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EXPERIMENTAL-BASED STUDY OF THE ROUGHNESS BLOCKS IN FLUME ON THE RESULTING DRAG FORCES

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Abstract

The goal of the present work is to investigate the effect of micro-roughness blocks on the bed and sidewalls of the flume on the practical resistance attributes, specifically the coefficient of drag of the flow. Three models of block types have been used (cubic, semi-cylindrical, and pyramidal cones) with four arrangements of rows (single, double, triple with equal spacing, and triple with unequal spacing).

Pyramid blocks revealed the lowest average drag coefficient of 0.373, compared to cubes (0.497) and semi-cylinders (0.496). This is attributed to the streamlined shape of the cones, which reduces boundary layer separation and thus reduces resistance. Pyramid blocks also recorded the lowest average water depth ratio (d_2/d_1) of 0.77, indicating their high-energy dissipation efficiency and reduced erosion risk. The triple block configuration with unequal spacing showed the lowest drag coefficients (C_d), reaching 0.166 in pyramid blocks and 0.199 in cubes. The spacing between groups increases flow dispersion and improves dissipation efficiency. Pyramid blocks, especially when configured in three groups with unequal spacing, are the most efficient at reducing drag forces and coefficients and dissipating flow energy in flume, compared to cubes and half-cylinders. This makes them an effective choice for improving channel stability and reducing erosion in hydraulic systems.

Keywords: Drag Forces, Drag Coefficient, Energy Dissipation, Micro Roughness Blocks, Open-Channel Flow

1. INTRODUCTION

Open channels are an essential component of irrigation and water transport systems, designed efficiently to convey water with less energy loss. Transporting more than 60% of the irrigation water used for agriculture (FAO, 2017). These channels experience the accumulation of natural (branches, silt, rocks) and engineered (gates, bridge supports) obstructions that block flow Iqbal and Bin Riaz, (2024).

Previous studies have shown significant concern in analyzing the flow characteristics of open channels and the impact of hydraulic phenomena on their stability. In this context, a field study

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by Mazlin Jumainet et al., (2016) addressed the important hydraulic effects of frequent floods and their impact on the morphology of river and channel beds. This study focused on monitoring the dynamic changes in roughness coefficient and bed shear stress distribution in channels with moving beds during overbank flow conditions. The results indicated a significant increase in the roughness coefficient with increasing flow depth, reaching 42% in the main section of the channel, reflecting the crucial role of roughness in dissipating flow energy and shaping the bed.

A study by Castro-Orgaz and Dey (2019) showed that the spatial distribution of coarse elements, particularly unequal and grouped spacing, increases turbulence generation and increases energy dissipation efficiency compared to regular arrangements. The results of this study show that the triangular, unequal block arrangement proved to be the most efficient, recording the lowest drag coefficient (0.166) for pyramidal blocks. Thus, this study provides empirical evidence of the importance of strategic, irregular spacing as a critical design criterion for improving energy dissipation and reducing drag in hydraulic systems.

Al-Mousawi et al. (2016) showed that increasing the aggregate size of roughness blocks used in the stepped spillways led to a significant increase in energy dissipation efficiency. Coarse surfaces with larger grains (20-25 mm) records the highest energy dissipation rate, reaching 73.18%.

In open channels, flow resistance results from friction with surfaces or the presence of obstacles, which play a key role in controlling flow characteristics. According to Zhang et al. (2024), drag force is one of the main resistance forces affecting flow in open channels, which becomes apparent when flow is influenced by extended elements on the bottom or sides, such as flexible vegetation or geometrically shaped obstructions. The presence of such roughness blocks or obstructions directly affects the flow pattern and velocity, and can lead to vortices by the formation of eddies and backwater effects. Accelerated sedimentation and erosion processes, reducing capacity and threatening structural stability, irregular pressure distribution, and energy losses. This is due to the fact that streamlined shapes, such as cones, minimize boundary layer separation and reduce drag (Schlichting and Gersten, 2017). At the same time, at the same time, it can be engineered to improve aeration, reduce erosion, or enhance mixing. The presence of such roughness blocks or obstructions directly affects the flow pattern and velocity, and can lead to vortices by the formation of eddies and backwater effects. Accelerated sedimentation and erosion processes, reducing capacity and threatening structural stability, irregular pressure distribution, and energy losses. At the same time, it can be engineered to improve aeration, reduce erosion, or enhance mixing.

