Local scour downstream of compound weirs under free and submerged flow conditions

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ABSTRACT

Local scour downstream of hydraulic structures poses a significant threat to bed stability in alluvial channels. This experimental study investigates the impact of compound weir geometry on flow dynamics and scouring characteristics. Four distinct cross-sectional configurations were tested Rectangular, Trapezoidal, Semicircular, and Triangular under varying hydraulic conditions and a constant discharge of 21 l/s. The results demonstrate that weir geometry plays a pivotal role in energy dissipation and jet trajectory. Among the primary shapes, the triangular configuration (127°) exhibited superior performance in mitigating downstream erosion compared to traditional rectangular designs. Furthermore, an optimization of the triangular apex angle was conducted, testing angles of 127°, 110°, 96° and 85°. The findings reveal that reducing the apex angle significantly enhances hydraulic control; the 85° triangular weir recorded the minimum scour depth of 4.8 cm, representing a 36% reduction compared to the 127° section. Strong correlations were established between the tailwater Froude number (Frt), longitudinal jet length (Ljet), and maximum scour depth (Zmax). These results suggest that optimizing the compound weir geometry to an 85° triangular shape provides a cost-effective and efficient strategy for bed protection in hydraulic engineering applications.

KEYWORDS

Energy dissipation, Local scour, Compound weirs, Sharp-crested weirs, Apex angle, Alluvial channels.

1. Introduction

Local scour in open channels represents a critical hydraulic phenomenon that significantly threatens the stability and longevity of water infrastructure. As emphasized by [1, 2], understanding the mechanics of sediment mobilization and scour development is paramount for the design of resilient and durable hydraulic structures. While early research established the fundamental principles of erosion, recent advancements have further elucidated the dynamics of this process. For instance, [3] demonstrated that local scour holes maintain a degree of shape similarity throughout their evolution, while [31] introduced modified prediction equations for scour parameters considering the impact of nonuniform sediment, which is essential for accurate field applications.

The dynamics of scour downstream of compound weirs are particularly complex, governed by a multifaceted interplay of variables. Geometry plays a pivotal role in this process; as noted by [6] and [13], the cross-sectional configuration significantly dictates the extent of scouring. To address these challenges, various mitigation and optimization strategies have been proposed. For instance, [27] demonstrated that optimizing trapezoidal labyrinth weir designs can enhance scour mitigation in straight channels. Other innovative configurations include combined triangular sharp-crested weirs with inverted V-shaped gates, as investigated by [28], and the use of slit weirs which provide unique discharge characteristics [32].

Energy dissipation and the influence of tailwater conditions are also crucial factors in controlling downstream bed morphology. [30] highlighted the effects of tailwater depth on scour cavity formation downstream of grade control structures, while [29] investigated the time evolution of scour characteristics downstream of sluice gates under submerged hydraulic jump conditions. Additionally, the use of structural features such as floor water jets [7, 8, 10, 25] and orifice-equipped gates [20, 26] has proven effective in improving hydraulic stability. Despite these extensive studies, a knowledge gap persists regarding the optimal geometric design of triangular compound weirs, particularly concerning the influence of the apex angle on scour minimization.

Despite the extensive literature on scour downstream of standard weirs, there is a notable lack of optimization studies focusing on the geometric apex angles of triangular compound configurations in alluvial channels. The primary objective of the current research is to fill this gap by experimentally investigating the hydrodynamic efficiency of four different compound weir shapes (Rectangular, Trapezoidal, Semicircular, and Triangular). Furthermore, this study aims to identify the optimum apex angle for triangular sections that minimizes downstream local scour. By providing a comparative analysis of flow patterns and bed morphology, this work offers practical design recommendations for more stable and cost-effective hydraulic structures.

2. Experimental Setup and Methodology

The experimental campaign was conducted at the Hydraulics and Irrigation Laboratory, Faculty of Engineering, Benha University, Egypt. All tests were carried out in a high-precision, tilting recirculating flume with a total length of 15.0 m, a width of 0.4 m, and a depth of 0.65 m. To ensure a fully developed, uniform flow distribution and to mitigate upstream turbulence, a gravel-filled stabilization box was strategically positioned at the flume's inlet. Flow depth and tailwater conditions were precisely regulated using a calibrated tailgate located at the flume's terminus. The discharge was maintained at a constant rate of 21 l/s, monitored via a pre-calibrated ultrasonic flow meter to ensure steady flow conditions during all experimental runs.

