Effect of bed roughness shape on mitigating scour the downstream of parallel sluice gates

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ABSTRACT

Parallel sluice gates are crucial components in hydraulic structures, offering cost-effective and operationally flexible solutions for flow control in wide channels. This laboratory investigation examines the effectiveness of different bed roughness configurations—specifically trapezoidal and cubic geometries—in mitigating local scour downstream of parallel sluice gates, a persistent challenge that threatens structural integrity. The study systematically evaluated scour parameters under varying flow conditions and gate configurations, employing both quantitative measurements and qualitative flow visualization techniques. Results demonstrate that trapezoidal roughness elements significantly outperform their cubic counterparts across all measured parameters. Specifically, trapezoidal configurations achieved reductions of 25.3% in Average scour depth, 22% in scour length, 30.5% in cross-sectional area, and 50% in scour volume, compared to modest reductions of 20%, 14.35%, 21.57%, and 34.7% respectively for cubic roughness elements. The flow expansion ratio (e) emerged as a critical parameter, with optimal performance observed at e = 0.56 (two gates open). However, effectiveness significantly decreased at lower expansion ratios (e = 0.283, single gate open) due to asymmetric hydraulic jumps and reverse flow patterns. Analysis of Froude number (Fr) effects revealed that trapezoidal roughness maintains superior performance even under high Froude numbers (Fr > 5) during asymmetric flow conditions, while cubic roughness shows diminished effectiveness. These findings provide valuable insights for optimizing hydraulic structure design, emphasizing the superiority of trapezoidal bed roughness configurations for enhanced scour protection and system stability in irrigation and drainage applications.

KEYWORDS

Bed roughness, Parallel sluice gates, Local scour mitigation, Scour reduction.

1. Introduction

Sluice gates are pivotal hydraulic structures widely utilized to control water levels, discharge sediments in diversion dams, maintain desired water levels, and measure flow in open channels [1]. However, using a single wide gate for Wide channels is often neither cost-effective nor operationally practical due to maintenance and control challenges. Consequently, engineers prefer deploying multiple parallel gates to achieve similar results [2].

The hydraulic conditions downstream of these parallel gates can become complex due to variations in gate openings. Adjusting all open gates to a certain value may result in more favorable flow conditions, which can be impractical under real-world constraints [2]. When multiple gates are operated in parallel, challenges may arise during low-flow periods, potentially reducing downstream water delivery. A common practice is to open all gates slightly to share the flow evenly. However, this strategy is susceptible to blockages caused by floating debris or sediments and operational issues due to lifting forces, which may lead to gate malfunctions. Alternatively, opening fewer gates with larger openings has been suggested by [1]. This approach, while beneficial in certain scenarios, can disrupt flow dynamics, influence velocity profiles and flow patterns, and potentially increase scour risk [3]. Additionally, improper gate operation can lead to severe localized scour downstream of the stilling basin [4].

Understanding the scour phenomenon is crucial when scour depth is significant enough to affect the foundations of river structures, potentially threatening their stability or causing substantial damage. Traditional methods for evaluating scour depth primarily rely on empirical formulas or physical modeling [5]. Despite extensive research in this field, a comprehensive and general formula for predicting local scour depth around river structures remains elusive. This gap has led researchers to focus on specific cases and conduct laboratory experiments to address this knowledge gap [6]. One effective method to reduce scour hole dimensions is through bed roughening. Rajaratnam [7] was the first to investigate hydraulic jumps over rough beds and demonstrated that hydraulic jump lengths are shorter on rough surfaces than on classical smooth beds. Since then, various configurations of bed roughness have been examined to determine their effects on hydraulic jump length [8–11]. Numerous studies have also evaluated these configurations, assessing their impact downstream of sluice gates.

The following sections review research on the influence of bed roughness and flow expansion on the characteristics of hydraulic jumps [12–19]. Moreover, several studies have investigated the effects of bed roughness and adverse slopes on hydraulic jumps [20–22]. Finally, extensive research on the impact of bed roughness on downstream scour of sluice gates is discussed in the subsequent sections [22–29].

Karimi et al [12] investigated the influence of bed roughness on pressure fluctuations within a stilling basin featuring sudden divergence. Their findings demonstrated that roughness elements substantially dampened turbulent hydraulic jump fluctuations. Their observations revealed that the maximum pressure fluctuation intensity coefficient for a rough divergent jump was 0.023, representing a reduction of approximately 53% compared to a smooth divergent jump and 70% compared to a classical hydraulic jump. Furthermore, Abbaspour and Abdian Rukni [13] conducted a comprehensive study examining the combined effects of bed roughness and stilling basin divergence on hydraulic jump characteristics. Their results demonstrated that increasing the basin's divergence angle reduced the conjugate depth by up to 25.5% and the jump length by as much as 66.2% when rough beds were incorporated into the design. The implementation of cubic roughness elements alone was found to reduce jump length by an average of 60.3%. Their study also examined the effects of basin divergence without bed roughness, revealing that under these conditions, the hydraulic jump length decreased by 37% to 47%, with more substantial reductions observed at higher divergence angles. These findings emphasize the significance of both wall divergence and bed roughness in reducing hydraulic jump length and conjugate depth, which can significantly enhance the cost-effectiveness of basin

designs and improve control over hydraulic jumps. These insights provide valuable contributions to engineering applications in water management systems.

Daneshfaraz et al. [14] examined the impact of channel bed roughness on secondary jump depth and length reduction. Their research indicated that diverging stilling basins with rough beds reduced conjugate jump depth by an average of 12% to 16% compared to smooth-bed diverging basins, regardless of opening ratios. The average reduction in jump length across all opening ratios for diverging basins with rough beds was approximately 20%. Moreover, Hasani et al. [16] investigated hydraulic jump pressure fluctuations within a stilling basin featuring a rough bed. Their findings demonstrated that the introduction of bed roughness significantly reduced the intensity of pressure fluctuations in stilling basins with sudden expansions. In these expanded sections, energy loss increased while pressure fluctuation intensity decreased, a phenomenon attributed to lateral vortex formation. Mahtabi et al. [17] analyzed 581 data points, including 280 natural bed data and 301 artificial bed data, using artificial neural networks to classify hydraulic jumps in uneven beds. Their findings revealed that shear stress in rough beds was significantly higher than in smooth beds and increased sharply with rising Froude numbers. Fallahi and Heidarpour [18] introduced an innovative approach to analyzing hydraulic jump characteristics under varying conditions, including expansion ratios (1, 1.33, 1.6, and 2), bed roughness (0, 1.33, and 2 cm), and Froude numbers (4.9–9.5). Their research demonstrated that abrupt expansions combined with bed roughness reduced sequent depth and jump length by 49.5% and 22.34%, respectively. Energy dissipation was enhanced by 31.1% compared to classical hydraulic jumps.

