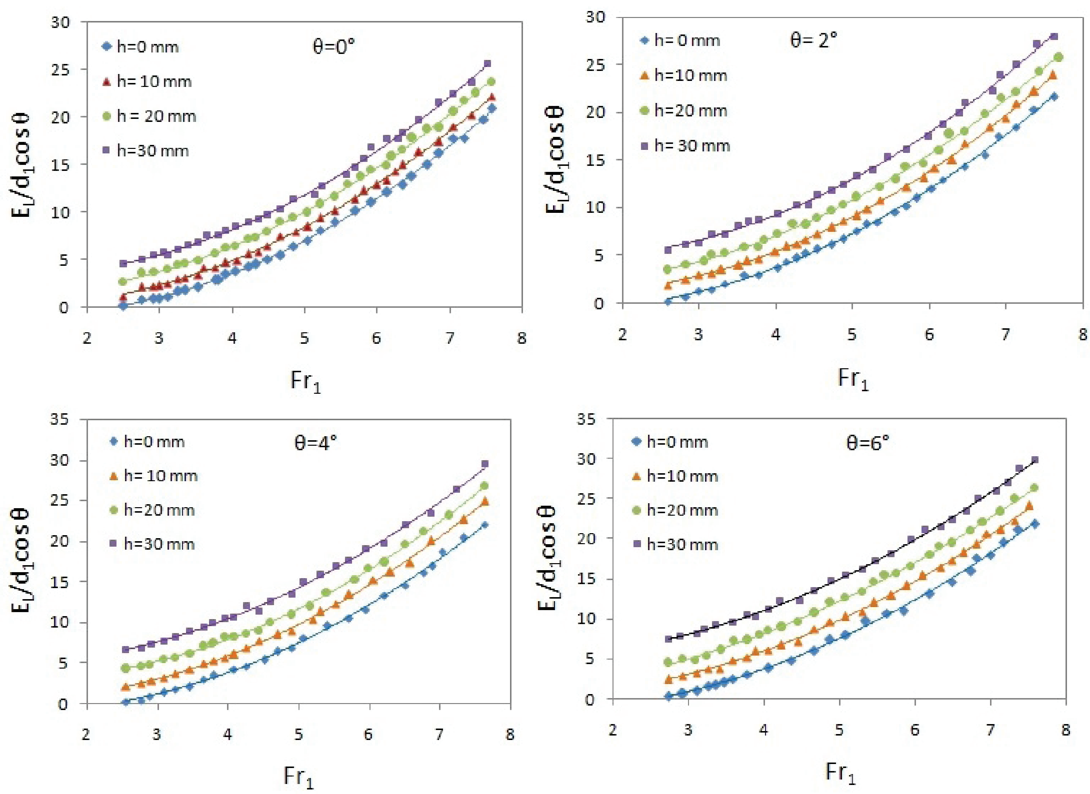

Figure 6. Variation of relative energy dissipation ($E_L/d_1\cos\theta$) with inflow Froude number (Fr_1) at different gravel bed material size (h) and channel slope (θ).

Table 3. Average value of relative energy dissipation ($E_L/d_1\cos\theta$) at different roughness height and bed slope

θ	h = 0 (mm)	h = 10 (mm)	h = 20 (mm)	h = 30 (mm)
0°	7.718968	8.766059	11.34531	12.24006
2°	8.399065	10.01645	11.97937	14.27351
4°	9.104673	11.12459	12.72183	15.55609
6°	10.10752	12.29758	13.97727	17.04819

variation of $E_L/d_1\cos\theta$ with Fr_1, h and θ. Through experimental investigation, it was discovered that the relative energy dissipation rises with increment in inflow Froude number (Fr_1), channel slope (θ) and also with gravel bed material size (h). The average value of relative energy dissipation ($E_L/d_1\cos\theta$) at different roughness height and bed slope is shown in Table 3.