2.1. Test Section and Sediment Properties

The experimental models were installed at the flume’s midsection, approximately 7.0 m from the entrance. A movable sand bed section was established 1.0 m downstream of the weir structures, extending for a length of 3.0 m with a thickness of 0.25 m. The bed material consisted of non-cohesive sand characterized by a median particle size d_{50} of 0.8 mm, d_{90} of 1.95 mm, and a geometric standard deviation σ_g of 2.45. To eliminate the influence of sediment size on the scouring process and avoid scale effects, the ratio of channel width (D) to median grain size d_{50} was maintained at $D/d_{50} > 50$, in accordance with the criteria proposed by **Ettema (1980)**.

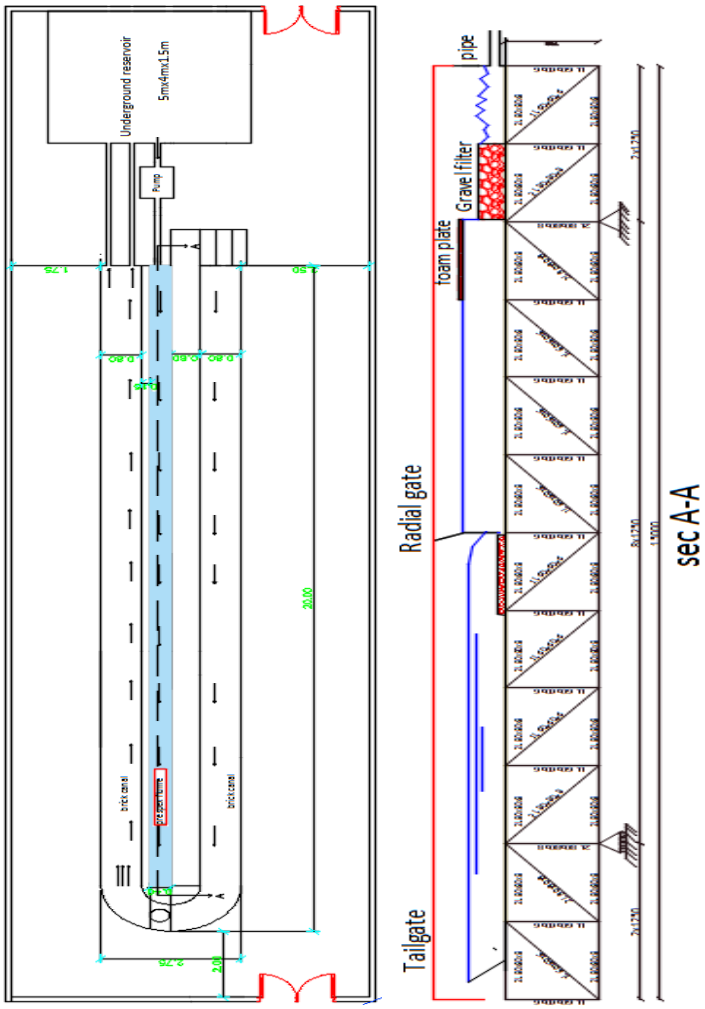


Figure 1. Layout of the experimental flume at Laboratory

2.2. Compound Weir Models and Stilling Basin

Four distinct geometric configurations of compound weirs were fabricated from high-quality timber and tested under a constant discharge of 21 l/s. Each weir was integrated with a 1.0 m long wooden stilling basin located immediately downstream. The tested geometries, as illustrated in **Figure (1)**, were designed as follows:

- **Shape (1) Rectangular (Rec.):** A primary rectangular section (26 cm wide, 10 cm deep) with the crest positioned 30 cm above the channel bed, superimposed over a smaller rectangular notch (10 cm wide, 5 cm deep).
- **Shape (2) Trapezoidal (Trap.):** The same primary rectangular section combined with a lower trapezoidal notch (top width 15 cm, bottom width 5 cm, and height 5 cm).
- **Shape (3) Semicircular (Cir.):** The primary rectangular section integrated with a lower semicircular opening (14 cm wide, 5 cm high).
- **Shape (4) Triangular (Tria.):** The primary rectangular section combined with a lower V-notch. This configuration was further investigated by varying the apex angle across four values: 127°, 110°, 96°, and 85°