Akib et al. [19] conducted a study to explore the effects of various roughness shapes on hydraulic jumps. The findings revealed that at lower Froude numbers, the influence of rough bed elements was minimal. However, as the Froude number increased, the roughness shapes played a significant role in reducing the hydraulic jump length. Gandhi's research [20] focused on hydraulic jumps in a rectangular canal with sudden expansions. His findings highlighted the significant benefits of incorporating baffle blocks and sills. These structural elements enhanced energy dissipation, leading to more controlled and efficient flow behavior. Tahmasbipour et al. [21] investigated T-jumps in channels with abrupt expansions and sinusoidal bed roughness. Their results demonstrated that the introduction of this roughness resulted in a decrease in energy dissipation. Sajadi et al. [22] examined S-jumps in expanded canals, employing cross-beam roughness elements arranged in various configurations. Their innovative approach successfully stabilized the flow, eliminated asymmetry, and reduced the length of the hydraulic jump.

Parsamehr et al. [23] investigated hydraulic jump behavior on rough beds with reverse slopes, demonstrating that increasing roughness element height and spacing, in combination with steeper reverse slopes and higher Froude numbers, contributed to a reduction in secondary jump depth, while simultaneously increasing energy loss and shear stress. Gupta and Dwivedi [24] studied the effect of gravel size on hydraulic jumps in stilling basins. Their results showed that larger gravel reduced relative jump height and increased energy dissipation. These findings highlight the role of optimized bed roughness in improving energy dissipation and hydraulic performance.

Hamidifar and Nasrabadi [25] conducted 33 experiments investigating the erosion behavior of noncohesive sediments downstream of smooth and rough aprons under five roughness conditions (k = 0, 1, 1.85, 3.35, and 5 mm). Their results demonstrated that rough aprons significantly reduced scour characteristics, achieving a minimum 60% reduction in maximum scour depth compared to smooth beds. Increased submergence factors further

reduced scour depth while altering scour hole geometry, resulting in flatter dune formations. Additionally, hydraulic jump length exhibited a positive correlation with submergence levels. In a related study, Ali et al. [26] investigated the impact of triangular serrated bed designs within stilling basins, demonstrating significant improvements in scour mitigation. The serrated bed configuration notably reduced both scour depth and length compared to traditional designs. Specifically, the serrated bed achieved a 63.4% reduction in scour depth for fine sands and a 44.2% reduction for coarse sands. Furthermore, scour length decreased by 30.2% for fine sands and 20.6% for coarse sands, highlighting the effectiveness of incorporating rough bed designs in optimizing stilling basin performance. Aamir and Ahmad [27] further examined the effectiveness of roughened stilling basins in mitigating maximum scour depth. Their research documented substantial reductions in scour depth, ranging from 69.8% to 82.8%, demonstrating the potential of roughened surfaces to significantly enhance hydraulic performance.

Urbański et al. [28] investigated the effects of various energy dissipator designs on local scour downstream of sluice gates, comparing three configurations: flat slabs, slabs with baffle blocks, and riprap layers. Their findings indicated that flat slabs resulted in the greatest scour depth and erosion rate, posing significant risks to structural integrity. In contrast, baffle blocks and riprap layers effectively reduced scour depth and delayed erosion. Among these configurations, double-row baffle blocks proved most efficient, providing superior scour mitigation and structural stability. An experimental study by Aamir et al. [29] investigated scour behavior under wall jet influence, focusing on differences between rough and smooth stiff aprons. Their research demonstrated that maximum scour depth decreased with larger sediment sizes, wider sluice openings, and longer apron lengths. Specifically, rough aprons significantly reduced maximum scour depth compared to smooth counterparts. Finally, Maleki and Fiorotto [30] examined the influence of bed roughness on hydraulic jump and scour dynamics. Their findings revealed that increased roughness reduced subcritical depth and jump length, leading to a 30–35% reduction in stilling basin dimensions. Rough beds also mitigated scour intensity by decreasing near-bottom velocities and altering shear stress distributions. An experimental study conducted by Mahmoudi et al. [1] investigated the phenomenon of local scour occurring downstream of parallel sluice gates. The research highlighted that as the gate opening ratio decreased, the scour dimensions increased significantly, compared to scenarios where the gates were fully open. Additionally, Mahmoudi et al. [31] proposed a predictive equation specifically designed to estimate the scour depth downstream of parallel sluice gates.

While considerable research has been dedicated to understanding the effects of bed roughness on hydraulic jumps and its role in mitigating scour, there remains a notable gap in studies focusing on the specific impact of rough bed structures on scour downstream of parallel sluice gates. To address this research deficiency, the present study undertakes experimental investigations aimed at evaluating the influence of cubic and trapezoidal roughness elements on the dimensions of scour holes downstream of parallel sluice gates. By examining these effects, this study seeks to contribute valuable insights into improving scour mitigation strategies and advancing hydraulic engineering practices.

2. Materials and Methods

2.1. Laboratory equipment

The present study was conducted in a laboratory flume located in Farhoudi's applied Hydraulic Laboratory at Urmia University. The flume, featuring a rectangular cross-section, measured 8 meters in length, 60 cm in width, and 75 cm in height. A sediment recess, integrated into the flume setup, was 20 cm deep and 1.8

meters long. The flume walls were constructed from transparent plexiglass, enabling clear observation of sediment transport and flow dynamics within the channel and sediment recess. The experimental setup included a pump capable of delivering a nominal flow rate of 60 Lit/sec. Flow rates were precisely measured using an ultrasonic flow meter (model UFM610P) manufactured by Krohne, with an accuracy of ±2%. Water depth measurements were conducted using a point gauge with an accuracy of 1 mm, while the final bed profiles were determined using a laser meter with the same level of accuracy. To examine the effects of parallel sluice gates on hydraulic behavior, three steel sluice gates, each with a width of 17 cm (3.4 b/a), were installed. The minimum gate opening was set to 5 cm to avoid scale effects, as recommended by Roth and Hager [32]. Based on the gate opening and the design criteria of the USBR Type I stilling basin, the stilling basin length was established at 164 cm. An end gate was employed to stabilize the hydraulic jump inside the flume and to form a free jump. The hydraulic jump was adjusted by manipulating the end gate according to the sliding gate openings and the inflow entering the channel. For each experimental scenario, the gate opening was maintained constant while the upstream water level was modified to achieve the desired Froude number range of 3.5 to 6.5 (Based on laboratory limitations) .

The positioning of roughness elements within the flume was guided by established recommendations. Abdellateef [33] suggested that the distance between the first roughness element and the gate should be twice the maximum gate opening, while Aboulatta [34] recommended this distance to be 4.5 times the initial depth of the hydraulic jump. Considering these guidelines and accounting for the flow contraction coefficient, the first row of roughness elements was placed 13.75 cm downstream from the gates. Regarding roughness element dimensions, Abdelsalam [35] recommended that for Froude numbers between 4 and 8, the height of roughness elements should not exceed half of the initial hydraulic jump depth. In this study, with a gate opening of 5 cm and a flow contraction coefficient of 0.61, the initial depth of the hydraulic jump was calculated to be 3.05 cm. Consequently, the height of the roughness elements was determined to be 1.5 cm.