The regression equation of relative energy dissipation ($E_L/d_1\cos\theta$) was developed considering the effects of Fr_1, Re_1, relative height of roughness (h/d_1) and slope of bed (θ) and could be represented by Eq. 13 having determination coefficient (R^2) equal to 0.995.

$$\frac{E_L}{d_1\cos\theta} = 2.5\left(\frac{Fr_1^{\,1.1}}{\mathrm{Re}_1^{\,0.03}}\right) + 7\tan\theta + 1.85\left(\frac{h}{d_1}\right) + 0.85 \quad (13)$$

From Eq. 13, it is perceived that the $E_L/d_1\cos\theta$ rises with increment in Fr_1, Re_1, θ and also with relative gravel bed material height (h/d_1). When the Froude number increases, it stipulates that the flow velocity is increasing relative to the wave speed of the flow. This results in a higher flow momentum. A higher momentum leads to increased turbulence and energy dissipation. As the flow velocity increases, more energy is required to overcome the increased frictional losses and eddy formation, resulting in higher energy dissipation. The channel bed's slope has an impact on energy dissipation as well. When the channel slope increases, the flow velocity increases to maintain the same discharge. This increase in velocity leads to greater energy dissipation due to increased turbulence and frictional losses along the channel bed and walls. The steeper slope creates more resistance to the flow, resulting in enhanced energy dissipation. Larger gravel bed material size creates rougher channel surfaces. As the water flows over these rough surfaces, it experiences increased frictional resistance. The roughness generates turbulent eddies and flow disturbances, which dissipate energy through the conversion of kinetic energy into heat. Therefore, with larger gravel bed material size, there is more roughness-induced energy dissipation. Gravel bed material size influences the formation of bed forms, such as ripples and dunes, on the channel bed. Larger gravel particles have a higher threshold for motion, requiring greater flow velocities to initiate movement. Consequently, as the flow encounters these bed forms, it experiences additional resistance and energy dissipation. The irregularities and obstacles provided by the larger gravel particles promote energy dissipation through the generation of turbulence and flow disturbances. Larger gravel particles cause increased turbulence in the flow. As the water moves through the interstices of the gravel bed, it encounters obstacles and irregularities, which promote turbulent mixing. This mixing enhances the dissipation of energy by converting the flow's kinetic energy into heat through viscous dissipation. Larger gravel bed material size leads to an overall increase in channel roughness. The rougher channel bed presents a larger surface area for the flow to interact with, resulting in more frictional losses and energy dissipation. The irregularities and variations in particle size contribute to the complexity of flow patterns and increase the overall energy dissipation. Hydraulic jumps are typically associated with a transition from supercritical flow to subcritical flow, leading to turbulence and energy dissipation. Higher Reynolds numbers often correspond to more turbulent flows. In turbulent conditions, energy dissipation is distributed across a larger volume of the flow, potentially resulting in lower energy losses per unit length. In hydraulic jumps, vortices and turbulence play a significant role in dissipating energy. As Reynolds number increases, there is a tendency for the formation of larger and more persistent vortices. These vortices can effectively dissipate energy, contributing to a smoother transition and reducing the overall energy loss compared to lower Reynolds number flows.

Figure 7 compares the measured value of current experimental observation to the value calculated by the correlation of relative energy dissipation of jump ($E_L/d_1\cos\theta$) by Eq. 13 using Bhutto [37] data for validation of present finding. The results indicated that the matched measured data and the computed data, which had an R^2 value of 0.995 and were close to regression agreement line, varied by roughly ±10%. The results demonstrated that applying Eq. 13 to calculate relative energy dissipation of jump ($E_L/d_1\cos\theta$) produced high agreement and efficacy which validate the correlation developed by predicting relative height of jump (H_j/d_1) and present finding.

Comparison

From the current finding, it was observed that the average increment in energy dissipation ($E_L/d_1\cos\theta$) was found 46.27% and average decrement in relative jump height ($H_j/$

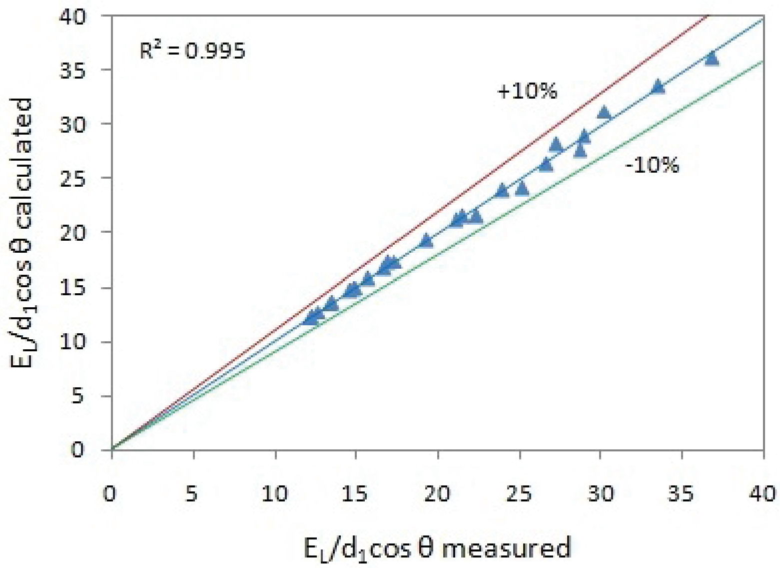

Figure 7. Comparison of the relative energy dissipation ($E_L/d_1\cos\theta$) calculated by correlation and experimental measured values.