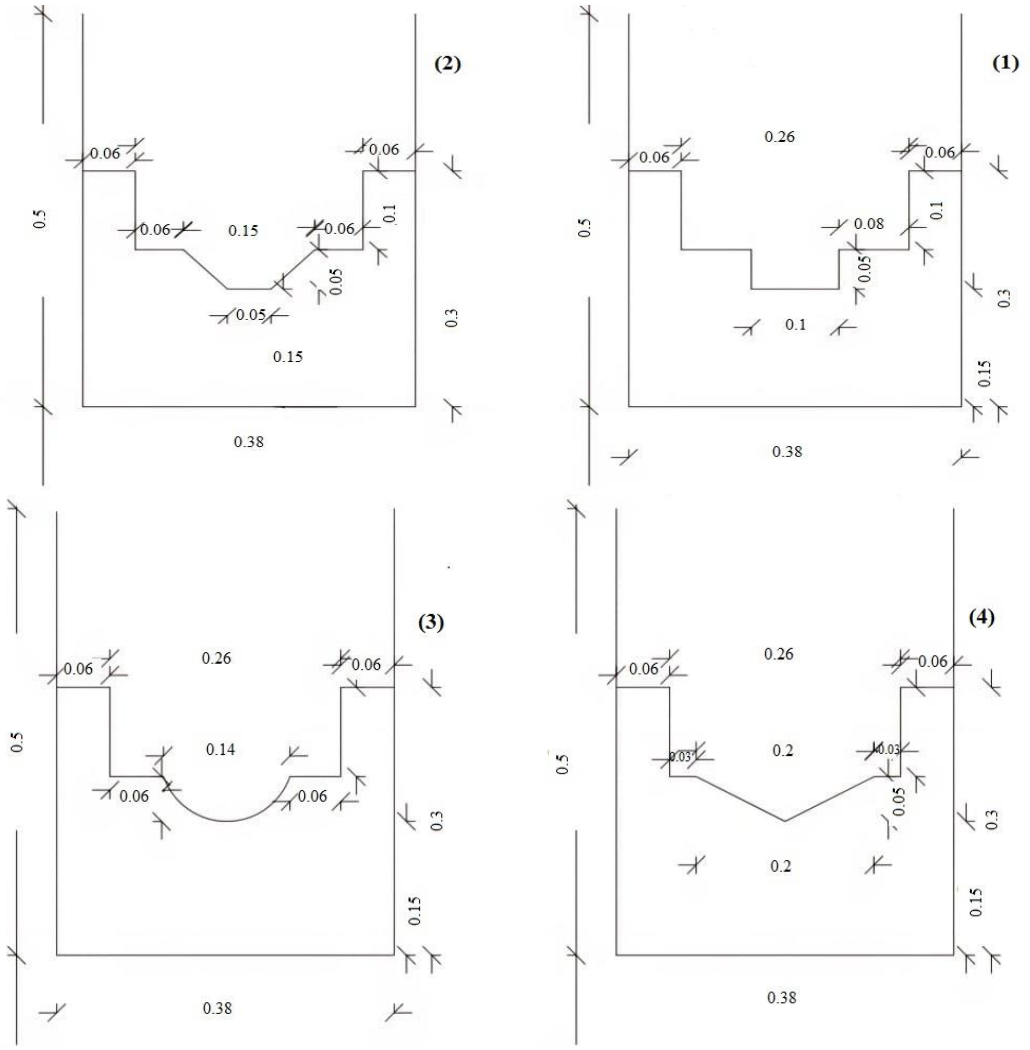


Figure 2. Different shapes of compound weirs

3. Theoretical Formulation (Dimensional analysis)

To generalize the experimental results and establish a functional relationship for the maximum scour depth (Z_{max}), dimensional analysis was performed using the **Buckingham π-theorem**. The maximum scour depth downstream of the compound weirs is influenced by several physical variables representing the fluid properties, flow conditions, sediment characteristics, and weir geometry:

$$Z_{max} = f\begin{pmatrix} V, y, \rho, \mu, g, \rho_S, D_{50}, \\ \sigma_g, B, b, h, \theta, Y_t, Ljet \end{pmatrix} \quad (1)$$

Where:

V = flow velocity; y = upstream flow depth; ρ= fluid density; μ = dynamic viscosity; g = gravitational acceleration; ρs = sediment density; d_{50} = median grain size; σ_g = geometric standard deviation of sediment; B = channel width; b = weir opening width; h = weir height; θ = apex angle; Yt= tailwater depth; and Ljet = longitudinal jet length.