Despite numerous studies on flow in open channels, limited efforts have focused on systematically and experimentally evaluating the influence of obstacle geometry, spatial distribution, and both longitudinal and lateral arrangements on drag forces and flow behavior. Earlier research by Koenig and Roshko (1985) addressed the impact of geometrical configurations on drag and flow field interactions between bluff bodies. More recently, Anjum and Ali (2022) examined the influence of heterogeneous vegetation patch shapes and configurations—such as circular and square clusters arranged linearly or in staggered patterns

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on the spatial variability of flow structures. Their findings indicated that circular patches induce stronger momentum exchange and more pronounced flow separation zones, resulting in enhanced flow resistance and velocity reduction. Similarly, Gupta et al. (2023) investigated the effect of submerged roughness elements on drag characteristics. Furthermore, Idrees et al. (2024) and Rezaie et al. (2024) emphasized the role of roughness and vegetation elements in modifying flow resistance, turbulence levels, and sediment transport efficiency. These findings show the potential of improved obstacle design to improve hydraulic structure performance, enhance flow conveyance, and reduce maintenance requirements through better energy dissipation and increased channel stability.

Dissanayaka and Tanaka (2023) presented a study in an open channel examining the effect of the geometric shape and spatial arrangement of prominent obstructions (cylindrical and rectangular) on flow characteristics under different Froude number conditions. The study focused on the effect of different geometries of rough masses and their distribution within the channel on the drag forces and drag coefficient, supporting the importance of obstructions as a geometric shape influencing flow characteristics. It was observed that changing the shape of the obstruction leads to a clear difference in the characteristics of the bow-wave front and the length of the hydraulic jump detachment. Significant differences in the height of the wall-jet-like bow-wave were also recorded between circular and rectangular obstructions, especially in super-hydrophobic flow. Empirical equations were developed to relate the hydraulic characteristics to the geometric shape and spatial arrangement of obstructions.

Obead and Sahib (2023) carried out a numerical study using Compound Fluid Dynamics (CFD) to study the impact of flow deflector angle, location, shape, and passageway ratio on the erosion depth under different statuses of the flow. The included deflectors are two individual perforated shapes (one semicircular and one triangular) along with two paired solid shapes. The governing equations were solved by adopting finite-volume and finite-difference schemes, the turbulence was modeled using the RNG κ-ε approach. The volumetric effort (VOF) was applied as a method for modeling the free surface, while the flow-induced excess shear stress was used to determine the bottom convection model. The results showed that a single semicircular perforated deflector achieved the highest efficiency in minimizing the maximum local erosion by approximately 76.8%, followed by the double semicircular solid deflector with a reduction of 75.7%. In comparison, the triangular perforated deflector along with its solid counterpart double one achieved a reduction of 22% and 71.1%, respectively, relative to that of the conventional stilling basin. The study recommends the single semicircular perforated as the better choice for reducing maximum local erosion.

Kannangara and Tanaka (2023) conducted an experimental study to analyze the effect of the geometric shape of emerging obstacles on the flow characteristics in an open channel under different Froude number conditions. Their results showed that the geometric shape and lateral column arrangement significantly affected the formation of bow-waves, hydraulic jump separation, and the formation of wall-jet-like flows. Rectangular cylinders recorded longer wave-front lengths and earlier hydraulic jump separation compared to circular cylinders, highlighting the importance of geometric shape in modifying the flow resistance and energy dissipation pattern. These results directly intersect with the objectives of the current study, which evaluates the effect of the shape and arrangement of rough blocks on the drag forces and flow resistance under open channel conditions.

Based on prior mention, Gupta et al. (2023) conducted a laboratory experiment on an acrylic flume; researchers arranged rough, circular blocks of varying dimensions and numbers to study their effect on the drag force and drainage coefficient. They found that increasing the number and length of blocks resulted in an overall increase in the drag force due to the interference between the vortices generated by the blocks. They also found that the distance between the blocks played a key role, with a critical distance at which the effect of the blocks on the drag was greatest.

Ali et al. (2023) conducted a numerical study of the behavior of unsteady flow around a cylinder using FEATool in MATLAB. The study focused on the effect of changing the Reynolds number on the pressure and velocity distributions and the values of dynamic force coefficients such as the drag coefficient (Cd) and the lift coefficient (Cl). The study showed that increasing the Reynolds number leads to the development of vortices behind the cylinder and an increase in the density of the flow pattern, which directly affects the values of the drag and lift forces. While this work is not directly related to open-channel applications, it aids as an important reference for interpreting the physical phenomena of vortex formation and pressure distribution changes. These provide conceptual support for the present study, which experimentally examines the effect of small roughness blocks on the drag forces and energy dissipation in open channels.

