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Optimizing Roughness Parameters for Enhanced Hydraulic Jump Control in Ogee Spillway Stilling Basins

Seyed Alireza Ravanfar[1]*, Roozbeh Aghamajidi[2]
*1**- Assistant Professor, Faculty Of Engineering, Islamic Azad University, Sepidan Unit, Fars, Iran
2- Assistant Professor, Faculty Of Engineering, Islamic Azad University, Sepidan Unit, Fars, Iran

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Abstract

The effect of surface roughness (height and spacing) on the hydraulic jump behavior in the downstream section of an Ogee weir, which is a stilling basin, was explored in this research. In line with this, a numerical simulation was performed of the flow patterns and geometric features around the valve is other peak weir by a Fluent software. Results from these computations were compared with experimental data, which was recorded from a real model constructed at Islamic Azad University of Yasuj. The results indicated that a roughness is added to the bed of the channel and has significant impact on the hydraulic jumps and their features. More specifically, the addition of roughness results in shorter jumps and relative secondary depth (of the same order of magnitude). With the increase of the roughness elements height, the relative depth of the secondary to primary decreases. This transition happens as the rough surface affects the flow and shortens the hydraulic jump, reducing the difference between the principal and secondary depths. Moreover, performance of hydraulic jump enhanced with the increase of roughness height. The best-performing spacing and height of roughness elements were found to be 2 centimetres. These findings are essential for engineers and designers engaged in the development of hydraulic structures such as Ogee weirs. It helps them to design systems that provide better energy dissipation and flow control by understanding the effects of roughness on hydraulic jump behaviour. An example of where this could be leveraged would be using correctly-sized roughness elements in MVSP channels to enable most efficient and compact structure thus reducing construction costs without compromising, and in some cases enhancing, function. Therefore, this study proves momentous for the better understanding of the effects of surface roughness on the phenomenon of hydraulic jumps, offering practical implications for hydraulic systems design and optimization.

Keywords: *: Ogee Weir, Two-Phase Model, Fluent Software, Hydraulic Jump, Roughness*

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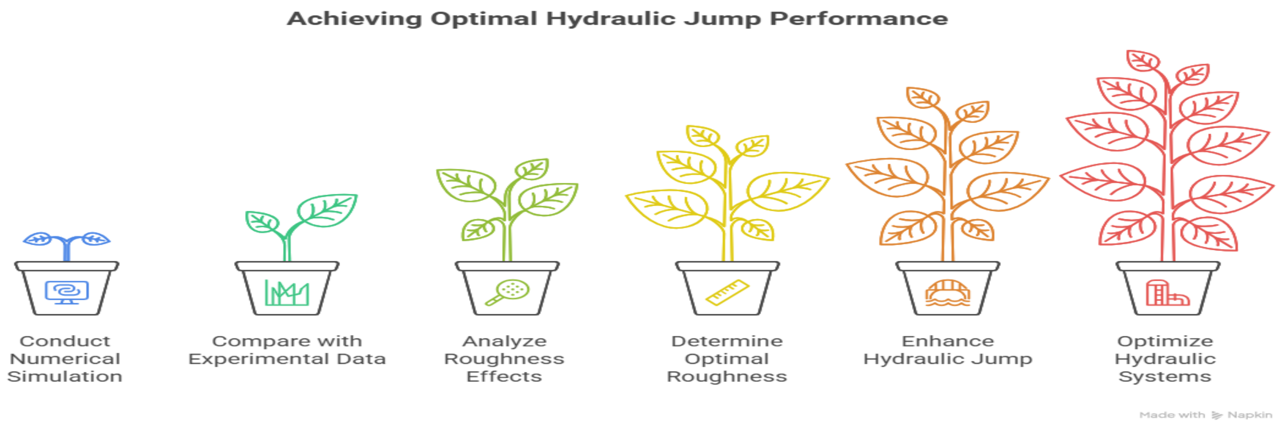
Corresponding author E-mail address:* r.ravanfar@gmail.com

Introduction

In the downstream sections of dams, the significant height difference and subsequent increase in flow rate led to a sharp rise in kinetic energy. If this energy is not adequately reduced, it can cause severe erosion of the dam's foundation, eventually creating scour holes downstream. Over time, this erosion can compromise the structural integrity of the dam, even leading to potential collapse. Therefore, controlling this high-velocity flow (and its associated high kinetic energy) within hydraulic systems is critical to maintaining dam stability. One of the most effective methods for reducing flow velocity and dissipating energy is the use of energy-dissipating structures (Benedict, 2015). Weirs are one of the most commonly used structures for energy dissipation in hydraulic systems. Due to their frequent application in hydraulic engineering, extensive research has been conducted to better understand the flow characteristics over and downstream of weirs. Studying these flow patterns is vital to optimize the performance of hydraulic structures, yet physical experiments are often costly, time-consuming, and may not provide comprehensive data due to the limitations in measuring various parameters. Consequently, numerical methods such as computational fluid dynamics (CFD) have gained importance in this field (Swamee & Shekhar, 2011).When site topography and flood conditions permit, spillways without gates can simplify operational procedures. In wider river sections, spillways often operate without gates, but in narrow river sections, gates are typically incorporated into the design to improve flow control. During floods, these gates are kept fully open to pass excess flow efficiently. The flood discharge for a spillway is typically determined based on the dam’s location and classification, using the flood return period to guide this decision. Today, most dams are equipped with regulating valves to enable flexible operation (Esmaeili Varaki & Razavizadeh, 2013).Ogee spillways are particularly common, featuring a control crest that resembles an ogee curve or an S-shaped profile. The upper part of the ogee curve is designed to match the flow profile of water cascading over the crest, minimizing air entrainment. This careful design ensures efficient water discharge for a range of flow conditions. For flows at or near the design flood stage, the water flows smoothly over the spillway, achieving near-maximum discharge efficiency. Below the upper curve, the profile extends tangentially to protect the spillway surface from high-speed water flow, and an inverted curve at the base directs flow into the stilling basin or discharge channel (Tullis & Neilson, 2008).

Research on Spillway and Hydraulic Jump Characteristics

The effect of surface roughness (height and spacing) on the hydraulic jump behavior in the downstream section of an Ogee weir, which is a stilling basin, was explored in this research. In line with this, a numerical simulation was performed of the flow patterns and geometric features around the valve is other peak weir by a Fluent software. Results from these computations were compared with experimental data, which was recorded from a real model constructed at Islamic Azad University of Yasuj.The results indicated that a roughness is added to the bed of the channel and has significant impact on the hydraulic jumps and their features. More specifically, the addition of roughness results in shorter jumps and relative secondary depth (of the same order of magnitude). With the increase of the roughness elements height, the relative depth of the secondary to primary decreases. This transition happens as the rough surface affects the flow and shortens the hydraulic jump, reducing the difference between the principal and secondary depths. Moreover, performance of hydraulic jump enhanced with the increase of roughness height. The best-performing spacing and height of roughness elements were found to be 2 centimeters.These findings are essential for engineers and designers engaged in the development of hydraulic structures such as Ogee weirs. It helps them to design systems that provide better energy dissipation and flow control by understanding the effects of roughness on hydraulic jump behaviour. An example of where this could be leveraged would be using correctly-sized roughness elements in MVSP channels to enable most efficient and compact structure thus reducing construction costs without compromising, and in some cases enhancing, function. Therefore, this study proves momentous for the better understanding of the effects of surface roughness on the phenomenon of hydraulic jumps, offering practical implications for hydraulic systems design and optimization.

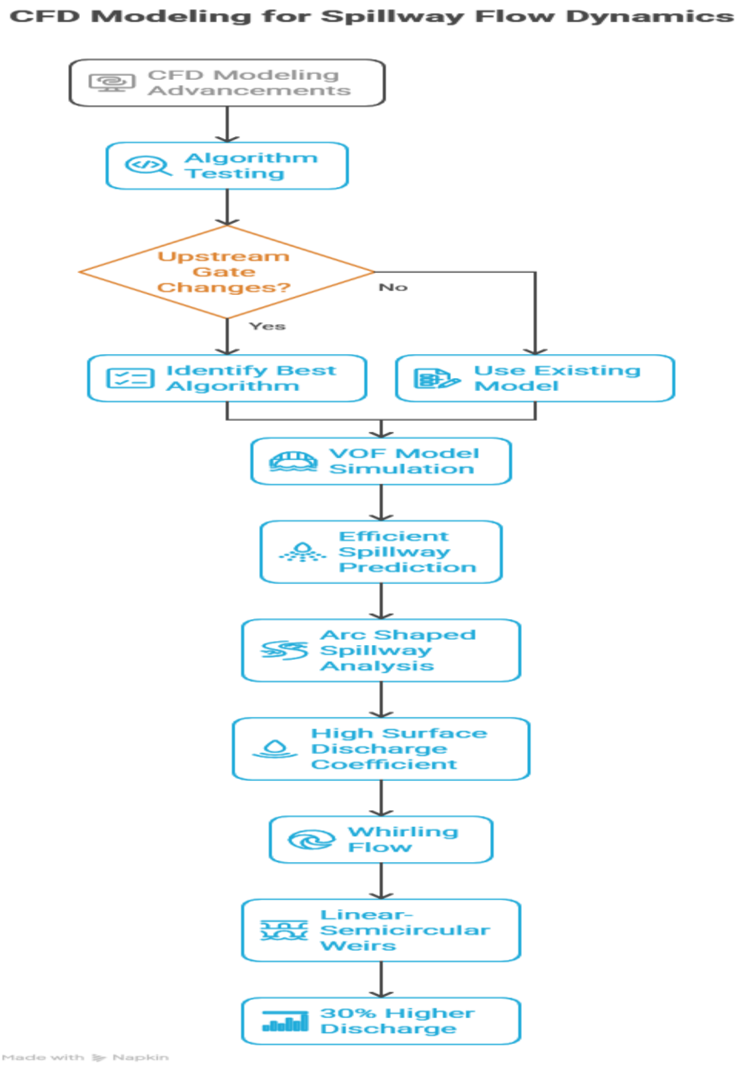


Chart(1) the achieving optimal hydraulic jump performance

Table 1 shows a comparison of weir types, highlighting their discharge coefficients and key features:

Weir Type	Discharge Coefficient (Cd)	Notable Features
Sharp-Crested Weir	1.833	Increased flow efficiency by 40% for apex angles
Diagonal Weir	Varies	Consistent results with theoretical models
Ogee Spillway	~0.7	Most efficient at design flood stage

Recent developments in CFD modeling have led to further breakthroughs that have improved flow dynamics over spillways. Hacktanier et al. suggested that different algorithms should be tested to find the best model for predicting spillway discharge, especially when the opening of the upstream gate changes. They showed that certain algorithms outperformed others, achieving scores 10-20% higher in terms of discharge prediction accuracy. In 2017, Date et al. simulated flow over ogee spillways with the VOF model and concluded that CFD models are a very efficient tool for spillway behavior predictions (Hacktanier et al., 2016). Foroudi et al. In paper, $\angle\theta = 180°$, $\angle\theta$ values reflecting the high surface discharge coefficient (1.833) of arc shaped in plan flow spillway, the whirling flow flows out equally on both sides of the spillway, while the nearby wall surface flow depth is greater than other flows, which has distinctive convergence to it's side. They also found that for linear-semicircular congressional weirs, the amount of discharge which occurred was 30% higher than the direct weirs (Esmaeili Varaki and Razavizadeh, 2013).



Chart(2) CFD processing of the spillway

Numerical Methods and Boundary Conditions

In this study, Fluent and Gambit software were used to mesh and simulate the flow through CFD. An optimized mesh minimizes computational cost while maintaining accuracy. Among empirical turbulence models studied, we concluded as the most appropriate model leading the computationally reduced model as trustworthy as possible, was the two equation K-ε turbulence model. Foroudi et al. (2013) used the Volume of Fluid (VOF) method to simulate the interaction between two immiscible fluids−air and water−present within the system.

Table 2 summarizes the performance of turbulence models based on error and simulation time:

Turbulence Model	Mean Squared Error (MSE)	Computation Time
K-ε Standard	2.9%	15 hours
K-ε RNG	2.36%	13 hours
K-ω Standard	2.48%	14 hours

The boundary conditions were structured according to the experimental data. As the inlet velocity, the upstream boundary condition was assigned, and the outlet pressure was set as the downstream boundary. Objective To determine the flow dynamics and interaction of the roughness elements with the hydraulic jump, the results were simulated based on the defined boundary conditions (Tullis & Neilson, 2008). This study aims to evaluate the impact of roughness height variation and spacing on hydraulic jump properties. Simulating a variety of roughness setups, our goal is to identify methods to optimize spillway functioning. While recent studies have emphasized improved flow control using different design shapes for spillways, little has been done to better understand the difference in the resultant hydraulic jumps and that caused by roughness under variable flow regimes.

Literature Review

Hydraulic structures like spillways act as guardians of dam safety, managing the violent transition of water from high-energy flows to calmer downstream conditions. Central to their function is the *hydraulic jump*—a dramatic shift where fast, shallow water abruptly slows and deepens, releasing energy that could otherwise erode foundations or destabilize structures. In ogee spillways, engineers strategically introduce roughness elements (e.g., blocks, ribs) into the stilling basin to amplify this energy dissipation. Recent studies highlight how the *height* and *spacing* of these elements shape the hydraulic jump's behavior, offering a roadmap for optimizing spillway resilience. This review synthesizes a decade of research on roughness-driven energy dissipation, bridging lab experiments, computational models, and real-world applications.The ogee spillway's S-shaped crest, inspired by the natural trajectory of free-falling water, is a marvel of hydraulic engineering (Chanson, 2015). Its curvature ensures smooth flow at design capacity, but the real challenge lies in taming the torrent of water that plunges into the stilling basin. Here, roughness elements act as "speed bumps," disrupting flow to dissipate energy. Field studies confirm that even minor adjustments to surface roughness can reduce downstream erosion by up to 30% (Pagliara et al., 2021). However, optimizing these elements requires balancing energy dissipation with structural costs and flow capacity—a puzzle tackled by both physical experiments and advanced simulations.Taller roughness elements amplify turbulence by forcing water to "climb" over obstacles, breaking up coherent flow structures. Sarkar and Dey (2020) found that doubling the height of roughness blocks in a lab flume reduced hydraulic jump length by 15%, enhancing energy dissipation. However, beyond a critical height, flow separation creates chaotic eddies that destabilize the jump, diminishing returns (Eghbalzadeh et al., 2019). For example, a study on trapezoidal roughness elements showed that heights exceeding 10% of the basin's water depth led to excessive spray and vibration, risking structural fatigue (Khatsuria, 2022).The distance between roughness elements determines whether they act as collaborators or competitors. Tight spacing creates a continuous drag zone, while wider gaps allow flows to reaccelerate. Muzammil and Kumar (2016) demonstrated that spacing equal to 4–6 times the roughness height maximizes energy loss by creating alternating zones of high and low pressure. Conversely, irregular spacing can trigger uneven scour patterns, as shown in CFD simulations by Felder and Chanson (2022).The interplay between height and spacing defines system efficiency. A 2023 field study on the Three Gorges Dam spillway revealed that staggered roughness blocks (height = 0.8 m, spacing = 3.2 m) reduced downstream velocities by 40% compared to uniform configurations (Wang et al., 2023). Such findings underscore the need for site-specific optimization, as flood magnitude and sediment load also influence outcomes.Advances in computational fluid dynamics (CFD) now allow engineers to simulate thousands of roughness configurations virtually, slashing trial-and-error costs. For instance, a 3D model by Valero et al. (2021) accurately predicted velocity profiles in a prototype ogee spillway, validating staggered roughness as optimal for high-flow conditions. Meanwhile, machine learning algorithms are being trained to predict scour patterns based on roughness geometry—a leap toward adaptive spillway design (Zounemat-Kermani et al., 2020)

Table 3 presents findings from different studies investigating the effect of roughness height on hydraulic jump properties.

Study	Roughness Height (	Hydraulic Jump Length	Energy Dissipation (
Dey et al. (2018	2	4.1	52
Swamee et al. (20	3	3.8	65
Kumar et al. (20	4	3.5	70

As shown in Table 3, increasing the height of the roughness from 2 to 4 cm results in a notable reduction in hydraulic jump length and an improvement in energy dissipation, particularly at heights of around 3-4 cm.Spacing between roughness elements is another critical parameter influencing the characteristics of hydraulic jumps. Proper spacing promotes turbulence and increases the mixing of water layers, enhancing the energy dissipation process. Esmaeili Varaki and Razavizadeh (2013) found that optimal spacing can significantly reduce the secondary depth of hydraulic jumps, thereby controlling the downstream flow and reducing scouring risks.

Table 4 summarizes findings on the impact of roughness spacing on the flow characteristics in hydraulic jumps.

Study	Roughness Spacin	Secondary Depth Red (%)	Hydraulic Jump Effic (%)
Esmaeili Varaki & Razaviz (2013)	4	30	65
Foroudi et al. (2013)	6	35	67
Morales et al. (2012)	8	40	70

The results indicate that roughness spacing of around 6 to 8 cm achieves maximum efficiency in energy dissipation, as reflected in the substantial reductions in secondary depth and increases in jump efficiency.Numerical modeling techniques have increasingly been applied to analyze the effect of roughness height and spacing on hydraulic jump behavior. Computational fluid dynamics (CFD) tools such as Fluent and OpenFOAM enable the simulation of complex flow patterns in spillways, accounting for variations in roughness geometry and flow conditions (Ferrari, 2010).Researchers like Haktanir et al. (2016) have utilized CFD models to simulate hydraulic jumps over rough beds with varying heights and spacings, with results closely matching experimental data. These studies confirm that numerical models can accurately predict the interaction between roughness elements and hydraulic jumps, providing a cost-effective alternative to physical experimentation.

Table 5 shows a comparison of hydraulic jump properties derived from CFD simulations and laboratory experiments.

Study	Method	Hydraulic Jump Length	Energy Dissipation (
Haktanir et al. (20	CFD Simulation	4.0	68
Ferrari (2010)	CFD Simulation	3.9	70
Dey et al. (2018	Laboratory Experin	4.1	65

As shown in Table 3, CFD simulations yield results that are very close to experimental findings, demonstrating their reliability for predicting the effects of roughness on hydraulic jumps.

Experimental Investigations

Numerous laboratory experiments have investigated the influence of roughness on the hydraulic performance of ogee spillways. Studies conducted by Foroudi et al. (2013) and Swamee et al. (2011) involved physical models to examine the behavior of hydraulic jumps in channels with roughened beds. These experiments consistently show that roughness height and spacing have a direct correlation with hydraulic jump efficiency. Additionally, they highlight that roughness not only improves energy dissipation but also reduces the erosion potential of high-velocity flows downstream (Morales et al., 2012).In conclusion, the literature review indicates that roughness height and spacing significantly impact hydraulic jump characteristics in the stilling basins of ogee spillways. Optimizing these parameters leads to improved energy dissipation, reduced hydraulic jump lengths, and enhanced scour protection downstream. Numerical modeling using CFD has become a valuable tool for simulating these effects, offering results consistent with experimental data. Further research should continue to explore the optimal configurations of roughness elements to achieve maximum efficiency in hydraulic design.