By selecting ρ (density), V (velocity), and y (flow depth) as the repeating variables, the primary dimensionless groups (π -terms) were derived. After rearranging and combining these groups to reflect standard hydraulic parameters, the functional relationship is expressed as:

$$\frac{Zmax}{y} = f\left(Fr, Re, \frac{\rho s}{y\rho}, \frac{d50}{y}, \sigma_g, \frac{b}{h}, \frac{B}{y}, \theta, \frac{Yt}{y}, \frac{Ljet}{y}\right) \quad (2)$$

3.1. Simplification of the Functional Relationship

To refine the analysis and focus on the most influential parameters, several simplifications were applied:

- **Viscous Effects:** The Reynolds number (Re = ρVy/ μ) was neglected as the flow in the flume is characterized by high turbulence (Re > 10^4) where inertial forces dominate.
- **Sediment Properties:** Since a consistent soil sample was used (σ_g = 2.45), the density ratio (ρ_s/ρ) and sediment grading remained constant and were excluded from the variable parameters.
- **Geometric Constants:** The channel width (B) and median grain size (d_{50}) were constant throughout the experiments.

The final simplified non-dimensional relationship used for the analysis is:

$$\frac{Zmax}{y} = f\left(\mathrm{Fr_t}, \theta, \frac{b}{h}, \frac{Yt}{y}, \frac{Ljet}{y}\right) \quad (3)$$

Where:

- **$\mathbf{Fr_t = V/\sqrt{gy}}$:** Tailwater Froude number (representing inertial vs. gravitational forces).
- **$\mathbf{Z_{max}/y}$**: Relative maximum scour depth.
- **$\boldsymbol{\theta}$** : Apex angle (for triangular configurations).
- **$\mathbf{Y_t/y}$**: Relative tailwater depth (submergence ratio).
- **$\mathbf{L_{jet}/y}$**: Relative longitudinal jet length.

4. Results and Discussion

The experimental measurements were systematically recorded for all weir configurations. Table(1) presents a representative sample of the collected data and calculated dimensionless parameters for the trapezoidal compound weir, while the complete comparative analysis is illustrated in the subsequent figures.

Table 1. Experimental data and dimensionless parameters for the trapezoidal compound weir.

Trapezoidal section						
Y_u (cm)	Y_t(cm)	L_{jet}(cm)	Z_{max}(cm)	Fr_t	L_{jet}/Y_t	Z_{max}/Y_t
31	22	16	7	0.162439	0.727273	0.318182
31	20	17.4	6.8	0.187404	0.87	0.34
31	18.5	18.6	7.1	0.210653	1.005405	0.383784
31	17	19	7.2	0.23914	1.117647	0.423529
31	16	19.5	7.4	0.261906	1.21875	0.4625
31	14.5	20.9	7.5	0.30358	1.441379	0.517241
31	13.5	22.5	7.7	0.337928	1.666667	0.57037
31	12	23	8	0.40323	1.916667	0.666667
31	10.5	24.2	8.9	0.492653	2.304762	0.847619
31	9	25.5	9	0.620813	2.833333	1

4.1. Influence of Compound Weir Geometry on Relative Scour Depth

The impact of varying compound weir geometries specifically rectangular, trapezoidal, semicircular, and triangular (127°) on the relative maximum scour depth Z_{max}/Y_t is illustrated in Figure (2). The experimental results demonstrate a direct correlation between the tail Froude number Fr_t and the relative scour depth; as Fr_t increases, the erosive power of the flow intensifies, leading to a deeper scour hole.