Several experimental and numerical studies have revealed that the presence of submerged roughness within a flow profile, whether vegetation or artificial obstructions, leads to significant changes in flow resistance and hydraulic distribution patterns. Zhang et al. (2020) presented a model that considered the flexible submerged vegetation and its effect on drag forces, indicating that the drag coefficient decreases with increasing velocity but is obviously affected by vegetation density and relative submergence depth. In their detailed study, Idrees et al. (2024) further shown that adding roughness to the surface of broad-crested weirs significantly increases drag forces and creates vortices, which affect flow stability and reduce the discharge coefficient. Similarly, Chen et al. (2024) confirmed that a high density of submerged vegetation increases flow turbulence and results in an irregular shear stress distribution, reflecting the effect of roughness on the vertical velocity distribution and the drag coefficient (Cd). These results support the aim of the present study.

A more detailed examination of the initial mention, Rezaie et al. (2024) conducted an experimental study using a composite laboratory channel to examine the effect of rigid and flexible vegetation on flow resistance and sediment transport. The Darcy-Weisbach friction coefficient was found to be up to 1.5 times higher in vegetated floodplains than in unvegetated floodplains. The results also showed that the density and geometric distribution of vegetation directly affect the flow pattern and sediment transport efficiency. These results are consistent with the objectives of the present study, which investigates the effect of rigid geometric blocks on flow resistance by contributing the drag forces within the channels.

Djunur et al., (2024) conducted experimental study focused on enhancing the initial energy dissipation of water flow in a spillway to protect hydraulic structures, using rectangular baffle blocks with variable angles and flow rates. The study aimed to determine the effect of rectangular block angles on flow energy dissipation down the spillway. The results showed that blocks at an angle of 30° achieved a relative total energy dissipation directly proportional to the initial and successive Froude numbers, while this dissipation decreased with increasing Froude numbers for blocks at an angle of 180°. The maximum relative total energy dissipation (53.66%) was recorded at a relative water level of 2.5 cm above the baffle with the use of blocks at an angle of 30°. The inclined rectangular blocks were characterized by their ability to gradually reduce the flow velocity through the spaces between them, preventing the formation of retrograde momentum in the flow.

Mostefaoui et al. (2025) conducted an experimental analysis of the drag forces generated by cuboidal obstacles placed in a super hydrophobic flow and showed that the drag coefficient (Cd) is significantly affected by the ratio of the obstacle width to the water depth and decreases with increasing Froude number. A momentum-based hydraulic model was developed to explain the observed behavior, resulting in an accurate semi-empirical formula for calculating the drag coefficient. These results align with the aim of the present study, which focuses on measuring and interpreting the effect of geometric block shapes and arrangements on drag forces in open-channel flow. In this context, the geometric properties of obstacles, whether natural or artificial, lead to significant changes in flow patterns and hydraulic resistance forces.

Kashyap and Barman (2025) presented a recent experimental study examined the behavior of turbulent flow in a narrow open channel containing submerged flexible and rigid vegetation patches distributed on both sides of the channel. The results showed that the presence of these vegetation obstacles leads to a decrease in velocity within the vegetation zone and an increase above it. These results converge with present study expected findings that the existence of geometric elements such as blocks clearly affects the velocity distribution and momentum transfer within the waterway. The study highlights the role of distributing obstacles to improve flow resistance and modify its hydraulic properties.

The present study aims to conduct a laboratory investigation into the effect of roughness blocks of varying geometric shapes, dimensions, and arrangements distributed on the bed and walls of the flume on the generation and distribution of drag forces in open-channel flow, specifically at a low head flow pattern in the channels.

2. MATERIALS AND METHODS

The present work was carried out in the hydraulic laboratory within the Civil Engineering Department of the College of Engineering at the University of Babylon. S6-tilting flume of length (10m) and has a rectangular cross-section of 0.3×0.45m dimensions is used. It included hardened glass sidewalls and a stainless steel bed. Two portable carriages equipped with three ultrasonic water surface measurements were taken using point gauges positioned on brass rails along the flume apex edges, as presented in Figure 1