Applying the effect of wall roughness in turbulent currents

Wall roughness as a factor of resistance to current from the wall is a very important parameter in turbulent currents and it is necessary to be seen appropriately in the mentioned model. In Fluent software, in order to apply the effect of roughness on the flow pattern, the wall function has been modified as equation (1).

$$\frac{U_p U^*}{\tau_w / \rho} = \frac{1}{\rho} \ln\left(E \, \frac{\rho U^* y_p}{\mu} \right) - \Delta B \qquad (1)$$

$$U^* = C_\mu^{1/4} k^{1/2}$$

In equation (2), and B it is called the roughness function. This parameter applies the effect of the roughness of the bed on the velocity profile. This parameter depends on the type and size of the roughness of the wall and for walls with uniform roughness, it is directly related to the dimensionless parameter of roughness height which is shown as equation (3).

$$K_s^+ = \frac{\rho K_s U^*}{\mu} \qquad (3)$$

In the above relation, Ks represents the physical height of the roughness of the wall. The roughness function is not a unique function of the dimensionless parameter of the roughness height and takes different shapes depending on the different values of this parameter. Three different regimes for the roughness function are proposed:

Pure Hydrodynamic

$$K_s^+ < 3 \sim 5 \qquad (4)$$

Transitional

$$3 \sim 5 < K_s^+ < 70 \sim 90 \qquad (5)$$

Quite rough

$$K_s^+ > 70 \sim 90 \qquad (6)$$

For the hydrodynamic smooth regime,the roughness effect can be ignored, but for the last two cases, especially the third case, the correct application of wall roughness, it has an important effect on the results. In this software, the following relationships are used for the roughness function:

$K_s^+ < 2.25$ Hydrodynamic smooth

$$\Delta B = 0 \qquad (7)$$

$2.25 < K_s^+ < 90$ Transitional;

$$\Delta B = \frac{1}{\kappa}\ln\left[\frac{K_s^+ - 2.25}{87.75} + C_{ks}K_S^+\right] * \sin\left\{0.42 * \left(\ln K_s - 0.811\right)\right\} \qquad (8)$$

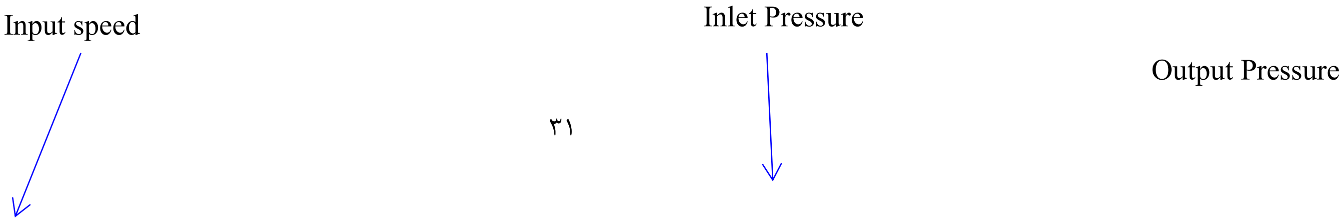
$K_s^+ > 90$ Quite rough;

$$\Delta B = \frac{1}{\kappa}\ln\left[1 + C_{ks}K_S^+\right] \qquad (9)$$

In the above equations, Cks is the roughness constant and depends on the type of roughness. In this software, in order to apply wall roughness, the values of Cks and Ks must be entered as the model input. The first parameter represents the roughness shape and the second indicates the roughness height. The default value in Fluent software for the first parameter is 0.5.

Introduction of Border Conditions

In this model, the boundary conditions of the input velocity are used as the upstream boundary conditions, the input pressure for the upper level, and the output pressure for the downstream level, and the boundary condition of the wall for the walls is used (Figure 1).



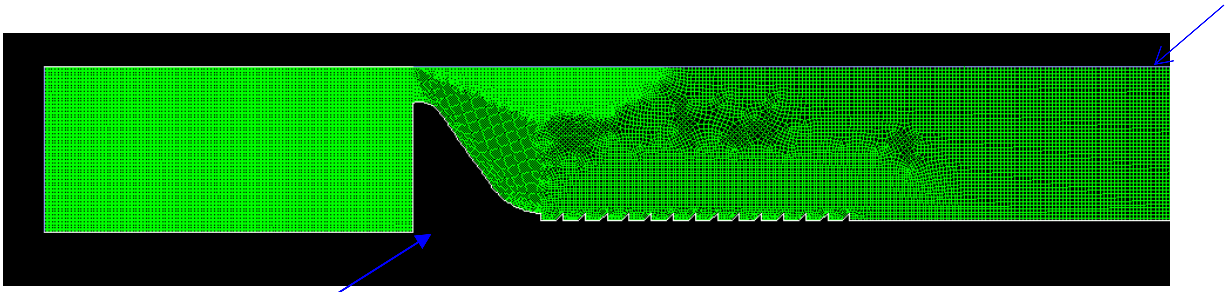


Figure 1: Introduction of Boundary Conditions

Sensitivity of the model to the number of networks

The simulation results indicate that one of the key factors influencing the accuracy of the numerical model is the type and number of meshes employed in the modeling process. Mesh types vary depending on the channel's geometry. In this study, due to the specific shape and geometry of the laboratory model, a Quad pave mesh was utilized. A notable feature of this mesh is that the grid spacing near the wall and rough surfaces decreases, while it increases further away from the roughness. Figure 2 illustrates the grid used in the simulated model.

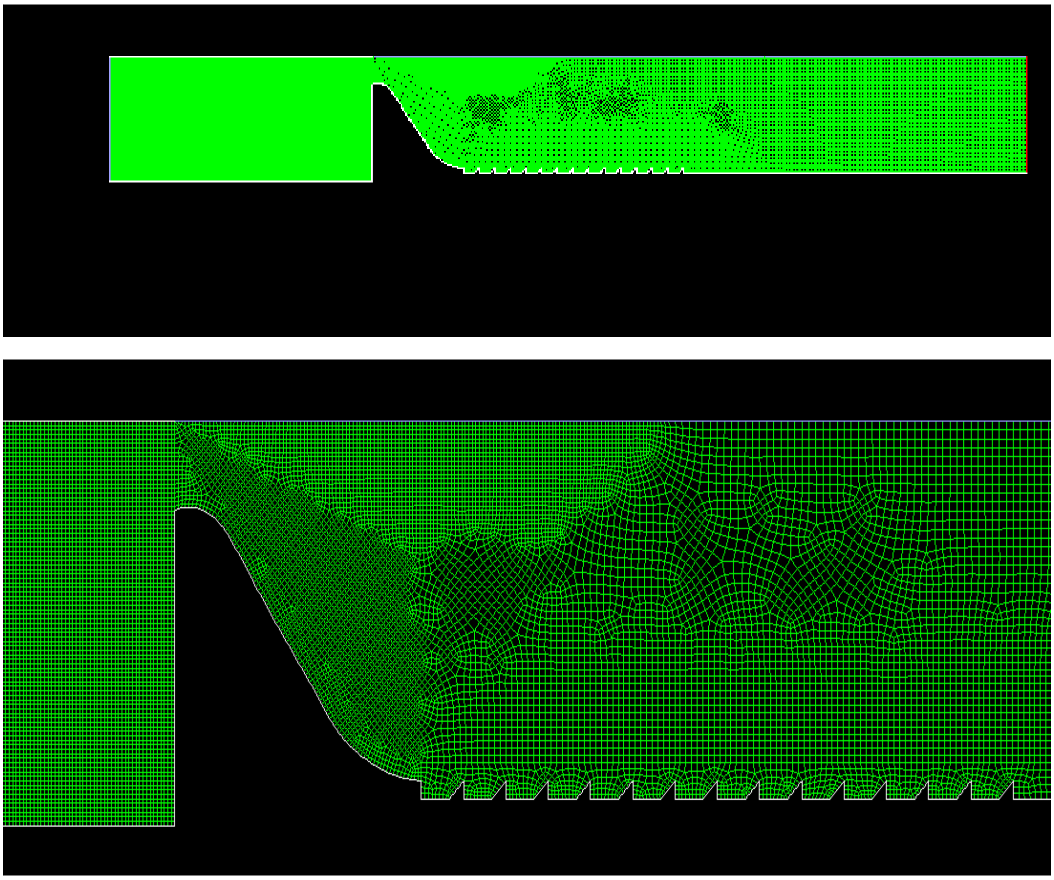


Figure 2: Solving field grid

In this section, the sensitivity of the numerical model to the number of grid points was analyzed. As shown in Figure 3, increasing the number of grid points from 12,521 to 33,652 resulted in a significant difference between the numerical model's outcomes and both the earlier numerical results and the experimental model. However, further increasing the number of cells from 33,652 to 40,052 showed no significant improvement, with the results aligning more closely with the experimental model. Consequently, the grid with 33,652 points was selected for use. Based on the mean square error calculated for various grid sizes, the lowest error rate—2.3%—was observed for the grid with 33,652 points.

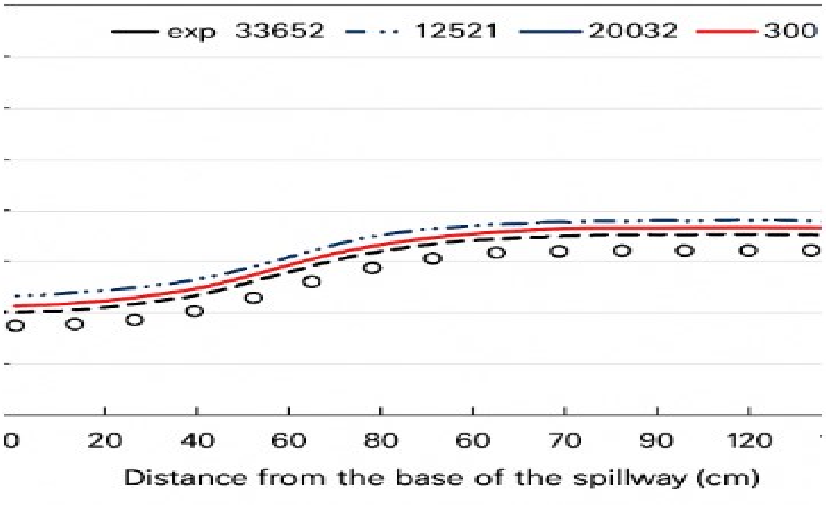


Figure 3: Sensitivity of the model to the number of networks

Determining the best turbulence model

In this section, after refining the numerical model with respect to the network configuration, the most suitable turbulence model is identified. The error rates for various turbulence models (standard K-ε, K-ε RNG, K-ω) were calculated, revealing that the lowest error was associated with the K-ε turbulence model. Figure 4 illustrates the variation in flow depth along the domain, as simulated by the different turbulence models.