2.2. Experimental procedure

To mitigate the occurrence of initial unwanted scour in the sediment recess, a controlled experimental procedure was implemented. The channel was pre-filled with water before the gradual opening of the main gate valve. This method allowed for the establishment of the required upstream water level in a controlled manner. The progression of scour profiles was systematically monitored under various test scenarios using a digital camera, which was positioned at a fixed distance from the sedimentation recess to ensure consistency in data collection. The frequency of measurements was adjusted over time to capture the evolution of scour profiles effectively. During the first hour, measurements were taken every 5 minutes. This interval was extended to every 15 minutes during the second hour and subsequently to every 30 minutes for the remainder of the experiment. The digital images of the scour profiles were processed using specialized software, Get Data, to extract quantitative information. Long-term experimental tests, conducted over a 12-hour period, revealed that more than 90% of the maximum scour depth was achieved within the first 8 hours of testing. These findings align with previous research conducted by Mahmoudi et al. [1], further validating the methodology and results. A schematic representation of the experimental flume setup, including the layout of parallel gates, is illustrated in Figure 1. Additionally, Figure 2 provides a detailed depiction of the roughness elements utilized in this research.

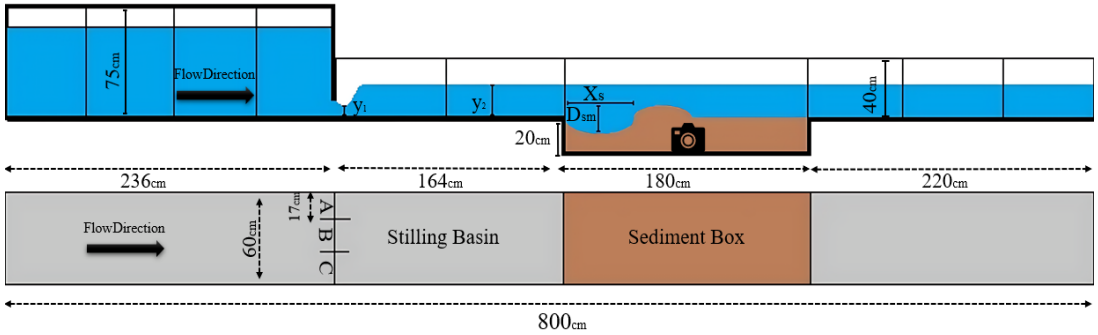


Figure 1. Schematic View of a Laboratory Flume

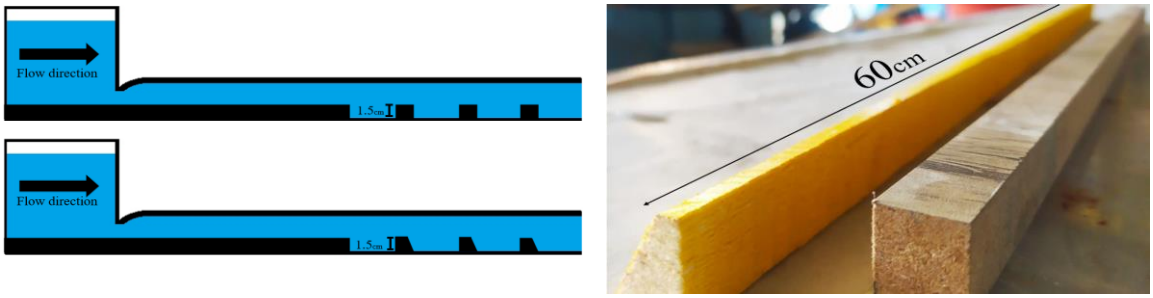


Figure 2. Schematic Diagram of Roughness Elements

2.3. Dimensional analysis

Local scour downstream of parallel sluice gates under different operating conditions is a complex phenomenon. Based on the investigations conducted, the parameters influencing the scour indices examined in this study (scour depth D_{sm}, scour volume $\forall$, scour hole length x_s, and scour cross-sectional area A) are as follows:

$$f(D_{sm}, x_m, A, \forall) = f\begin{pmatrix} h, y_1, y_2, y_t, v_1, g, b, B, a, \\ L, L_r, L_w, L_o, d_r, D_{50}, \rho_s, \varphi, \\ \sigma_g, F.S, \rho, \mu, t \end{pmatrix} \quad (1)$$

where y_1 and y_2 represent the conjugate depths located upstream and downstream of the hydraulic jump, y_t is the tailwater depth, V_1 is the velocity at the constriction section, g is the acceleration due to gravity, b is the width of the gates, B is the channel width, a is the opening of the gate or gates, L is the length of the stilling basin, L_r is the height of the roughness elements, L_W is the length of the divided wall, b_w is the width of the divided wall, L_o is the distance between roughnesses, D_{50} is the mean diameter of sediment particles, ρ_s is the specific weight of sediment particles, σ_g is the geometric standard deviation of particles, C_u is the uniformity coefficient of particles, F_S is the shape factor of sediment particles, ρ is the specific weight of water, μ is the dynamic viscosity of water, and t is time. Buckingham π theorem, the dimensionless parameters are defined as equation (2).

$$f\begin{pmatrix} \varphi, \sigma_g, C_u, F.s, \frac{a}{h}, \frac{y_2}{a}, \frac{y_t}{a}, \frac{b}{a}, \frac{B_c}{a}, \\ \frac{y_1}{a}, \frac{L_w}{L}, \frac{L_r}{a}, \frac{d_r}{a}, \frac{D_{50}}{a}, \frac{\rho_s}{\rho}, \mathrm{Re}, Fr \end{pmatrix} = 0 \quad (2)$$

Table 1 presents the distribution of sediment particle sizes used in this research. According to Raudkivi [36], when the geometric standard deviation of the particles (σ_g) is less than 1.3, the effect of particle non-uniformity on erosion is minimal. Furthermore, Das [37] suggests that if the uniformity coefficient of the particles (C_u) is less than 4, the sediment can be considered uniform.

Table 1. Characteristics of Sediment Particles (Unit: mm)

D_{10}	$D_{15.9}$	D_{30}	D_{50}	D_{60}	D_{84}	σ_g	Cu
1	1.1	1.24	1.37	1.45	4.7	1.24	1.45

$$Cu = \frac{D_{60}}{D_{10}} \quad (3)$$

$$\sigma_g = \sqrt{\frac{D_{84.1}}{D_{15.9}}} \quad (4)$$

In the realm of sediment transport research, simplifying complex systems into manageable models is crucial for advancing our understanding. According to the findings presented in Table 1, several parameters in sediment flow experiments can be justifiably disregarded due to their uniformity and constancy. This section explores these parameters and the rationale behind their exclusion from analytical considerations. Firstly, the consistency in sediment particle distribution allows us to overlook certain intrinsic properties such as the angle of repose, average particle diameter, and particle volume mass. Additionally, the dimensions of the divided walls, which are consistent across experimental setups, are also deemed negligible in influencing the outcomes. These decisions are grounded in the assumption that such uniformities do not significantly alter the dynamics under investigation. The experimental conditions further justify the exclusion of specific parameters. The experiments were conducted under free flow conditions at the outlet, indicating that the depth of flow exiting the gate or gates did not impose any constraints on the system. Consequently, the outlet depth parameter was omitted from the analyses.

$$\frac{D_{sm}}{a}, \frac{x_m}{a}, \frac{A}{a^2}, \frac{\forall}{Ba^2} = f\left(Fr, \frac{b}{B}\right) \quad (5)$$

In the following discussion, for the sake of brevity, the dimensionless parameter $\frac{\forall}{BL_w{}^2}$ representing scour volume will be referred to as V_s. Additionally, the expansion ratio will be denoted by the letter e

2.4. Experimental Matrix

The experiments were categorized into different scenarios based on gate configurations (single or dual gate openings), Froude numbers, expansion ratios, and bed roughness shapes (smooth, trapezoidal, cubic). The experimental matrix is detailed in Table 2.