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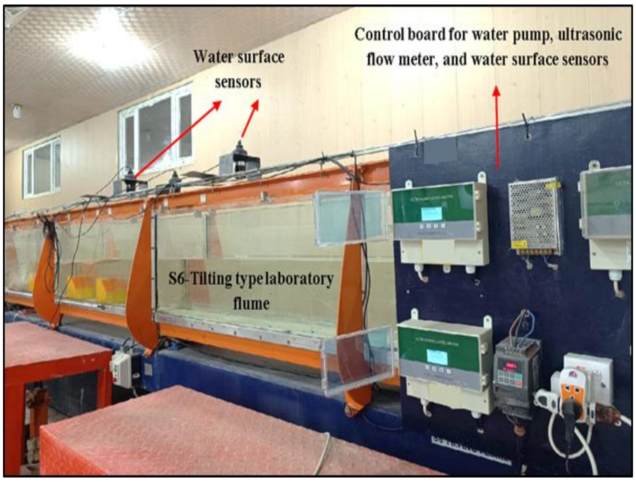
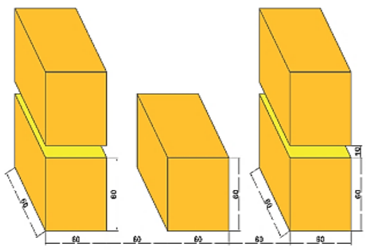
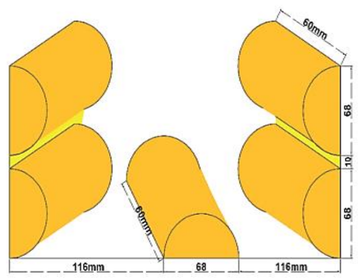


Figure 1 Experimental setup

To measure the depth-averaged velocity before and after the roughness blocks, a Pitot tube was equipped and installed along the region of the installation of the blocks. The geometric shapes, dimensions, arrangements, and operational hydraulic conditions of micro roughness blocks that were used in the present study are presented in Table 1.

Table 1 Details of the micro-roughness blocks used in the present work

Description	Arrangement/Number and Spacing	Dimensions (mm)	Configurations
Micro cubes installed on the two sidewalls and the bed of the flume.		Length= 60 width=60 height=60	
Micro semi-cylinder installed on the two sidewalls and the bed of the flume.	<u>**Group No.(1):**</u> 5 blocks	Diameter =68 Length= 60	

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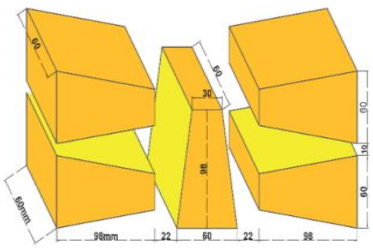
Micro pyramid installed on the two sidewalls and the bed of the flume.	**Group No. (2):** 10 blocks in two sets, 30cm apart. **Group No. (3):** 15 blocks in three sets, one at a distance of 30 cm and the last at a distance of 60 cm.	Bottom width=60 Top width=30 Height=98	

A calibration process via the volumetric method was used to check the accuracy of ultrasonic flow-meter measurements. A set of runs was performed to collect prescribed volumes and record their corresponding times. At the same time, the flow rates measured by the ultrasonic flow meter were monitored, and the total height of the water in the flume and the water depth over the tailgate were recorded. The results of the calibration process confirm the accuracy of measurements. A related head-discharge equation in the flume was derived based on recorded Q-H data, as shown in Figure 2.

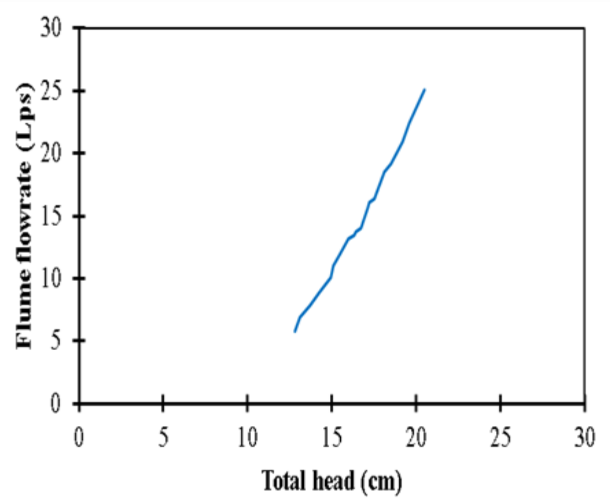


Figure 2 Rating curve for the flume

The head-discharge rating curve equation is expressed as:

$$Q = 0.003H^{3.0021} \qquad \ldots[1]$$

where Q is the flume discharge in (Liter/sec) and H is the total head in the flume (cm). Statistically, the coefficient of determination (R^2 = 99.2%) shows that the Eq. (1) excellent correlated between Q-H that is validating a high accuracy in the relationship between the variables. The exponent of 3.0021 specifies that the correlation is approximately cubic, which is reliable with hydraulic laws such as the flow through gates in open channels (Zhang et al. (2024). A range of heads versus their corresponding discharge are selected to simulate the low flow conditions in the flume as presented in Table 2.

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Table 2 Head versus discharge for experimental runs

Discharge, Q (Lps)	Total head, H (cm)
6.9	13.1
13.2	16.0
18.5	18.1

The measurements and experimental runs were carried out according to the methodology presented in Figures 3, and 4, respectively.