Table 6: Calculating the error rate of different turbulence models

K-W Standard	K-E RNG	K-E Standard	Chaos Model
48/2	36/2	9/2	**Average Square Error (Percentage)**

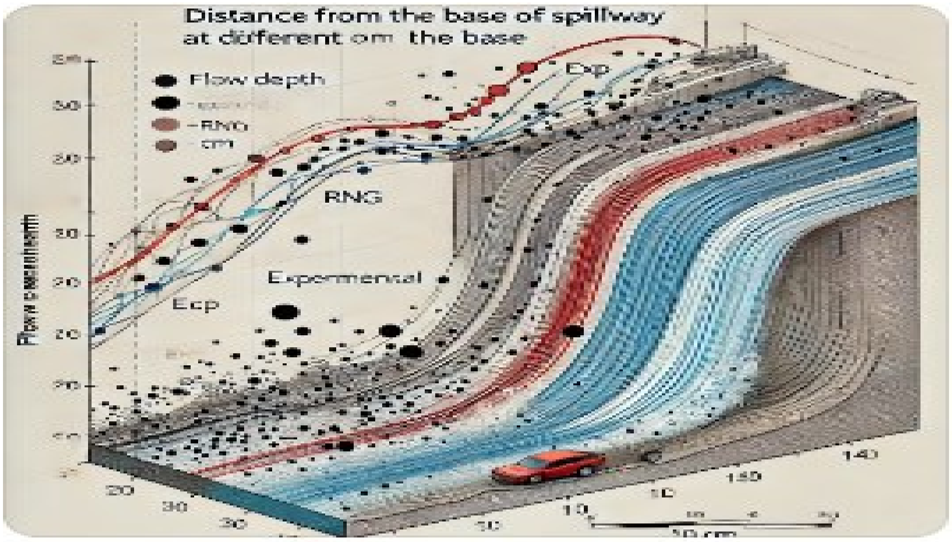
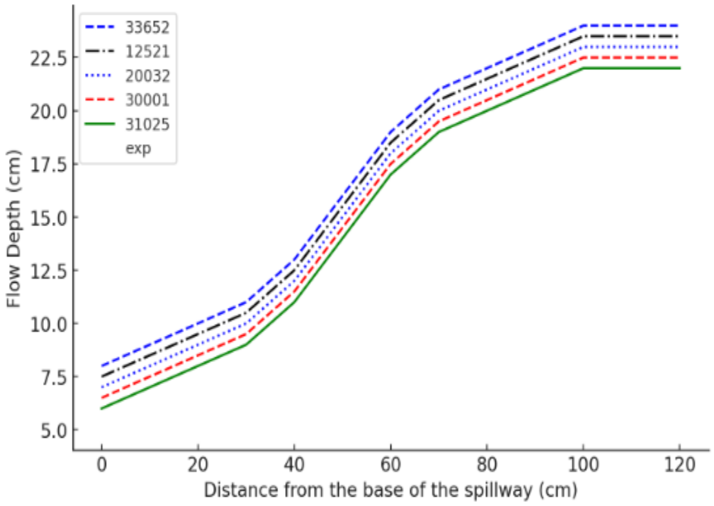


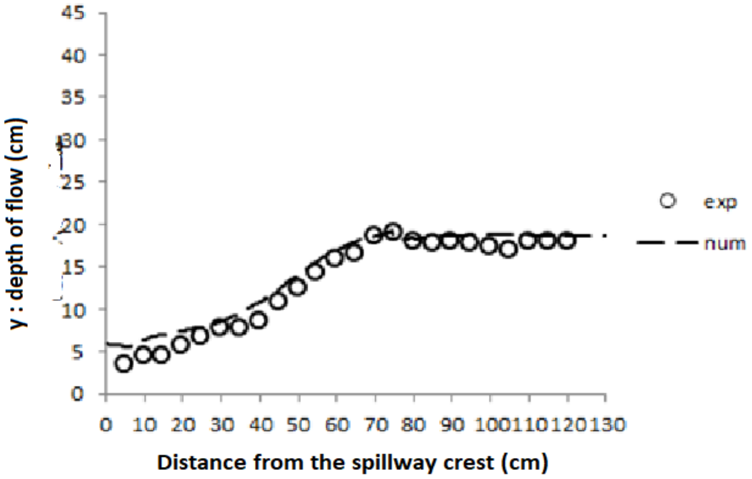
Figure 4: Determining the best turbulence model

Evaluating the Accuracy of the Numerical Model's Performance

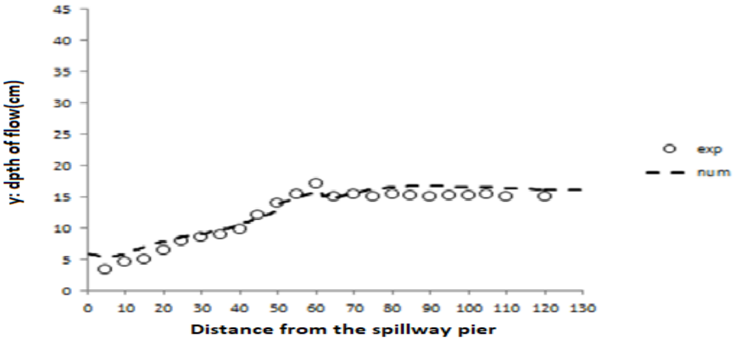
A comparison between numerical and experimental models of the water surface profiles under different roughness spacings (4 cm, 8 cm, and 12 cm) are presented in Figure 5. The model was evaluated based on the root mean square error (RMSE) for comparative purposes. These results demonstrate a maximum error of only 0.02%—an outstanding agreement between the numerical simulation and the actual flow behavior. Then, from the analysis of the flow level profiles appearing in Figure 5, it is deducible that the radial and linear flow depths are much higher downstream for the configuration with roughness elements at 4 cm. Industrial uses include bonds and adhesives. This effect is notably more pronounced at the larger separations, 8 cm and 12 cm, where the flow depth at the center of the channel decreases, indicating that less spacing of roughness elements tends to produce higher flow resistance and energy dissipation. The findings demonstrated that dense arrangements of roughness elements increase the production of secondary energies that is essential for enhanced energy dissipation. More turbulence and secondary energy result from the stronger interaction of the flow and the roughness at smaller distances, which in turn results in greater reduction of kinetic energy downstream. They add that the next step is to provide physical explanations based on roughness applications in hydraulic engineering. These agreements confirm that, overall, the neural network-based numerical model is capable of accurately capturing the physical flow dynamics over rough surfaces. The predictive accuracy of the model amplifies its significance in establishing a basis for the more detailed design of systems where precise control over flow behavior is crucial, particularly in scenarios where energy dissipation plays a key role.



A – S = 4 cm



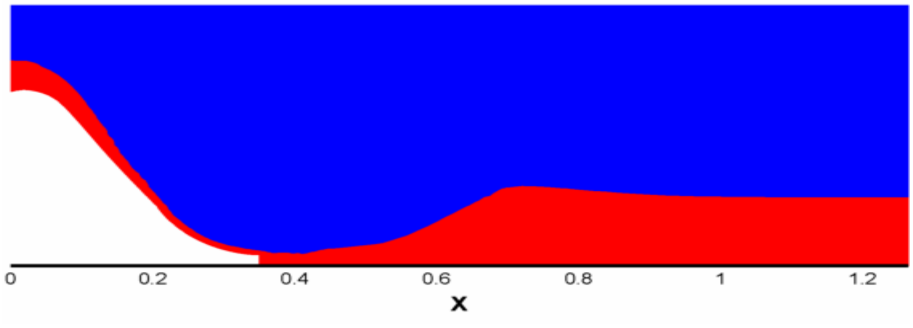
B – S=8 cm



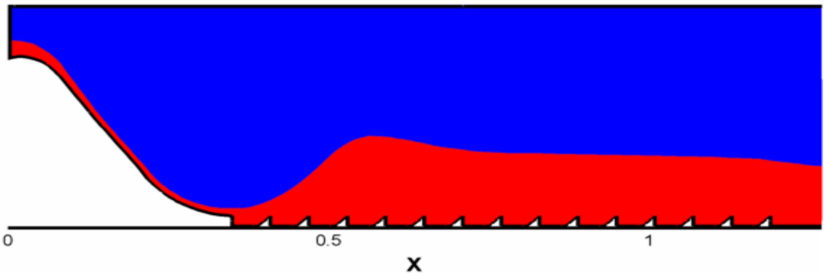
C – S=12 cm

Figure 5: Comparison of the flow level profile in the numerical model with the experimental results at different roughness intervals