Notably, at lower Fr_t values, the difference in scour depth between the four shapes is minimal, with the results converging as the flow remains relatively stable. However, as the Fr_t rises (indicating higher inertial forces), the geometric configuration of the weir becomes a dominant factor in governing the scour morphology.

- **Rectangular Configuration:** Conversely, the rectangular weir produced the maximum relative scour depth. The abrupt edges of the rectangular section likely induce greater local turbulence and stronger vortices, which accelerate the sediment removal process downstream.
- **Trapezoidal and Semicircular Shapes:** These configurations exhibited intermediate performance, with their scour depth values converging as Fr_t increased, suggesting a similar degree of hydraulic resistance and turbulence induction.

As illustrated in **Figure 3**, a consistent increase in the relative maximum scour depth (Z_{max}/Y_t) is observed with the increment of the tail Froude number (Fr_t). This is attributed to the enhanced kinetic energy and turbulence intensity associated with higher flow velocities. Notably, the triangular configuration effectively mitigates the erosive impact by promoting a more concentrated and streamlined flow transition, which leads to better energy dissipation compared to the abrupt edges of the rectangular weir.

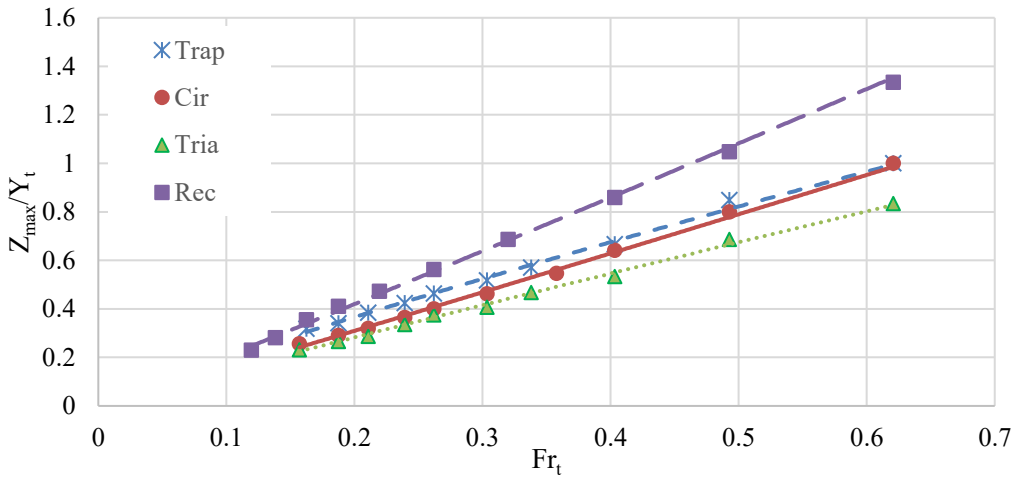


Figure 3. Relationship between relative scour depth (Z_{max}/Y_t) and tail Froude number (Fr_t) for different shapes of compound weirs

Key observations from the data include:

- **Triangular Configuration (127°):** This shape consistently yielded the minimum relative scour depth Z_{max}/Y_t across all high-velocity runs. This performance can be attributed to the triangular geometry's ability to promote smoother flow transitions and potentially more effective energy dissipation compared to other shapes.

4.2. Influence of Weir Geometry on the Relative Length of Jet

The characteristic behavior of the relative jet length L_{jet}/Y_t as a function of the tail Froude number Fr_t for the four investigated weir configurations is depicted in Figure (4). Consistent with hydraulic principles, an increase in Fr_t results in a corresponding expansion of the relative jet length across all geometries. This trend is driven by the increased kinetic energy and momentum associated with higher flow velocities.

Similar to the observations made for scour depth, the influence of the weir's cross-sectional shape becomes significantly more pronounced and divergent at higher Fr_t values. At lower flow intensities, the hydraulic response of the different shapes tends to converge, suggesting that geometric nuances have a diminished impact under subcritical or low-velocity conditions.