Table 2. Experimental Matrix

No.	*Test Identifier*	*Open Gates*	F_r	*e*	*roughness shape*
1	T_1	*A*	6.5	0.283	*smooth*
2	T_2	*A*	6.5	0.283	*trapezoidal*
3	T_3	*A*	6.5	0.283	*cubic*
4	T_4	*B*	6.5	0.283	*smooth*
5	T_5	*B*	6.5	0.283	*trapezoidal*
6	T_6	*B*	6.5	0.283	*cubic*
7	T_7	*A&B*	6.5	0.56	*smooth*
8	T_8	*A&B*	6.5	0.56	*trapezoidal*
9	T_9	*A&B*	6.5	0.56	*cubic*
10	T_{10}	*A*	5	0.283	*smooth*
11	T_{11}	*A*	5	0.283	*trapezoidal*
12	T_{12}	*A*	5	0.283	*cubic*
13	T_{13}	*B*	5	0.283	*smooth*
14	T_{14}	*B*	5	0.283	*trapezoidal*
15	T_{15}	*B*	5	0.283	*cubic*
16	T_{16}	*A&B*	5	0.56	*smooth*
17	T_{17}	*A&B*	5	0.56	*trapezoidal*
18	T_{18}	*A&B*	5	0.56	*cubic*
19	T_{19}	*A*	3.5	0.283	*smooth*
20	T_{20}	*A*	3.5	0.283	*trapezoidal*
21	T_{21}	*A*	3.5	0.283	*cubic*
22	T_{22}	*B*	3.5	0.283	*smooth*
23	T_{23}	*B*	3.5	0.283	*trapezoidal*
24	T_{24}	*B*	3.5	0.283	*cubic*
25	T_{25}	*A&B*	3.5	0.56	*smooth*
26	T_{26}	*A&B*	3.5	0.56	*trapezoidal*
27	T_{27}	*A&B*	3.5	0.56	*cubic*

3. Results and Discussion

3.1. Maximum scour depth

Scour depth is a critical factor in the design and evaluation of hydraulic structures, as it can lead to unpredictable alterations of the riverbed, potentially resulting in structural damage and jeopardizing safety and functionality Melville [5] and Chow [38]. Consequently, accurately understanding and predicting scour depth is paramount for ensuring the stability of these structures. This research underscores the significant influence of bed roughness on mitigating scour depth downstream of parallel sluice gates.

All results and scour depth reductions in this study are presented in dimensionless form to enhance the generalizability of the findings and ensure their independence from specific units of measurement. The analysis demonstrates that bed roughness, particularly cubic and trapezoidal configurations, effectively reduces scour depth, achieving an average reduction of 22% with a maximum reduction of 56%. Notably, trapezoidal roughness exhibits a more pronounced impact, achieving average reductions of 25.3% compared to 20% for cubic roughness (Table 3). These results align with prior investigations focused on scour reduction downstream of single sluice gates. Studies by Ali et al. [26], Amir and Ahmad [39], and Amir et al. [29] have documented significant scour reductions ranging from 30% to 63%, 31% to 82%, and 70% to 83%, respectively. A crucial factor governing scour downstream of parallel sluice gates is the flow expansion ratio (e), a dimensionless parameter representing the ratio of effective gate

opening to the channel width. This study explored various scenarios and identified that roughness elements performed optimally with an expansion ratio of 0.56 (two gates open), while the least effective results were observed with an expansion ratio of 0.283 (one gate open). Trapezoidal roughness elements yielded average reductions of 30.3% and 20.85% in scour depth for expansion ratios of 0.56 and 0.283, respectively. Similarly, cubic roughness configurations resulted in average reductions of 33% and 14.05% for the same respective expansion ratios. These findings align with prior research by Mahmoudi et al. [1] and Khalili Shayan et al. [40], which highlights the complexities arising from central sluice gate operation in abruptly expanding stilling basins. Specifically, the formation of an asymmetric S-jump, characterized by concentrated high-velocity jets along one sidewall and reverse flow along the opposite wall, leads to uneven energy dissipation. This uneven distribution intensifies the potential for localized scour near the sidewalls, posing a significant threat to the structural integrity and long-term durability of stilling basin infrastructure [41].

As Figure 3 shows, for side gate operation, both cubic and trapezoidal roughness configurations modestly attenuate the scour development rate, reducing the slope from 0.18 (smooth bed) to 0.15. Middle gate operation demonstrates more nuanced behavior. The significant impact of roughness on scour downstream of the middle gate, particularly at low Froude numbers (Fr), results in a steeper slope for both roughness types. Slopes increase to 0.47 for cubic and 0.80 for trapezoidal roughness (Note the difference in the starting point of the scour on the D_{sm}-Fr line.), compared to 0.27 for a smooth bed. However, at Fr exceeding 5, all configurations converge to a similar slope of 0.25, indicating diminished sensitivity to roughness effects at higher flow velocities. With both side gates open, both roughness types effectively mitigate scour development at Fr below 5, with slopes decreasing to 0.27 for cubic and 0.20 for trapezoidal roughness compared to 0.40 for a smooth bed. Conversely, at Fr exceeding 5, scour development intensifies, with slopes increasing to 0.53 for cubic and 0.27 for trapezoidal roughness, highlighting the superior performance of trapezoidal roughness in high-velocity flow conditions.

Table 3. Percentage Reduction of Observed Scour Hole Depth in Different Experiments

Test Identifier	*Percentage reduction in scour depth*	*Test Identifier*	*Percentage reduction in scour depth*	*Test Identifier*	*Percentage reduction in scour depth*
T_2	%18	T_5	%9	T_8	%29
T_3	%13	T_6	%4	T_9	%17
T_{11}	%27	T_{14}	%7.6	T_{17}	%34
T_{12}	%20	T_{15}	%7.6	T_{18}	%34
T_{20}	%19	T_{23}	%56	T_{26}	%28
T_{21}	%14	T_{24}	%26	T_{27}	%45