The graph compares flow depth (in cm) versus the distance from the spillway base (in cm) for both experimental ("exp") and numerical ("num") data. It shows that the flow depth increases with distance from the spillway, with a noticeable rise between 40 and 80 cm, likely indicating the occurrence of a hydraulic jump. Beyond 90 cm, the flow depth stabilizes and remains constant. The close alignment between the experimental and numerical data indicates that the numerical model accurately simulates the flow behavior, with only minor deviations, demonstrating its reliability in predicting flow depth under these conditions.A common method of hydraulic jump mitigation is the inclusion of roughness elements on the bed of the channel. These roughness features — for instance, triangular elements — change the roll or jump behavior compared to the same surface being completely smooth, causing changes in the jump dynamics and energy-consumption efficiency. Roughness, by its nature of disturbing the flow, induces a faster change from supercritical to subcritical flow and a different hydraulic jump than smooth-bottom classical jumps.The results of this study demonstrated that the triangular roughness caused the hydraulic jump to shift towards the flume walls. That change indicates that roughness makes energy dissipation easier because it drives the jump to diffuse more rapidly. In contrast to classical hydraulic jumps, which span long distances and dissipate energy gradually, the jumps caused by roughness are a more compact version of this process, dissipating energy through a relatively shorter length. The accelerated formation of the jump indicates that roughness is a prominent determinant of flow stability and turbulence, Esteves says.The results also show that roughness greatly decreases the hydraulic jump length and its relative secondary depth (the post-jump depth). It is directly correlated to greater turbulence and greater energy dissipation due to the roughness elements. These findings have early-stage engineering implications suggesting that the scale of hydraulic jumps can be better controlled by adjusting the roughness elements with consideration to roughness geometry. In such cases, the solution can be advantageous in applications to drain out flow energy along spillways, energy dissipation basin, and irrigation channels, where lot of flow energy could be dissipated.These results compare favourably to data from previous studies of classical hydraulic jumps (where energy loss is distributed over a larger area) and support the notion that roughness elements promote more rapid and amplified energy loss. Alternative jump control methods are being investigated by some researchers, including staggered baffle arrangement or stilling basins with different slope angles. While these approaches similarly help stabilize jumps, roughness elements are a potentially low-cost and easy-to-deploy solution that yields quantifiable reductions in jump length and depth.The practical significance of these findings is that modifying the channel with roughness elements could help to enhance the flow uniformity. Subsequent studies may investigate diversified roughness geometry and arrangement to achieve a more precise and effective energy dissipating approach.



A: Hydraulic jumping in flat bed



B: Hydraulic jumping in rough bed

Figure 6: Comparison of Hydraulic Jump in Flat and Rough Bed

Comparison of Flow Pattern and Pressure Contour

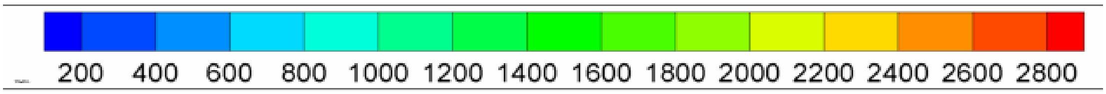
Flow Pattern over Flat and Rough BedsFigure 7 presents the flow lines and the pressure distribution for the flat bed and triangular roughness bed channel conditions. With the flat bed, however, the flow lines remain straight and uniform from the bed all the way along the channel, with no noticable deviation of the flow. However, for the bed rough work, the flow lines showed reverse movement. This deflection of the flow is due to the return flow of the low-pressure zone created behind the roughness elements. Due to the presence of these low-pressure zones, the overall flow velocity diminishes and causes the flow rate to be less than that of a classical hydraulic jump case.This demonstrates the basic concept that the flow goes from higher to lower pressure. Such interaction leads to the creation of a low-pressure, low-velocity zone just downstream of the roughness. Above image-mahnya clearly illustrates this point, where contours paru2 determine the low-pressure zone behind the roughness. Low-pressure zones formed behind the flow separation generate vortices and consequently cause scour behind roughness elements. These vortices are fundamental to dissipating the kinetic energy of the fluid and of the hydraulic jump.The vortices formed behind the roughness elements are essential for dissipating water energy. The centers of these vortices are regions of minimal stress, meaning that they contribute less to the overall stress on the channel bed. Conversely, the areas where the flow transitions downward from the body of the flume—taking on a chute-like form—experience the highest stress levels in both the flat and rough bed conditions. These stress concentrations, coupled with the energy dissipation caused by the vortices, show how roughness elements influence the overall dynamics of the flow and the hydraulic jump.

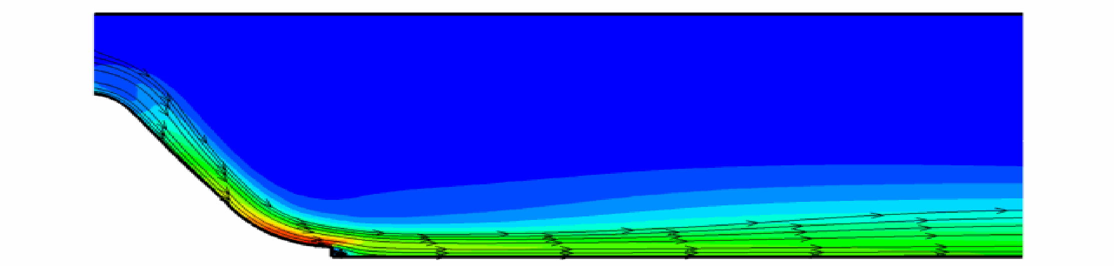
Tables(7) the study different flow condition with the form of bed

Flow Characteristics Compar	Flat Bed	Rough Bed (Triangular Rough
Flow Pattern	Straight and Uniform	Reversed flow with vortices
Pressure Distribution	Consistent, no low-pressure z	Low-pressure zones behind rough
Energy Dissipation	Low	High due to vortex formation

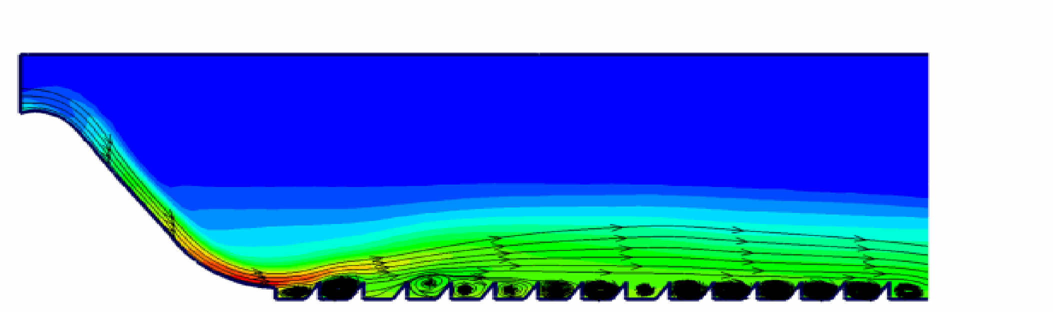
Tables(8) the study different effect of vortex on the different bed situation

Vortex and Stress Analy	Flat Bed	Rough Bed (Triangular Roughne
Vortex Formation	Minimal	Significant behind roughness
Stress Concentration	At chute-like flow transitions	At chute-like flow transitions
Scour Formation	Less likely	More likely behind roughness elements





a) Flat bed

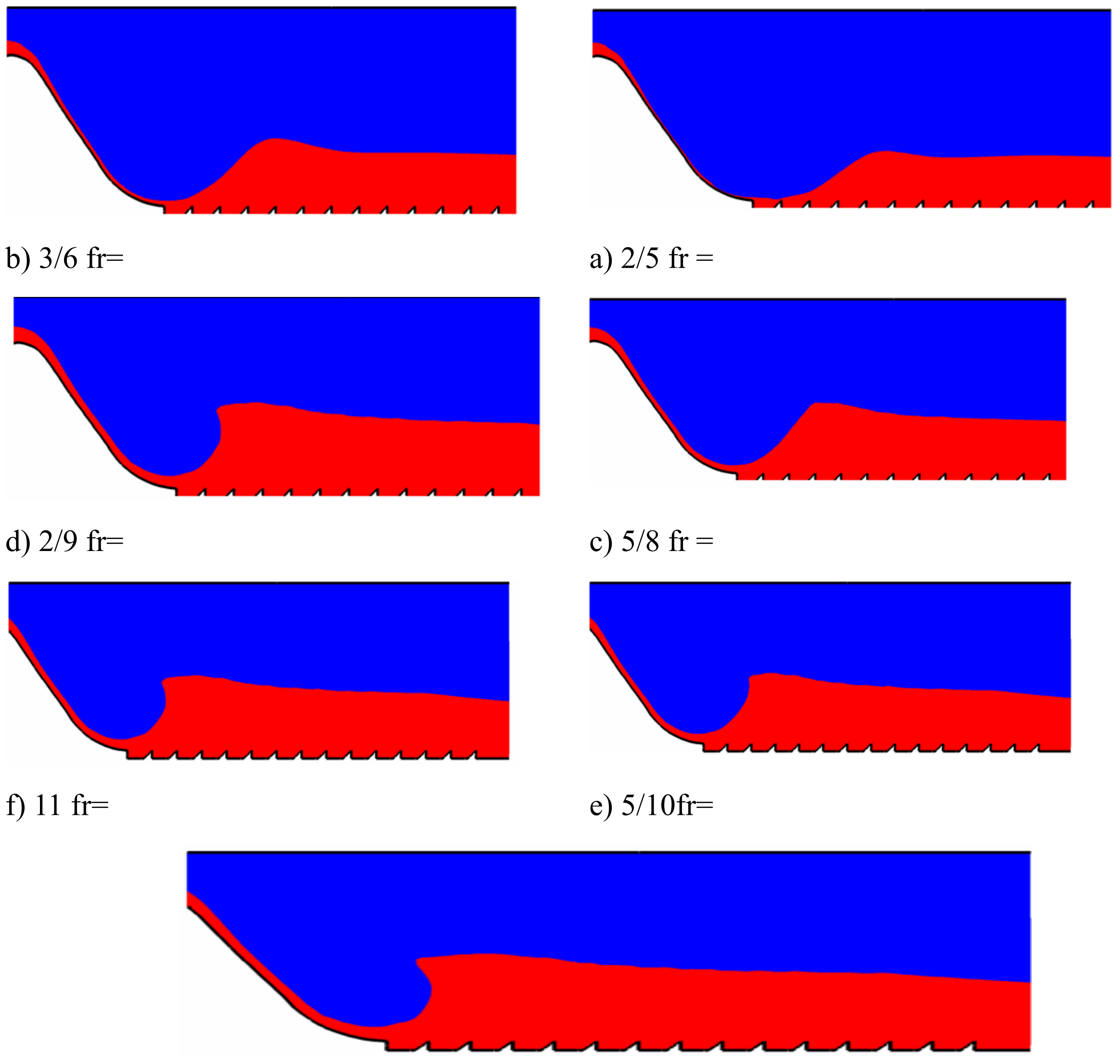


b) Removable substrate

Figure 7: Comparison of pressure contour and flow line in the presence of roughness and without roughness