The comparative analysis reveals distinct performance patterns:

- **Triangular Configuration (127°):** This geometry achieved the minimum relative jet length L_{jet}/Y_t. The triangular notch appears to facilitate a more controlled energy dissipation and a more concentrated flow distribution, which effectively limits the longitudinal extent of the jet.
- **Rectangular Configuration:** Conversely, the rectangular weir produced the maximum relative jet length. This is likely due to the uniform crest width which allows a broader, less-obstructed flow sheet to travel further downstream before dissipating its energy.
- **Circular and Trapezoidal Sections:** The data shows that the values for circular and trapezoidal sections tend to converge at higher flow intensities, following an intermediate path between the rectangular and triangular extremes.

The experimental results depicted in **Figure 4** indicate a positive correlation between the tail Froude number (Fr_t) and the relative jet length (L_{jet}/Y_t). As (Fr_t) increases, the kinetic energy of the flow over the compound weir intensifies, propelling the jet further downstream before it strikes the channel bed. It is observed that the **Triangular configuration** (127°) produces the shortest jet length, which suggests a higher rate of internal energy dissipation within the weir structure itself. In contrast, the **rectangular weir** allows for a broader, less obstructed flow, resulting in the maximum longitudinal extent of the jet. Minimizing the jet length is a critical design objective, as a shorter jet reduces the footprint of the stilling basin required and concentrates the energy dissipation closer to the structure, thereby protecting the downstream reach from extensive local scour.

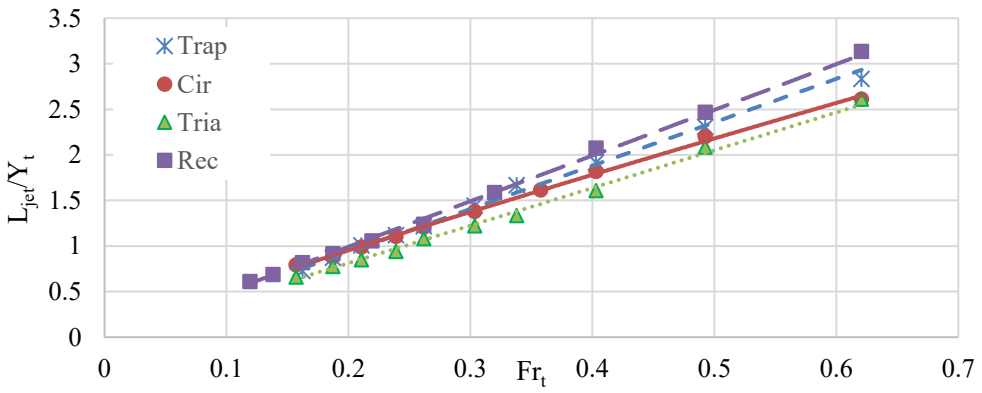


Figure 4. Relationship between relative length of jet (L_{jet}/Y_t) and tail Froude number (Fr_t) for different shapes of compound weirs

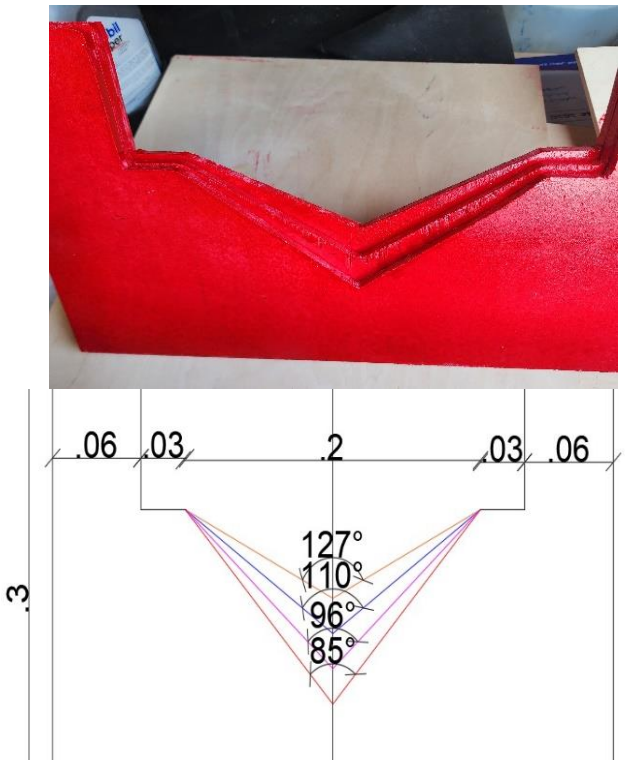


Figure 5. Different angles of triangular compound weir

4.3. Effect of Triangular Apex Angle on Relative Scour Depth

The influence of the triangular apex angle on the relative maximum scour depth Z_{max}/Y_t is analyzed in Figure (6). Four distinct angles (127°, 110°, 96°, and 85°) were tested across a range of tail Froude numbers Fr_t at a constant discharge of 21 l/s. Consistent with previous observations, an upward trend in Fr_t correlates with a systematic increase in Z_{max}/Y_t for all apex angles.