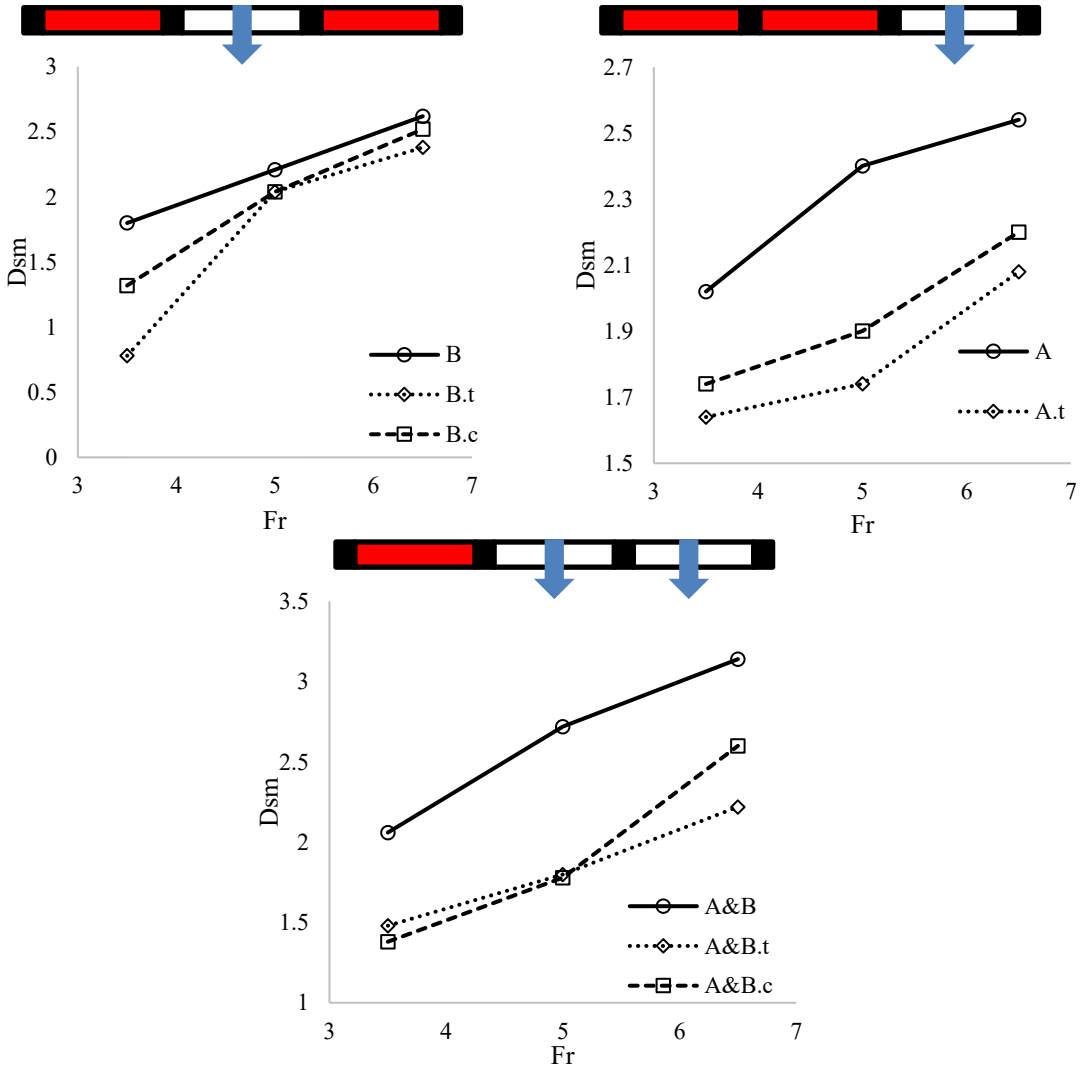


Figure 3. Effect of Roughness Shape on Scour Hole Depth under Different Gate Opening Conditions (Refer to the Symbols Section)

3.2. Length of scour

The formation and length of scour holes downstream of hydraulic structures are critical considerations in hydraulic engineering, as excessive scour can compromise the structural integrity of downstream installations. Current research highlights the effectiveness of incorporating bed roughness elements, specifically trapezoidal and cubic designs, in mitigating the extent of local scour downstream of parallel sluice gates. This study demonstrates that these roughness elements can significantly reduce scour hole length, with trapezoidal roughness emerging as the more effective option. The implementation of trapezoidal and cubic bed roughness elements has been shown to achieve an average reduction in scour hole length of 18.5%. Among these, trapezoidal roughness elements outperform cubic designs, achieving an average reduction of 22.6%, compared to 14.3% for cubic roughness elements. This distinction underscores the potential of trapezoidal roughness as a superior method for controlling local scour in hydraulic systems. Previous Studies on maximum scour length reduction have shown varying results across different research efforts. Amir and Ahmad [39] documented a maximum reduction of 64%, while Ali et al. [29] observed a slightly

higher reduction of 68%. Notably, the findings of the present study align with the latter, also reporting a maximum reduction of 68% (Table 4).

The present study also examines the impact of sluice gate configurations on flow dynamics and the efficacy of bed roughness elements in reducing scour length. When one or more gates are closed, the flow divides into primary and return flows (Sauida [42], Sauida [43] and Elsayed et al. [4]). This bifurcation becomes more pronounced when both side gates are open, as the reduced cross-sectional area for return flow diminishes the influence of bed roughness on scour mitigation. In scenarios where both side gates are open, the average reduction in scour hole length is 15.7% for trapezoidal roughness and 6.1% for cubic roughness. The diminished effectiveness in this configuration can be attributed to the limited interaction between the return flow and the bed roughness elements. When a single side gate is open, the effectiveness of both types of bed roughness elements improves. In this configuration, trapezoidal roughness achieves an average reduction in scour length of 19%, while cubic roughness achieves an average reduction of 15.6%. This increase highlights the importance of flow dynamics in optimizing the performance of bed roughness elements. The most significant reductions in scour length are observed when the middle gate is open. Under this configuration, trapezoidal roughness elements achieve a remarkable average reduction of 33.3%, while cubic roughness elements achieve an average reduction of 21.3%. These results indicate that central flow alignment enhances the interaction between flow and bed roughness, maximizing scour mitigation effectiveness (Table 4).

As Figure 4 shows, analysis of the Xs-Fr relationship reveals distinct behavioral patterns across different gate configurations. For side gate openings, the Xs-Fr line slope for trapezoidal and cubic roughness elements is 12.7 and 14, respectively, at Froude numbers below 5, decreasing to 2 and 0.33 at higher Froude numbers. A similar trend is observed with simultaneous side gate openings, where the slope values are 9.4 and 3.06 for Froude numbers below 5, reducing to 0.93 and 0.66 for higher Froude numbers. This significant variation in slope characteristics is attributed to the combined influence of Froude number and intensified backflows at elevated velocities.

Under symmetric gate opening conditions, particularly during middle gate operation, the Xs-Fr relationship exhibits notably different characteristics. The rate of change of scour pit length for Froude numbers lower than 5 is 10.8 and 7.7 times, and for numbers greater than 5 is 4.4 and 3.7 times for trapezoidal and cubic roughness, respectively. This stability is primarily attributed to symmetric flow patterns and reduced backflow effects. Across all gate configurations, trapezoidal roughness demonstrates superior consistency in performance across varying Froude numbers, underscoring its reliability and effectiveness in scour Length reduction.