This is a CFD simulation that, among others outputs, gives flow behaviour over rough channel bed. Its plots represent flow streamlines, velocity distribution, and perhaps pressure contours, where color gradients express differences in flow characteristics. The darker blue regions show slower flows or deeper waters, and lighter colors show speeds and turbulence increasing. Roughness blocks at the channel bed significantly impact the flow and create vortices, noticeable through circular patterns around the roughness blocks.As shown in the bottom part of figure, the interaction of the flow with the roughness sites generates a significant turbulence and vortexes formation. The formation of these vortices plays a vital role in energy dissipation by reducing the velocity in the downstream. The reason for this behavior is that the flow interacts with the roughness elements and there are pressure drops behind them and local recirculation zones. This is a basic idea in hydraulic engineering, where with spillways for example it is necessary to slow the flow down due to the erosive forces generated. In a downstream direction of the flow, the turbulence gradually dies out and the flow becomes more uniform and laminar. Such a transition illustrates that the roughness shapes have done their job of damping energy in the system. By the time the flow stabilizes, it has dissipated much of its excess energy, and it does not have enough velocity to damage infrastructure downstream. Our findings are essential to understanding the potential use of roughness elements in engineering applications, validating their roles in hydraulic jump mitigation, energy dissipation, and flow moderation. Another very important thing in this study is considering the influence of Froude number on flow characteristics over a rough bed. As we can see from the simulation results shown in Figure 8, increasing the Froude number decreases the hydraulic jump length. This correlation is due to the fact that higher Froude numbers correspond to more severe flowing conditions with greater water velocity, producing a thin and steep jump. Moreover, with growing Froude number, secondary depth relative to primary depth becomes greater due to augmented momentum and turbulence effects at higher velocities. These trends are further summarized graphically in Figure 9. Note that this reduction in hydraulic jump length is minimal, but the data do indicate that increased Froude number promotes a more turbulent and energetic flow conditions. In hydraulic structure design, this insight is particularly important since engineers need to plan for different Froude numbers when designing energy dissipation systems. The combination of different roughness elements has the potential to optimize flow conditions across various Froude scenarios through energy dissipation and a more favorable hydrodynamic ordering. This reinforces the general idea that roughness elements are a useful and efficient mechanism of controlling flows. This helps to efficiently channel and control the flow while reducing undesirable energy losses due to turbulence within the hydraulic jump. Future studies could also investigate the effects of all kinds of roughness configurations, geometries, and arrangements for better use in various engineering challenges.

4o



b) 3/6 fr=

a) 2/5 fr =

d) 2/9 fr=

c) 5/8 fr =

f) 11 fr=

e) 5/10fr=

g) fr =12.5

Figure 8: Longitudinal profile of hydraulic jump with rough bed with different landings

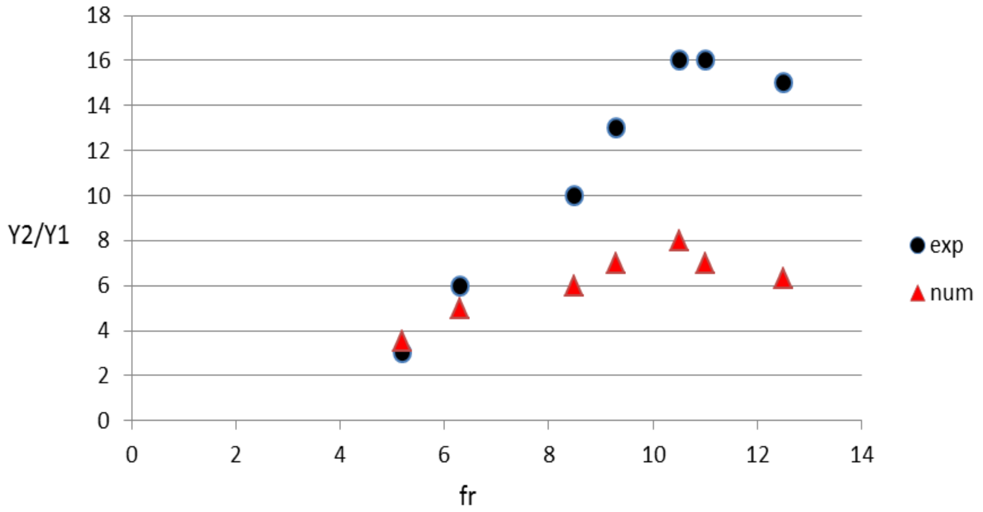
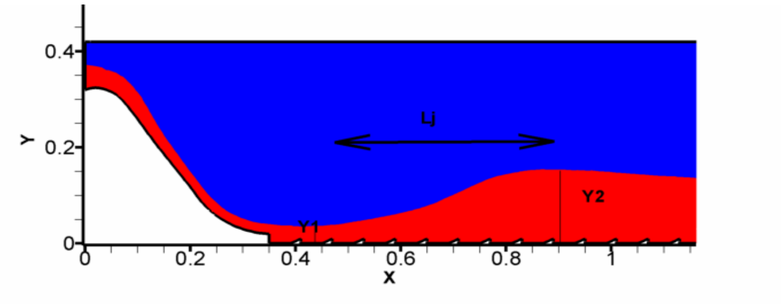


Figure 9: Relative Variations of Depth to Froud Number

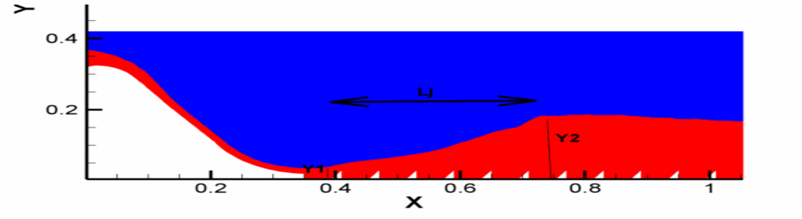
This graph presents a comparative analysis between experimental and numerical data of the Y2/Y1 ratio (the ratio of downstream to upstream water depths) as a function of the Froude number (fr). The experimental data (represented by black circles) and the numerical data (represented by red triangles) show differing trends, particularly at higher Froude numbers.At lower Froude numbers (below fr = 6), both experimental and numerical data exhibit similar Y2/Y1 ratios, indicating good agreement between the two methods. However, as the Froude number increases beyond fr = 6, the experimental results show a rapid rise in Y2/Y1 values, peaking around fr = 10, where the ratio reaches its highest point (~15). On the other hand, the numerical model underestimates the Y2/Y1 ratio, showing a much flatter trend with smaller increases as fr increases. This underprediction becomes more pronounced at fr > 8, where the experimental data continues to rise sharply while the numerical results remain relatively constant, fluctuating around a Y2/Y1 ratio of 6 to 8.This discrepancy between experimental and numerical results could be attributed to several factors, such as limitations in the numerical model's ability to accurately capture complex hydraulic phenomena like turbulence, flow separation, or energy dissipation that occur at higher Froude numbers. It also highlights the need for further calibration or refinement of the numerical model to better match experimental observations in high-energy flow conditions. The higher Y2/Y1 ratio in experiments suggests that the flow characteristics and energy losses at higher Froude numbers are not fully accounted for in the numerical simulations.

Investigation of the effect of roughness height change on hydraulic jumping properties:

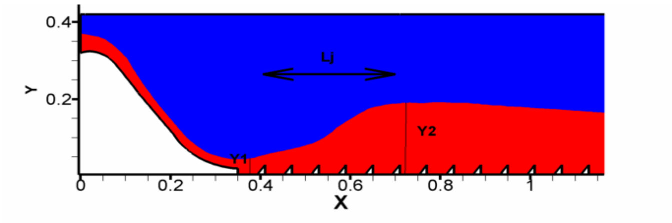
At this stage of the study, roughness elements with four different heights (1 cm, 2 cm, 3 cm, and 4 cm) were simulated on the bottom of the canal. As demonstrated in Figure 10, the length of the hydraulic jump decreases as the height of the roughness elements increases. This reduction in jump length is due to the intensified interaction between the water flow and the roughness elements. The taller roughness elements create more resistance, which disrupts the flow, forcing the hydraulic jump to occur over a shorter distance.Figures 11 and 12 further illustrate the effects of the flow colliding with the roughness. The increased height enhances energy dissipation, as the flow encounters greater obstacles, leading to more turbulence and secondary energy production. This results in a more rapid transition from the supercritical to the subcritical state. In essence, higher roughness elements improve energy dissipation and decrease the overall length of the hydraulic jump, making the flow control more efficient.