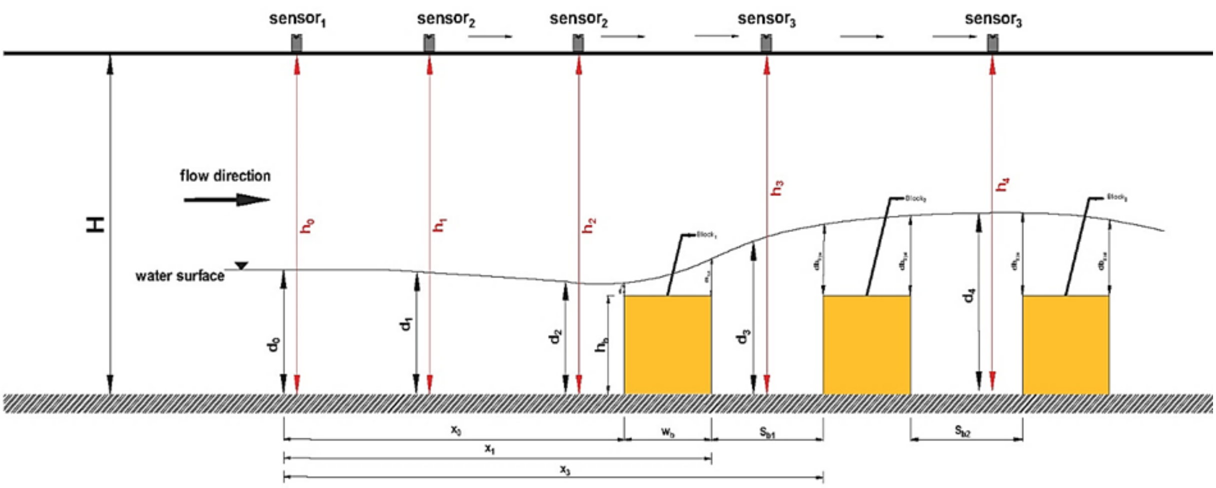

Figure 3 Schematic representation for experiments measurements

In open channel flow with roughness elements, the drag is measured by a dimensionless parameter denoted as C_d, which represents the proportion of the drag force acting on the surface of the block to the dynamic force of the flow. This dimensionless parameter can be expressed mathematically as follows (Liu, and Zeng, 2016):

$$C_d = \frac{F_d}{\frac{1}{2}\rho U^2 A_{proj.}} \qquad .....[2]$$

Where F_d is the drag force exerted on roughness block in (kN), U is the depth averaged velocity upstream of the roughness block in (m/sec), and $A_{proj.}$ is the submerged frontal projected area of the roughness block in (m^2). High disturbances and irregular flow separation lead to dynamic changes in the forces acting on the surface of the blocks.

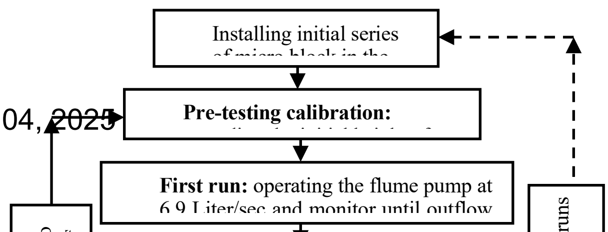

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Figure 4 Flow chart for experimental work methodology

The Momentum Loss method was used to measure the drag force F_d exerted on the blocks.

$$F_d = \rho Q \nabla U \qquad \text{.....[3]}$$

Where ρ is the unit weight of water (1000 kg/m^3), Q is the flow discharge (m^3/sec), and $\Delta U = U_1 - U_2$, in which; U_1, and U_2 are the depth- averaged velocities for upstream and downstream roughness groups in (m/sec), respectively. The submerged frontal projected area of the roughness blocks that facing the flow for roughness group can be calculated as:

$$A_{proj.} = N \times A_{Block} \qquad \text{.....[4]}$$

Where N is the total number of roughness blocks in the group, A_{Block} is the frontal projected area of single block (m^2). The procedure followed herein to measure U_1 and U_2 for each arrangement of roughness blocks is as descripted in Table 3.

Table 3 Measurements of depth-averaged velocity for block arrangements

Arrangement*	Location of measurement of depth average velocity	
	For U_1	***For U_2***
Group No.(1)	Upstream, frontal face of the block.	Downstream, back face of the block.
Group No. (2)	Before frontal face of block set(1)	After back face of block set(2)
Group No. (3)	Before frontal face of block set(1)	After back face of block set(3)
* As prescribed in Table 1.		