Table 4. Percentage Reduction in Scour Hole Length in Different Experiments

Test Identifier	*Percentage reduction in scour hole*	*Test Identifier*	*Percentage reduction in scour hole*	*Test Identifier*	*Percentage reduction in scour hole*
T_2	%0	T_5	%18	T_8	%0
T_3	%0	T_6	%17	T_9	%0
T_{11}	%8	T_{14}	%12	T_{17}	%4
T_{12}	%1	T_{15}	%7	T_{18}	%3
T_{20}	%48	T_{23}	%68	T_{26}	%43
T_{21}	%46	T_{24}	%39	T_{27}	%15

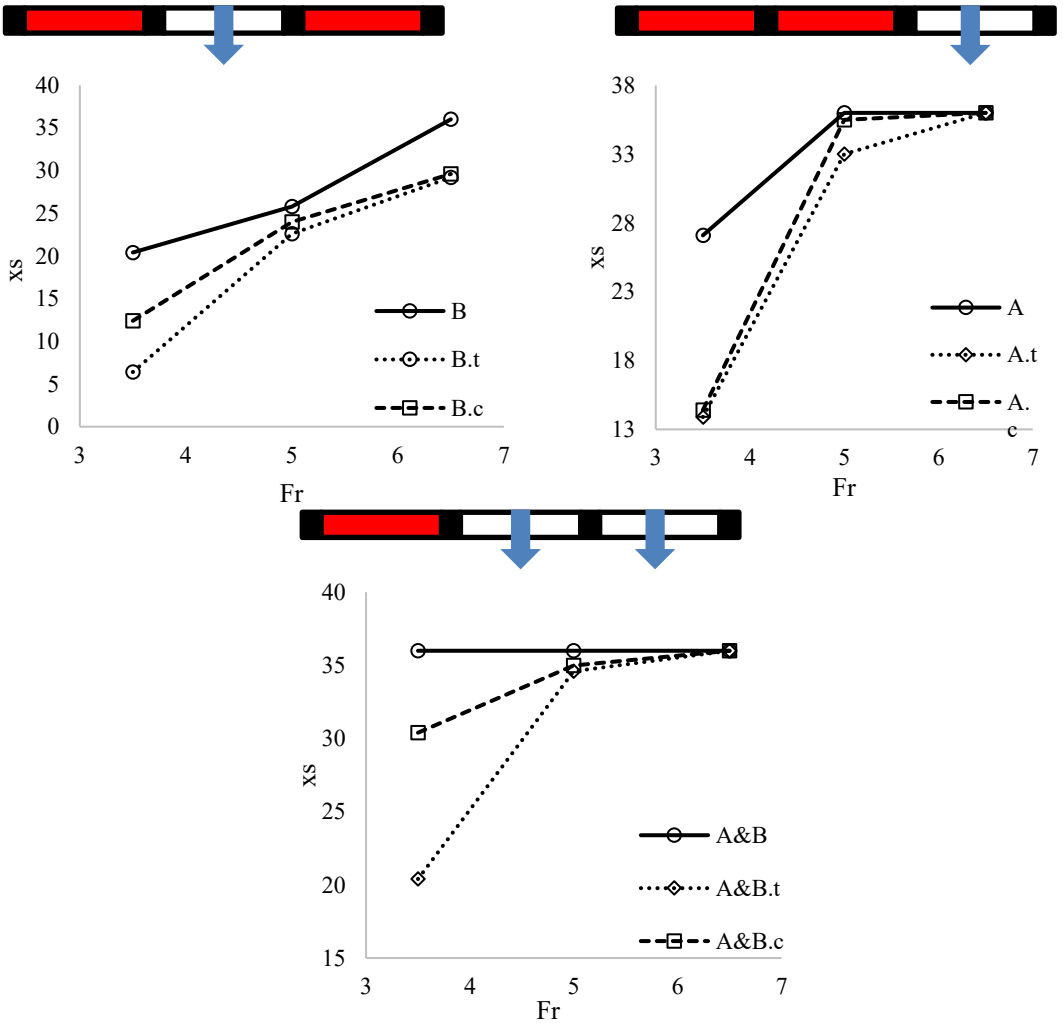


Figure 4. Effect of Roughness Shape on Scour Hole Length under Different Gate Opening Conditions

3.3. The Cross-sectional area of scour

This investigation elucidates the paramount significance of bed roughness in attenuating the scour cross-sectional area downstream of parallel sluice gates. The empirical findings demonstrate that the strategic implementation of roughness elements on the bed surface manifests a substantial mitigation in scour propagation, yielding an average reduction of 26.04%. Among the investigated roughness configurations, trapezoidal geometry performed better than cubic roughness in scour mitigation. Specifically, trapezoidal roughness achieved a 30.52% mean reduction in scour cross-sectional area, significantly exceeding the 21.57% reduction observed with cubic elements (Table 5). As evidenced in Figure 5, the most pronounced variations in the A-Fr gradient occurred during the simultaneous activation of two side gates, particularly in the presence of roughness elements. For trapezoidal and rectangular roughness configurations at low Froude numbers ($Fr < 5$), the recorded values were 69 and 78 respectively, while at higher Froude numbers ($Fr > 5$), values of 34 and 16 were observed, demonstrating disparities of 34.2 and 62.3 units. Similarly, side gate operation resulted in distinct rate differentials across various Froude regimes. For $Fr < 5$ flows, trapezoidal and rectangular roughnesses exhibited values of 77 and 95 respectively, while $Fr > 5$

conditions these values changed to 88 and 55, indicating variations of 10 and 39 units.

This behavioral pattern underwent substantial modification during the middle gate operation. At low Froude numbers (Fr < 5), the A-Fr gradient manifested values of 59 and 63 for trapezoidal and cubic roughnesses respectively, while higher Froude numbers (Fr > 5) conditions produced values of 51 and 34, revealing disparities of 7.7 units for trapezoidal and 29 units for cubic configurations. These trends underscore the significant influence of gate operational modes and bed roughness characteristics.

The distinctive performance differential is attributed to the respective roughness configurations' inherent geometrical and hydraulic properties. Through its sophisticated design, the trapezoidal roughness geometry demonstrates enhanced capability in turbulence generation and flow separation mechanisms compared to its cubic counterpart. These characteristics effectively disrupt high-velocity flow regimes and facilitate superior energy dissipation, consequently attenuating the erosive forces acting upon the bed surface.