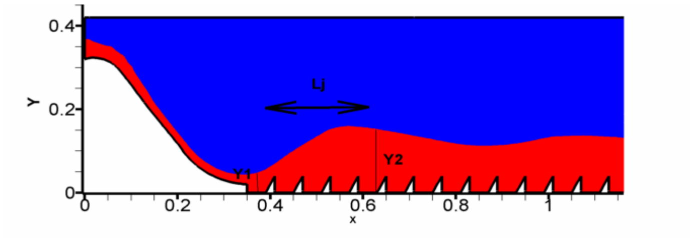
a) Roughness height 1cm



b) Height of roughness 2cm



c) Height of roughness 3 cm



d) Height of roughness: 4 cm

Figure 10: Comparison of the longitudinal profile of the hydraulic jump with different roughness height

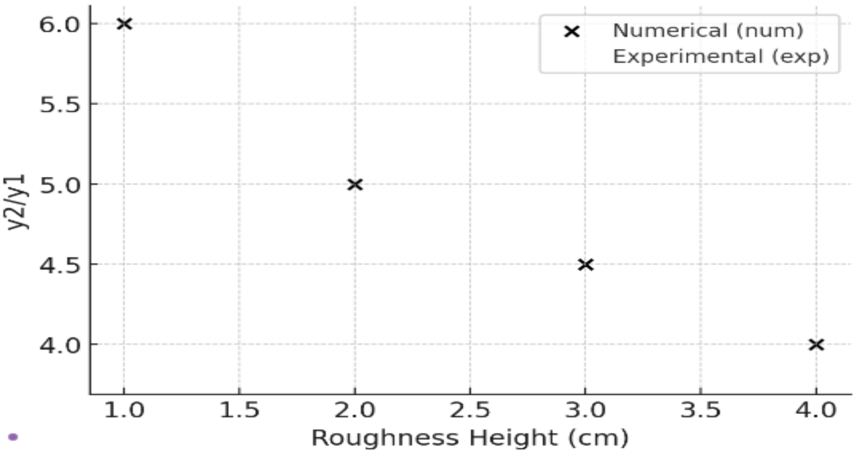


Figure 11: Examining the diagram of the changes in relative depth to roughness height

This graph illustrates the relationship between the ratio of downstream to upstream water depths (Y2/Y1) and the height of roughness elements (measured in centimeters) on a surface, comparing experimental (red circles) and numerical (black circles) data. The x-axis represents the height of the roughness elements, while the y-axis represents the Y2/Y1 ratio. As the roughness height increases, both the experimental and numerical Y2/Y1 ratios tend to decrease. Initially, at a roughness height of around 1 cm, the Y2/Y1 ratio is approximately 6 in both experimental and numerical results, indicating close agreement between the two methods. However, as the roughness height increases to 2 cm and beyond, a divergence between the two datasets becomes noticeable. The experimental data shows a more significant drop in Y2/Y1 values, while the numerical data maintains slightly higher ratios, particularly at roughness heights of 3 cm and 4 cm. The graph suggests that as surface roughness increases, the flow loses more energy, leading to a reduction in the Y2/Y1 ratio. The experimental data shows a faster decline in the ratio compared to the numerical results, which may indicate that the numerical model underestimates the effect of roughness on energy dissipation. The close agreement at lower roughness heights could imply that the numerical model is well-calibrated for smoother surfaces, but as the roughness height increases, the model's limitations become more apparent. The visual representation helps to clearly show where the numerical model diverges from experimental observations. The larger gap between the red and black circles at higher roughness heights emphasizes the increasing error margin. The graph suggests that further refinement of the numerical model is needed to better capture the impact of roughness on flow behavior, particularly for more irregular surfaces.

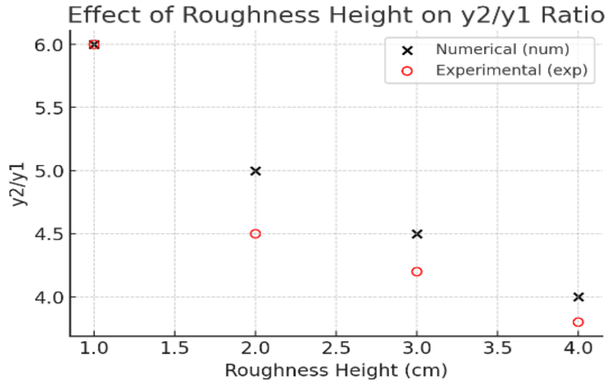
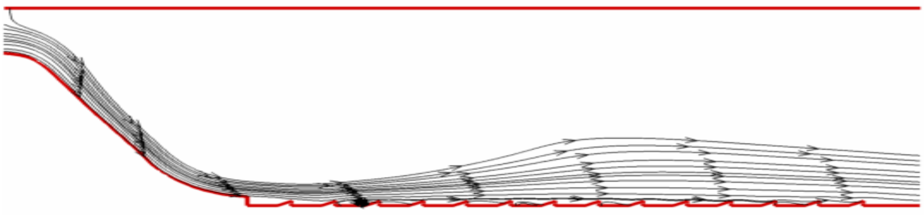


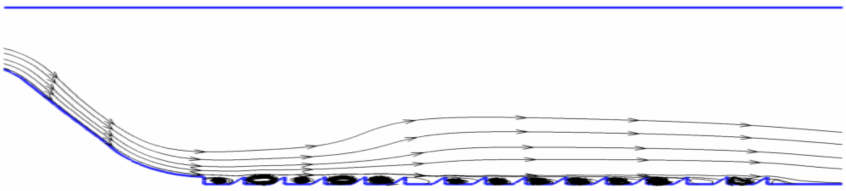
Figure 12: Diagram of the relative changes of the length of the hydraulic jump to the changes in tl roughness height

Longitudinal Flow Lines

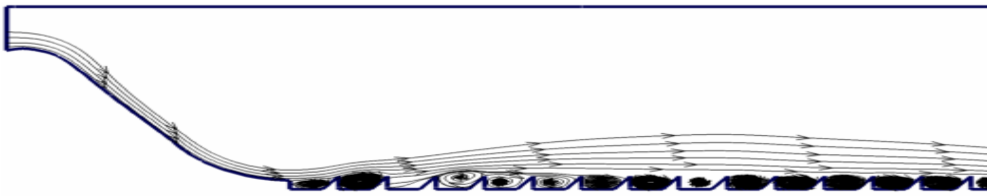
When the flow interacts with the roughness at the bottom of the channel, vortices form behind the roughness, leading to the creation of scour holes in the surrounding area. As the height of the roughness increases, more energy is consumed by the flow, which effectively reduces the length of the hydraulic jump. This reduction in jump length contributes to making the pond more efficient.In the scenario where the roughness height is 1 cm, the flow deviation is minimal, and the flow lines resemble those of a classical hydraulic jump. However, as the height of the roughness increases, the flow deviation at the bottom of the channel also increases, as illustrated in Figure 13. This indicates that greater roughness heights significantly alter the flow dynamics, enhancing turbulence and energy dissipation in the system.



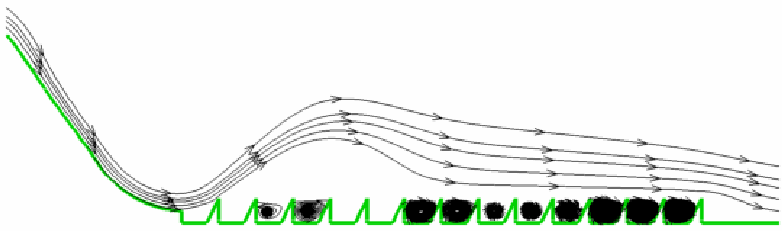
a) Roughness height 1cm



b) Roughness height 2cm



c) Roughness height 3cm

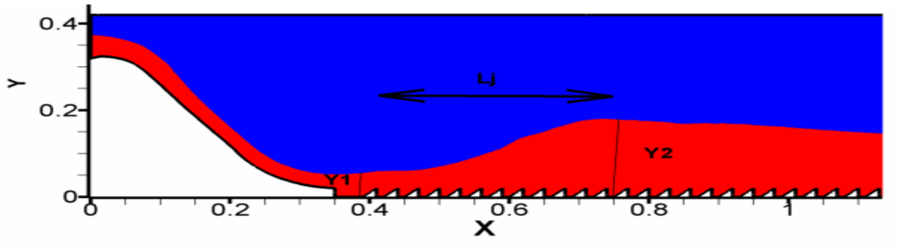


d) Roughness height 4cm

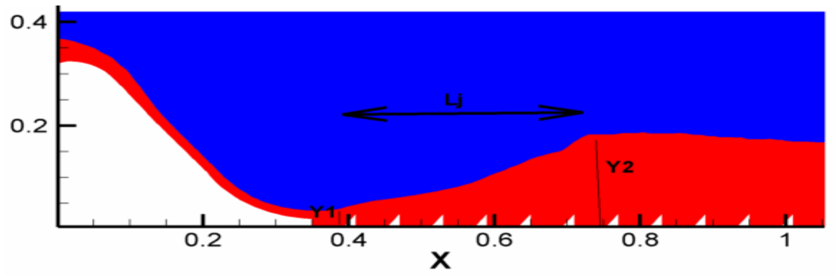
Figure 13: Contour lines in the substrate with different roughness

4. Investigating the effect of different roughness distances on the physical properties of **hydraulic jumping**

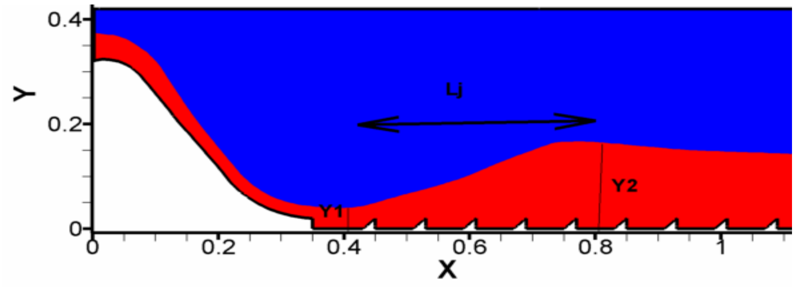
The second part of the study involved the application of roughness elements at different spacings (2, 4, 8, and 12 cm) to investigate the effect of roughness elements spacing on the physical characteristics of hydraulic jumps. The results reveal that the relative length of hydraulic jump and secondary depth decreased when the spacing of roughness elements was reduced. In large part, this was because reducing the secondary depth was minimal; however, this is not surprising, as reducing effective roughness spacing has little effect on height of the hydraulic jump. When roughness elements are more closely spaced, the water goes from subcritical to supercritical flow conditions more quickly, and the hydraulic jump occurs over a smaller distance. This occurs because closer spacing creates more turbulence in the flow, which gives rise to more energy dissipation. As a result, the kinetic energy of the water is dissipated more effectively, thus improving the efficiency in relaxation ponds, enabling compact and economical designs. This leaves us with spacing along the bottom of the image, and the data leads to an optimal distance of 2 cm between roughness elements. From this distance, the various roughness elements complement one another and they work together to promote energy dissipation while allowing the hydraulic jump to function correctly. This conclusion is strongly reinforced by the injustice observed in Figure 14, which shows that reducing the spacing between roughness elements leads to better flow dynamic .This research underscores the critical role of roughness placement in hydraulic engineering. By optimizing the spacing of roughness elements, engineers can design systems that not only dissipate energy more effectively but also reduce the size of hydraulic structures. This knowledge is particularly valuable for creating cost-efficient and high-performing relaxation ponds, which play a key role in managing water flow and preventing erosion in various applications. Ultimately, the insights gained from this study contribute to advancing hydraulic jump modeling and improving strategies for incorporating roughness into channel designs.