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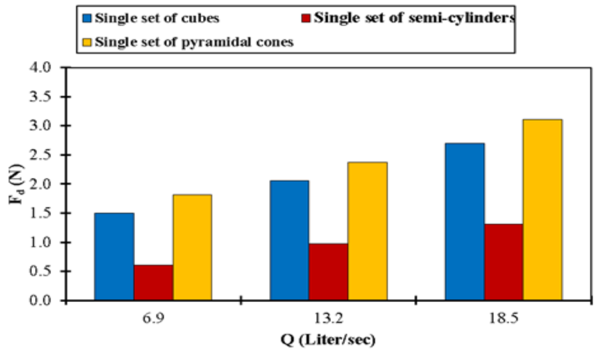
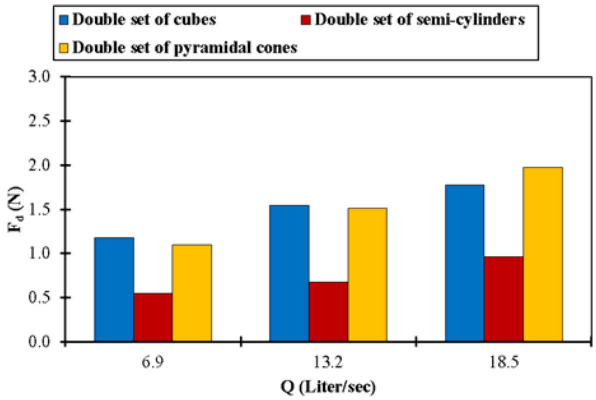
3. Analysis Of The Results

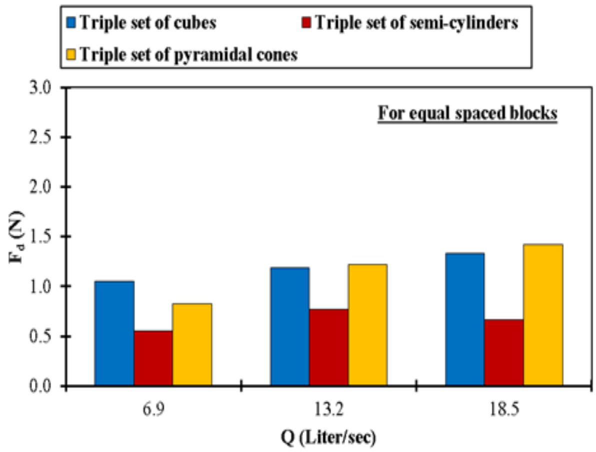
Figure 5 shows the variations in drag force against Froude number for each type and arrangement of micro roughness blocks used in the present work.



a- F_d vs. Q for single set of roughness blocks.



b- F_d vs. Q for double set of roughness blocks.



c- F_d vs. Q for triple set of equal spaced roughness blocks.

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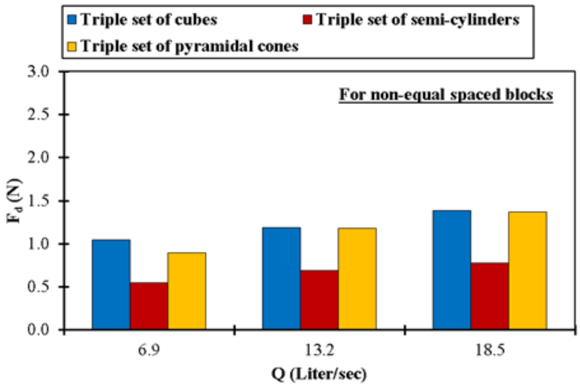
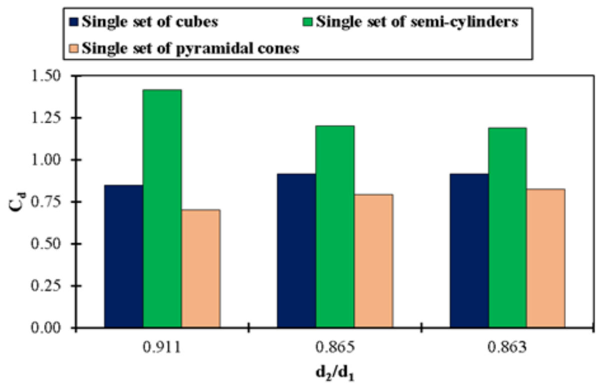


d- F_d vs. Q for triple set of un-equal spacing of roughness blocks.