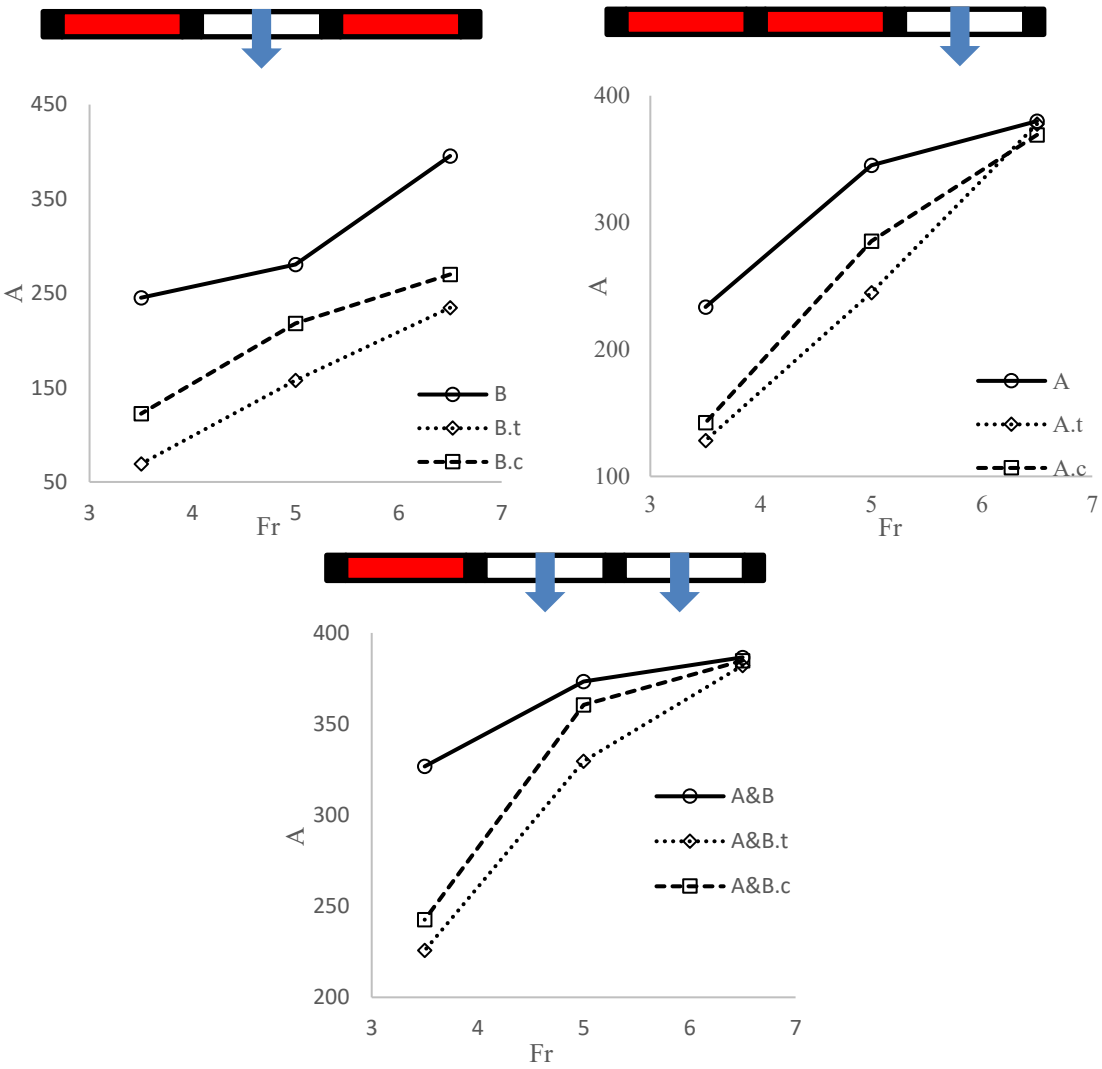


Figure 5. Effect of Roughness Shape on the Cross-Sectional Area of Scour Under Different Gate Opening Conditions

Table 5. Percentage Reduction of the Cross-Sectional Area of Scour Hole in Different Experiments

Test Identifier	*Percentage reduction in cross-section*	*Test Identifier*	*Percentage reduction in cross-section*	*Test Identifier*	*Percentage reduction in cross-section*
T_2	%1	T_5	%40	T_8	%1
T_3	%3	T_6	%31	T_9	%2
T_{11}	%29	T_{14}	%43	T_{17}	%11
T_{12}	%17	T_{15}	%22	T_{18}	%3.5
T_{20}	%45	T_{23}	%71	T_{26}	%30
T_{21}	%39	T_{24}	%50	T_{27}	%25

3.4. Scour volume

The present study underscores the significant potential of strategically implemented bed roughness elements in mitigating erosive process and reducing scour volume. Our findings demonstrate that the introduction of these elements can achieve an average scour volume reduction of 44.2%, highlighting their effectiveness as a scour countermeasure. The efficacy of bed roughness elements, however, is demonstrably influenced by their geometric properties. Among the configurations evaluated, trapezoidal roughness elements exhibited superior performance, achieving a 50% reduction in scour volume. Cubic elements, while still effective, provided a more moderate reduction of 34.7%. These results emphasize the importance of careful consideration and selection of roughness element geometry to optimize the hydraulic performance of the system. Previous investigations, such as that conducted by Ibrahim et al. [42], have explored various protective measures and reported scour volume reductions ranging from 33% to 89%. In comparison, the present study observed a reduction range from 18% to 63% (Table 6) when employing bed roughness elements.

According to Figure 6, the differences between the development rates of scour volume for different roughness shapes at various Froude numbers are closer to each other compared to other investigated parameters. However, the asymmetrical operation of the gates still has significant effects on the slope of the Vs-Fr line. When both side gates are open, the slope of the line for trapezoidal and cubic roughness shapes at Froude numbers below 5 is 9.4 and 11.3, respectively, while for Froude numbers above 5, it is 7.6 and 4.6, showing a difference of 1.8 and 6.7 units, respectively.

This trend is also evident when a single side gate is open, where the slopes for trapezoidal and cubic roughness shapes at Froude numbers below 5 are 5.8 and 8.8, respectively, and for Froude numbers above 5 are 7.4 and 5.8, resulting in differences of -1.6 and 3 units, respectively. However, this trend is completely corrected when the middle gate is open. The performance of bed roughness for Froude numbers below 5 is 4.46 and 5.46, and for Froude numbers above 5, it is 4.78 and 5.56, indicating differences of only 0.3 and 0.1 units for trapezoidal and cubic roughness shapes, respectively.

Scouring poses a significant threat to the stability of downstream structures, often leading to costly repairs and structural failures. This study demonstrates that both gate operation methods and optimal bed roughness design significantly influence scour pit parameters and associated risks. The findings emphasize that incorporating well-designed roughness elements into hydraulic systems can substantially enhance their durability and stability. Careful consideration of roughness geometry during the design phase is crucial for optimizing scour mitigation and developing more resilient and sustainable hydraulic infrastructure.

Table 6. Percentage Reduction in Scour Volume in Different Experiments

Test Identifier	*Percentage reduction in scour volume*	*Test Identifier*	*Percentage reduction in scour volume*	*Test Identifier*	*Percentage reduction in scour volume*
T_2	%36	T_5	%61	T_8	%42
T_3	%27	T_6	%49	T_9	%39
T_{11}	%49	T_{14}	%43	T_{17}	%40
T_{12}	%29	T_{15}	%18	T_{18}	%25
T_{20}	%60	T_{23}	%53	T_{26}	%63
T_{21}	%52	T_{24}	%18	T_{27}	%51