The results indicate that the sensitivity of the scour depth to the apex angle is highly dependent on the flow regime. At lower Fr_t values, the scour depths for all four angles converge, suggesting that geometric variations have a negligible impact under low-velocity conditions. However, a significant divergence occurs at higher Fr_t values, where the hydraulic efficiency of the triangular notch becomes more apparent.

Key findings from the angular analysis include:

- **The 85° Apex Angle:** This configuration yielded the minimum relative scour depth Z_{max}/Y_t throughout the high-velocity experimental runs. The narrower angle (85°) likely provides a more gradual flow transition and higher energy dissipation efficiency, which in turn reduces the intensity of the downstream turbulence responsible for bed erosion.
- **The 127° Apex Angle:** Conversely, the widest angle (127°) resulted in the maximum relative scour depth. As the apex angle increases, the weir behavior begins to approach that of a rectangular configuration, leading to a broader jet and more aggressive scouring.
- **Effect of Angle Reduction:** It is evident that decreasing the apex angle of the triangular section leads to a proportional reduction in Z_{max}/Y_t. This suggests that sharper triangular profiles are superior for protecting the channel bed from localized erosion.

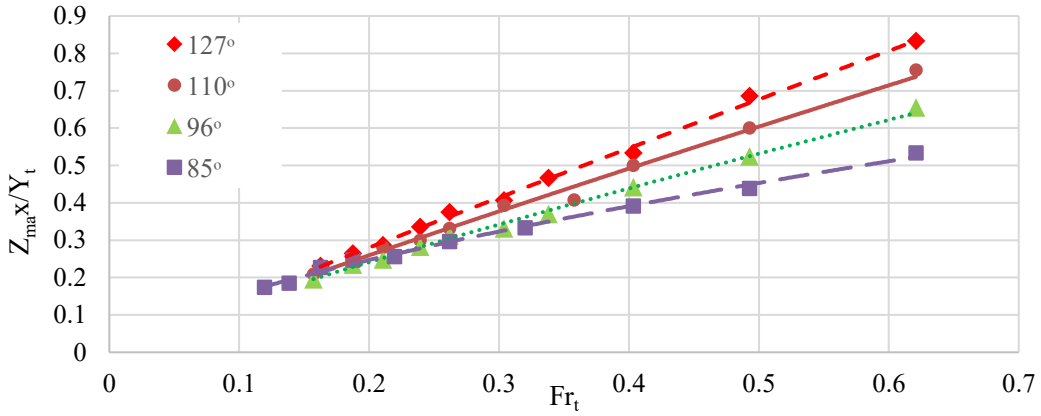


Figure 6. Relationship between relative scour depth (Z_{max}/Y_t) and tail Froude number (Fr_t) for different angles of triangular compound weir

A detailed comparison between different apex angles of the triangular weir is presented in **Figure 6**. The results demonstrate a significant reduction in the relative scour depth as the apex angle decreases. Specifically, the **85° triangular weir** exhibited the most superior performance, achieving a reduction in local scour by approximately **36%** compared to the 127° angle. This phenomenon can be physically explained by the Jet Concentration effect; a sharper apex angle 85° forces the flow into a narrower, more vertical jet structure. This concentration promotes a more controlled impact on the channel bed and increases the air entrainment, which significantly dissipates the flow's erosive energy before it reaches the alluvial bed. Consequently, the 85° angle provides a more stable hydraulic condition, making it the most effective geometric configuration for protecting downstream reaches in alluvial channels.