d_1) was found 16.21% with increment of roughness height but Ahmed et al. [20] reported only 15% decrement in relative height, Pourabdollah et al. [22] reported 33% decrement in H_j/d_1 and 27.41% increment in energy dissipation. As compare to the previous research reported in literature, it was found that energy dissipation is more in current research and the correlations developed for both the characteristics are validated which represents efficacy of the current finding. Despite the discrepancies, the correlations developed in the current study for both energy dissipation and relative jump height is validated. The validation suggests that the findings of the current research are effective and consistent with the established relationships between roughness height and the studied characteristics. The higher energy dissipation observed in the current study compared to previous research suggests potential advancements or variations in the understanding of the relationship between roughness and energy dissipation. The validation of correlations indicates that the methodologies and models used in the current study are reliable and provide accurate predictions for the observed characteristics.

CONCLUSION

The investigation's conclusions showed that gravel bed material size significantly affects the relative height and energy dissipation of hydraulic jumps. Larger gravel particles were found to increase the relative height of the hydraulic jump, while smaller gravel particles led to a decrease in the relative height. Furthermore, the size of the gravel bed materials had an impact on the hydraulic jump's energy dissipation efficiency. The key findings obtained from this study are listed below:

The average increment in relative jump height (H_j/d_1) is approximately 65.98% with increment in bed slope from 0° to 6°, while the average decrement is found approximately 7.03%, 16.04% and 25.56% for increase of gravel bed material size h=10 mm, h=20 mm and h=30 mm considering all channel slope varied from 0^0 to 6^0. With the rise in height of roughness, the average decrease in relative jump height is approximately16.21%, whereas the average decrease when compared to a classical jump is about 67.25%.

With the rise of bed slope from 0^0 (classical jump) to 6^0 with gravel bed material size 30 mm, the average increment in relative energy dissipation was found about 73.02%. The average increment in relative energy dissipation was found about 32.47%, 48.32% and 58.02% for gravel bed material size 10 mm, 20 mm and 30 mm respectively for increase of channel slope from 0^0 to 6^0.

The findings of this study have significant relevance for hydraulic engineering applications related to spillways, dams, notches, weirs, and other sustainable and eco-friendly environmental processes. In order to effectively build and manage sloped channels, designers and planners must have a thorough understanding of the effects that the size of the gravel bed material has on hydraulic jumps. By choosing and arranging gravel bed materials optimally, one can reduce erosion, increase hydraulic efficiency, and improve energy dissipation, all of which contribute to a sustainable and environmentally friendly environment.

Limitations

Physical models of channels may not perfectly replicate the behavior of full-scale natural channels. Scale effects can influence the accuracy of experimental results, especially when dealing with small-scale models.

The behavior of sediment in the experimental setup may not fully represent the complexities of natural sediment transport. Sediment properties, such as size and composition, can vary widely in natural channels, and replicating these variations in an experimental setup can be challenging.

The boundary conditions in an experimental setup may not precisely mimic those in natural channels. Factors such as upstream and downstream conditions, lateral inflows, and boundary roughness can influence the results and may differ from real-world scenarios.

Experiments are often conducted over shorter time scales compared to natural channel processes. Long-term geomorphic changes, vegetation growth, and other dynamic processes may not be adequately captured in a limited experimental timeframe.

NOMENCLATURE

d_1	depth before jump
d_2	depth after jump
E_1	specific energy in torrential flow
E_2	specific energy in tranquil flow
E_L	loss of energy due to jump formation
f	function of
Fr_1	inflow Froude number
g	gravitational acceleration
h	gravel bed material size
H_j	jump height
L_j	jump length
M_1	momentum flux in torrential flow
M_2	momentum flux in tranquil flow
P_1	hydrostatic force in torrential flow
P_2	hydrostatic force in tranquil flow
Q	discharge
Re_1	inflow Reynolds number
V_1	flow velocity before jump
V_2	flow velocity after jump
θ	channel slope

Greek symbols

ρ	fluid density
μ	fluid viscosity
ε	bed roughness

AUTHORSHIP CONTRIBUTION

All the authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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