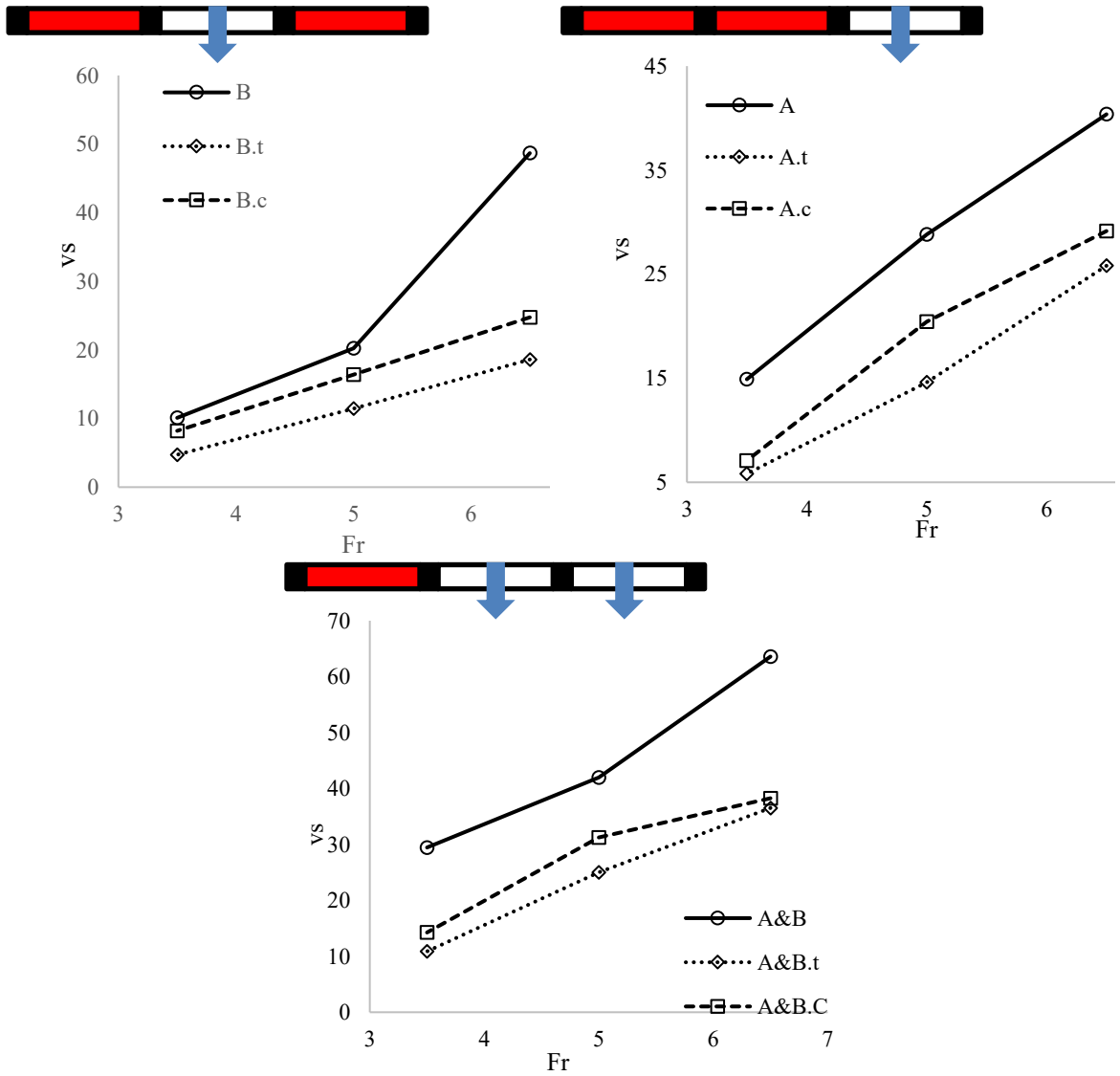


Figure 6. Effect of Roughness Shape on Scour Volume Under Different Gate Opening Conditions

4. Conclusion

This study comprehensively investigates the significant influence of bed roughness configurations on mitigating local scour downstream of parallel sluice gates under a variety of hydraulic conditions. Through an exhaustive analysis of multiple scour parameters, this research unequivocally establishes that trapezoidal roughness elements consistently outperform cubic configurations across all measured indices. Experimental results demonstrate substantial reductions in key scour parameters: maximum scour depth (25.3% for trapezoidal vs. 20% for cubic), scour length (22.6% vs. 14.35%), cross-sectional area (30.52% vs. 21.57%), and scour volume (50% vs. 34.7%). This consistent pattern of superior performance by trapezoidal roughness elements highlights their effectiveness in controlling erosion and dissipating energy.

The flow expansion ratio (e) is identified as a critical parameter affecting the efficacy of bed roughness elements. Optimal performance is observed at an expansion ratio of 0.56 (corresponding to two gates open), where cubic and trapezoidal roughness achieved scour depth reductions of 33% and 30.3%, respectively. In contrast, at lower expansion ratios (e = 0.283, one gate open), the effectiveness diminished significantly, yielding reductions of 14.05% and 20.85% for cubic and trapezoidal configurations, respectively. This variation can be attributed to the formation of asymmetric S-shaped hydraulic jumps and the resulting flow patterns.

The influence of the Froude number (Fr) on scour line slope development rate exhibits distinct patterns across different gate configurations, revealing the complex interplay between flow conditions and roughness effectiveness. Under symmetric flow conditions during middle gate operation, both roughness types demonstrate remarkable consistency across the Froude number range, with trapezoidal and cubic roughness maintaining stable scour volume expansion rates. This stability can be attributed to the symmetric flow patterns and minimized backflow effects typical of middle gate operation. However, during simultaneous side gate operation, performance diverged significantly at higher Froude numbers. While both roughness types effectively controlled scour development at Fr < 5, trapezoidal roughness maintained its effectiveness at Fr > 5, while cubic roughness showed diminished performance. This superior stability of trapezoidal roughness under high-velocity conditions, coupled with its consistent performance across various gate configurations, establishes it as a more reliable solution for scour mitigation in hydraulic systems.

The findings of this study have significant implications for hydraulic engineering practice, particularly in the design and optimization of stilling basins and parallel sluice gate systems. The superior performance of trapezoidal roughness elements in reducing scour parameters suggests that their implementation could significantly enhance the longevity and stability of hydraulic structures. The consistent effectiveness across various flow conditions and gate configurations further indicates that trapezoidal roughness elements offer a robust solution for scour mitigation in hydraulic systems.

Future research should focus on the further optimization of roughness geometries, especially exploring hybrid configurations that combine the beneficial characteristics of different shapes. Additionally, investigating the performance of roughness elements under extreme flow conditions and prolonged exposure to varying hydraulic loads could provide valuable insights for practical applications. The integration of computational fluid dynamics (CFD) modeling with experimental results could further enhance our understanding of complex flow patterns and energy dissipation mechanisms

associated with different roughness configurations.

Symbols:

A	: A gate opens
B	: B gate opens
A & B	: A & B gates open
A.t	: A gate opens with trapezoidal roughness
B.t	: B gate opens with trapezoidal roughness
A & B.t	: A & B gates open with trapezoidal roughness
A. c	: A gate opens with rectangular roughness
B. c	: B gate opens with rectangular roughness
A & B. c	: A & B gates open with rectangular roughness
e	: Expansion ratio

Statements and Declarations

Competing Interests

The authors declare that they have no competing interests.

Financial Disclosure

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Authors' Contributions

The first author was responsible for conducting the laboratory experiments, collecting data, developing the research methodology, and drafting the initial version of the manuscript. The second author contributed to data analysis and critically revised the manuscript for scientific accuracy and clarity. The third author performed scientific editing. The fourth and fifth authors contributed to the critical revision and editorial refinement of the manuscript. All authors made substantial contributions to the conception and design of the study, as well as to data acquisition, analysis, and interpretation. All authors have read and approved the final version of the manuscript and consent to its publication.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AI Statement

No artificial intelligence (AI) tools or technologies were employed in the preparation of this manuscript.

Consent for Publication

All authors have read and approved the final manuscript and consent to its submission for publication.

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