Figure 5 Variation of Drag force versus upstream flow rate in the flume for different types and arrangements of micro-roughness blocks

From the results of Figure 5, it is obvious that the geometric shape of the micro-roughness blocks is a significant factor in creating the drag force. Cuboidal micro-blocks generate moderate to high drag, increasing with the number of blocks but roughly fixed at a triple arrangement. Their drag behavior is intermediate between pyramidal (highest drag) and cylindrical (most streamlined). Pyramidal blocks are more effective at increasing flow resistance due to their sharp edges and corners, which create severe flow separation. The triple arrangement does not significantly increase the drag force for all shapes of blocks unless it is affected by effective dynamic interaction between the blocks. While the Froude number (Fr_1) is directly related to F_d, with the block type controlling the rate of this effect.

Investigation the variation of the drag coefficient (C_d) with the water depth ratio (d_2/d_1) of micro roughness blocks supports improving the hydraulic resistance modeling and the accuracy of energy loss estimations, and understanding the effect of roughness distribution as shown in Figure 6.



a- C_d vs. d_2/d_1 for single set of roughness blocks

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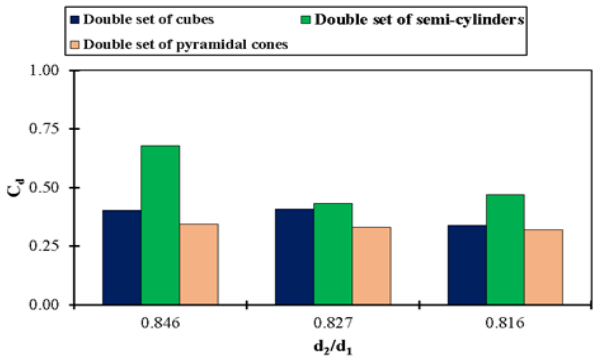
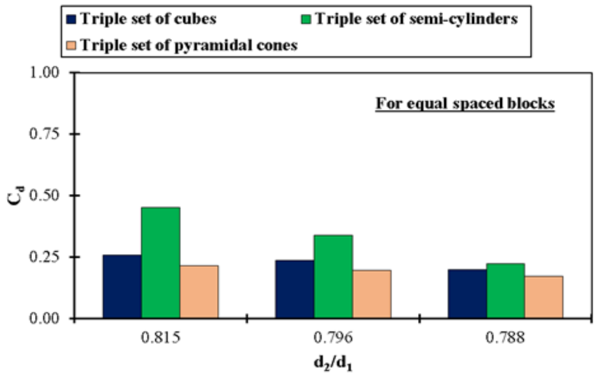
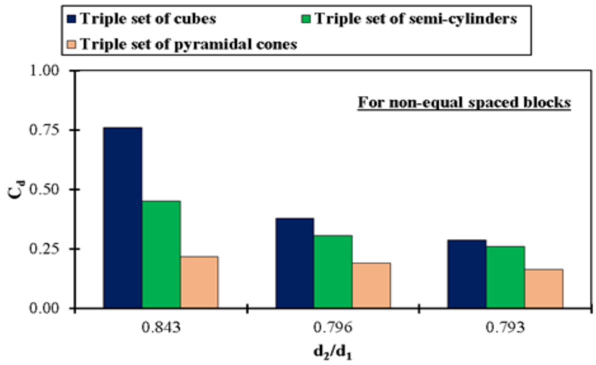


b- Cd vs. d2/d1 for double set of roughness blocks



c- C_d vs d_2/d_1 for triple set of roughness blocks



d- C_d vs d_2/d_1 for triple set of un-equal spacing of roughness blocks

Figure 6 Variation of Drag coefficient versus downstream/upstream water depth ratio for different types and arrangements of micro-roughness blocks

The hydraulic behavior for various types and configurations of micro roughness blocks can be statistically analyzed as presented in Table 4.

Table 4 Descriptive statistics for cd and d2/d1 for various micro roughness blocks.

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Block Type / Statistical Measure	Cubic (All groups)		Semi-cylindrical (All groups)		Pyramidal cones (All groups)	
	C_d	***d_2/d_1***	***C_d***	***d_2/d_1***	***C_d***	***d_2/d_1***
Mean	**0.497**	**0.830**	**0.496**	**0.830**	**0.373**	**0.770**
Standard Error	**0.081**	**0.0107**	**0.081**	**0.011**	**0.072**	**0.012**
Standard Deviation	**0.280**	**0.037**	**0.279**	**0.037**	**0.250**	**0.042**
Range	**0.719**	**0.123**	**0.078**	**0.001**	**0.658**	**0.128**
Minimum	**0.120**	**0.788**	**0.719**	**0.123**	**0.166**	**0.731**
Maximum	**0.918**	**0.911**	**0.199**	**0.788**	**0.824**	**0.860**

Findings presented in the Table IV are summarized as:

Effect of block shape on drag coefficient (Cd): Pyramidal cones recorded the lowest mean of Cd (0.373), than by cubes (0.497) and semi-cylinders (0.496). This behavior is theoretically supported by classical boundary layer theory, which indicates that streamlined shapes such as cones tend to minimize boundary layer separation and thus reduce pressure drag (Schlichting and Gersten, 2017). However, the present findings provide experimental confirmation of this concept under open-channel conditions.