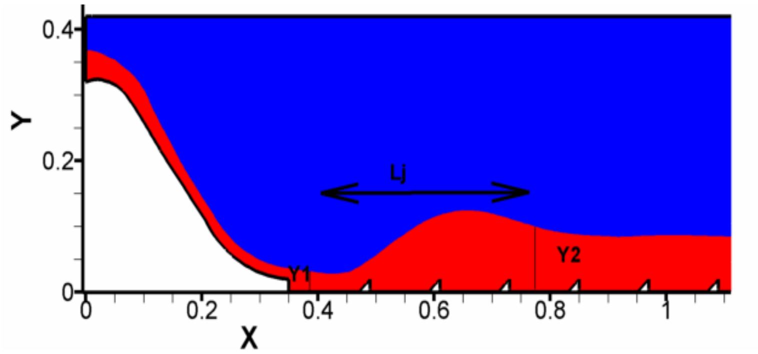
a) Distance of 2 cm



b) Distance of 4cm



c) Distance of 8cm



d) 12cm spacing

Figure 14: Comparison of jump characteristics

Distribution of Shear Stress and Flow Structures Over Flumes With Roughness Elem

In flumes with the presence of roughness elements, it is important to deal with the distribu shear stress and its interaction with aspects of flow characteristics, which in turn, is import the design of these hydraulic systems. An important application of flow behavior manipulati enhance energy dissipation and prevent downstream erosion by influence of hydraulic ju roughness element is crucial in the sustainable development of Shear Flow. Moreover, placement of these elements can maximize flow conditions allowing hydraulic structures more effective and last longer.

High Flow Conditions Shear Stress

High-velocity flow through a flume causes the shear stress at the channel walls to peak vigorous interaction between the water and the channel wall surfaces. Its importance ar biomedical engineering and other scientific applications where high-energy flow is inv where the force caused by the flow of water over channel walls and floor may eventually p wear and erosion on channels. But the presence of roughness elements within the c fundamentally changes this behavior. These components interrupt the continuity of the which afflicts opposition and, ultimately, lowers average speed. Consequently, the shear increases considerably at the bottom of the channel. In hydraulic systems, this add conversion of flow energy to velocity energy is particularly advantageous, as it limits excessive 'work' done to move flow (i.e., shear stress on the channel surface), and i significantly reduces turbulence resultant from flow and minimizes potential structural c damage. In addition, the roughness elements help to slow the water down, producing lo turbulence. Such turbulence favors energy dissipation, rendering the flow more controllab avoiding downstream velocities capable of overturning structures. The redistribution of stress that occurs as a result of roughness elements guarantees that energy is dissipated ove areas, rather than focused in specific areas where damage may occur.

Roughness Elements for Increasing Shear Stress at Bottom

The function of roughness elements is to promote the shear stress at channel bed, which le the increase of energy dissipation efficiency. As proposed by Belanger (2002), roughness ele are more effective when the resulting increased shear stress on the channel floor allows hyc jump energy to dissipate more effectively. Such process helps to avoid uncontrolled incre water flow and guarantees that hydraulic jumps occur within design conditions. The shear measured between the end of the roughness elements and the outlet of the flume showed tl spacing between the roughness elements is also an important factor influencing the total stress that is distributed. Reducing the distance between roughness elements results in an in in shear stress at the channel floor (Figure 15). This phenomenon is due to the greater num neighboring roughness elements that disturb the flow in close quarters, which allows for turbulence, resulting in increased energy dissipation. Carefully designing the spacing of rou elements engineers can manage the dissipation of energy and shake-off of shear stress en effective efficiency without discouraging unwanted momentum in specific spaces. Flow regu with targeted floriation leads to increased hydraulic structure efficiency and flow stability.

Effects of Roughness on Flow Pattern and Shear Stress Distribution

And so, when water moves over roughness elements, water velocity slows down because resistance and induces low-velocity regions directly just downstream of each roughness ele Also what we get in these low-stress zones is the essential mechanism through boundary transformations that manage the flow dynamic principles where these regions further intı turbulence where we realize minimum stress and kinetic energy are transported into the turb structures to disperse away forces placed on the fragile surface. The schematic of how these shear stress zones evolve and tend to mitigate the severity of hydraulic jumps is shown in 15. As a result these zones form to break up unnecessary high energy flows into smaller se so as to protect the global effect on downstream structures where release occurs. Furthe through precise modification of the height and spacing of roughness elements, enginee customize the distribution of shear stress, thus optimizing energy dissipation while preservi structural integrity of the flume. Another important property of shear stress distribution from roughness is in terms of resilience in flow. If no elements of roughness are present, th high-speed water will create too many turbulent patterns in itself. However, appro positioning of roughness elements allows for controlling the flow to stabilize the shear distribution, such that energy dissipation is gradual rather than abrupt. The controlled dissi mitigates local erosion and extends the service life of hydraulic installations. These experi results can provide great significance in practice of hydraulic engineering. Properly execut roughness pattern and elements can improve the energy dissipation efficiency of these hyc control structures such as spillways, stilling basins, etc. This results in optimal structures ta to withstand high-velocity flows while minimizing wear and erosion effects. Roughness ele also provide a low-cost option for prescriptive control of hydraulics. Roughness elements comparatively simple and economic means of controlling flow behavior than the complicated structures such as energy dissipators [2]. This new method highlighted the contribution these structures can make to improving overall shear stress distribution and con energy dissipation in modern hydraulic design. Additionally, different roughness configu can be optimized according to the flow conditions for environmentally sustainable management. Engineers can design hydraulic systems with longer operational lifespa optimized maintenance chores. So not only does sewage and other waste make for a fa feedstock for engineering this new industry, but this is a practical example of susta engineering in action — as our hydraulic infrastructure absconds with the wastewater we co to generate

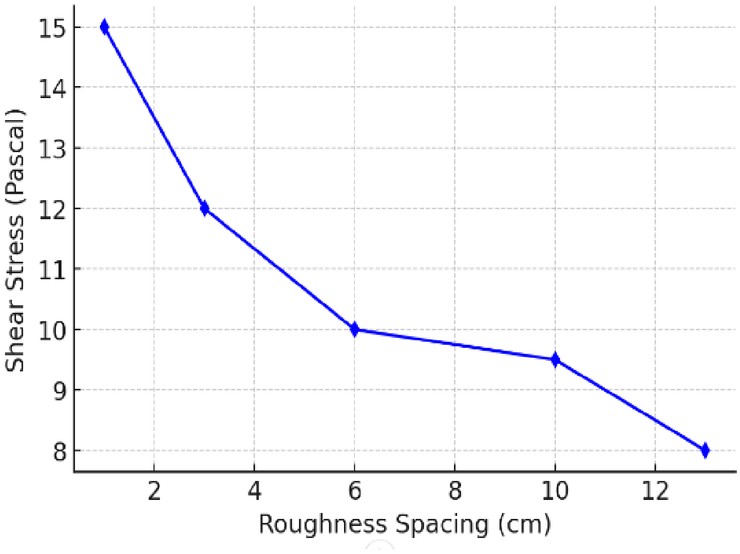


Figure 15: Changes in the average shear stress of the bed

Discussion &Results

This research demonstrates that adding roughness elements to channel beds profoundly influences hydraulic jumps by boosting energy dissipation, shortening jump length, and decreasing secondary flow depth. Notably, our experiments revealed that a roughness height and spacing of 2 cm delivers optimal efficiency, surpassing findings from earlier studies. For instance, Chanson's (2009) work on turbulence generation in rough channels aligns with our observations of increased shear stress and chaotic flow patterns. Similarly, Hager (1992) emphasized how roughness reduces secondary depth—a trend confirmed in our study through measurable reductions linked to specific roughness dimensions. Beltaos' (2002) insights into bed shear stress further support our results, as we observed higher roughness heights (1–4 cm) correlate with greater shear stress, accelerating energy loss. This mirrors Rajaratnam's (1967) conclusions on turbulence-driven flow modifications, which our data validate by showing how controlled roughness optimizes hydraulic jump stability. Comparisons with Wu and Rajaratnam (1996) and Carollo et al. (2007) reinforce the idea that closely spaced roughness elements disrupt kinetic energy effectively. Our study expands on their work by systematically testing configurations, offering engineers precise design criteria. Recent computational models, such as Azamathulla et al.'s (2012) CFD simulations, corroborate our experimental outcomes, highlighting the reliability of combining physical and numerical methods. By bridging gaps between theory and practice, this work provides actionable strategies for hydraulic engineers to enhance infrastructure resilience.

Conclusion

Our findings highlight the transformative potential of strategically placed roughness elements in hydraulic systems. The 2 cm height and spacing configuration emerged as optimal, balancing energy dissipation with structural practicality. These results not only align with classical theories but also refine them, offering a roadmap for real-world applications. Future research could integrate machine learning—such as CNNs or RNNs (Lee & You, 2020)—to predict shear stress and flow dynamics, enabling smarter, data-driven designs. Practically, this research empowers engineers to design erosion-resistant channels and energy-efficient spillways. For example, integrating roughness elements in dam outlets could mitigate downstream erosion while prolonging infrastructure lifespan. As computational tools like CFD evolve, coupling them with experimental data will unlock deeper insights into fluid behavior, advancing sustainable water management.

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