Effect of shape on depth ratio (d_2/d_1): Pyramidal cones recorded the lowest mean depth ratio (0.770), compared to (0.830) for other types. This indicates that lower d2/d1 reveals larger energy dissipation efficiency, which reduces the risk of downstream erosion.

Effect of block arrangement on variance, cubes recorded the higher range of Cd (0.719) and standard deviation (0.280), while semi-cylinders were more stable (Cd range = 0.078). This is because the random distribution of cubes is sensitive to flow direction, while curved shapes are less affected.

4. Empirical Model

Empirical equations transform observed data such as the variation of coefficient of drag Cd across different shapes and arrangements of roughness blocks into predictive models, involving hydraulic and geometric variables to the behavior of drag forces. A general non-dimensional model for the Cd for the investigated block types (cubic, semi-cylindrical, pyramidal cones) and configurations can be expressed by Buckingham π-theorem:

$$C_d = f(Fr_1, \frac{d_2}{d_1}, S, A_r) \qquad .....[5]$$

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Where S is the shape factor depending on the block types (can be set numerically: cubic = 1, semi- cylindrical = 2, pyramid cones = 3), and A_r is the arrangement types (can be set numerically: single = 1, double = 2, triple-equal spaced = 3, and triple unequal spaced=4). A proposed empirical formula has been adopted as:

$$C_d = \alpha_0 (Fr_1)^{\alpha_1} \left(\frac{d_2}{d_1}\right)^{\alpha_2} (S)^{\alpha_3} (A_r)^{\alpha_4} \qquad \text{.....[6]}$$

Where α_0, α_1, α_2,α_3, and α_4 are the regression parameters of the proposed model. A multiple nonlinear regression analysis has been carried out using IBM SPSS Statistics 27 software. The regression parameters estimates for Eq. (6) are presented Table 5. The results of ANOVA test performed to evaluate the prediction model are given in Table 4.

Table 5 Parameter estimates for eq. (6)

Parameter	**Estimate**
α_0	1.655
α_1	-1.032
α_2	0.253
α_3	1.00
α_4	-1.110

Therefore, the following form can write the empirical equation that correlate the drag coefficient to the hydraulic parameters under consideration:

$$C_d = \frac{1.655S}{(Fr_1)^{1.032}(A_r)^{1.11}} \left(\frac{d_2}{d_1}\right)^{0.253} \qquad \text{.....[7]}$$

Table 6 Results of anova test

Source	**Sum of Squares**	**df**	**Mean Squares**
Regression	12.136	5	2.427
Residual	0.511	31	0.016
Uncorrected Total	12.647	36	

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Corrected Total	3.786	35	
$R^2 = 1 - \frac{RSS}{CSS} = 0.865$			

Where RSS is the residual sum of squares and CSS is the corrected sum of squares.

Analysis of variance (ANOVA) in Table 6 shows that the multiple regression model (Eq. 7) used to predict the drag coefficient (Cd) has high explanatory power, explaining 86.5% of the variance in the Cd data (R2=0.865). The large sum of squares for the regression (12.136) compared to the residual (0.016) indicates solid statistical significance (p<0.001) for the independent flow characteristics variables (d2/d1, and Fr1) in determining Cd, approving the reliability of predictive model.

5. CONCLUSIONS

1. Pyramid blocks provide good hydraulic performance in terms of reduced flow resistance (C_d) and improved energy dissipation efficiency (lower d_2/d_1), while semi-cylindrical blocks have stable performance and low drag coefficient variation, indicating them more reliable in varying flow conditions.

2. The triple block arrangement with unequal spacing revealed the better hydraulic performance, reducing C_d values to a minimum (0.166 for the pyramid), showing the role of the compound spacing in improving flow characteristics and providing higher stability in the water section.

3. Statistical modeling and experimental analysis have confirmed the basic relationship between initial Froude number (Fr_1), depth ratio (d_2/d_1), and block arrangement in inducing drag forces, assisting the development of accurate block shape and configuration-based design tools to improve the hydraulic performance of irrigation and water conveyance canals.

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