4.4. Effect of Triangular Apex Angle on the Relative Length of Jet

The relationship between the relative length of the jet L_{jet}/Y_t and the tail Froude number Fr_t for various triangular apex angles is presented in Figure (7). A consistent trend is observed where the relative jet length increases proportionally with Fr_t across all tested angles (85°, 96°, 110°, and 127°).

At lower flow intensities low Fr_t, the values of L_{jet}/Y_t tend to converge, indicating that the geometric variations of the triangular notch have a limited impact on the jet trajectory under tranquil flow conditions. Conversely, as Fr_t increases, a significant divergence occurs, highlighting the sensitivity of the jet's longitudinal extent to the weir's apex angle.

Key insights from this analysis include:

- **The 85° Apex Angle:** This configuration consistently yielded the minimum relative jet length. The narrower apex angle promotes a more streamlined and hydraulically efficient discharge, which effectively dissipates energy more rapidly and limits the downstream reach of the jet.
- **The 127° Apex Angle:** This wider angle produced the maximum relative jet length, as the flow behavior begins to mimic a wider rectangular crest, allowing the jet to maintain its momentum over a greater distance.
- **Physical Justification:** It is evident that decreasing the apex angle of the triangular section optimizes the flow concentration. By narrowing the flow passage, the weir enhances the hydraulic control over the discharging jet, thereby reducing its relative length and, consequently, its erosive potential on the downstream bed.

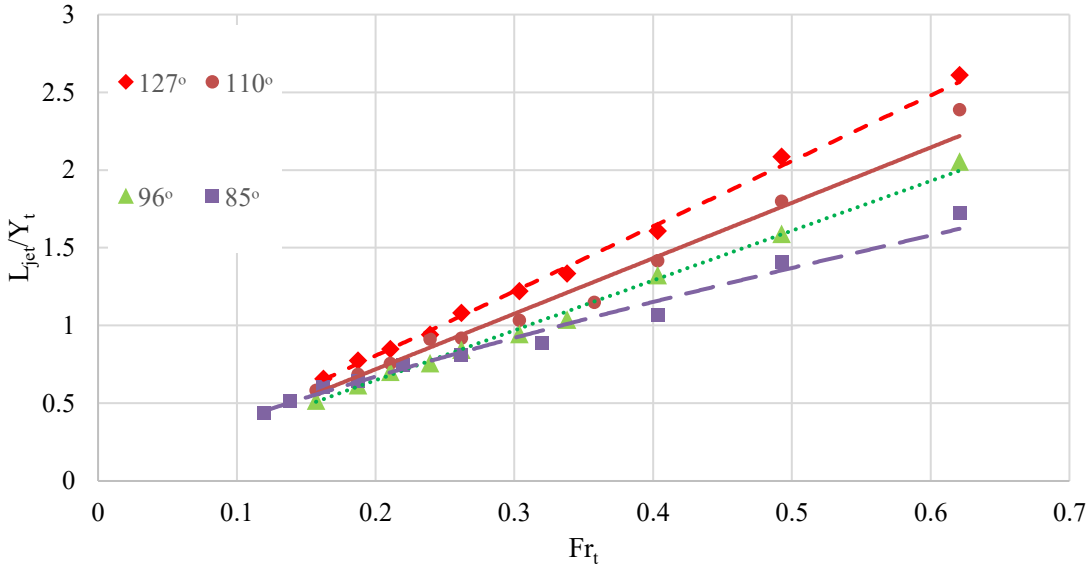


Figure 7. Relationship between relative length of jet (L_{jet}/Y_t) and tail Froude number (Fr_t) for different angles of triangular compound weir

The spatial characteristics of the scour hole, specifically the relative scour length (L_{jet}/Y_t), are illustrated in **Figure 7** for varying apex angles. The data reveals that the **85° triangular weir** not only minimizes the scour depth but also significantly restricts the longitudinal extent of the scour hole. This localized scouring pattern is a direct result of the improved flow alignment and the reduced turbulence at the bed-water interface. By confining the scour hole to a smaller area, the 85° configuration ensures higher structural stability for the channel bed and reduces the volume of eroded sediment that could be deposited further downstream. This comprehensive reduction in both scour depth and length confirms that optimizing the weir geometry to an 85° triangular shape is a highly effective strategy for sustainable sediment management in alluvial streams.

5. Conclusions

- **Flow Dynamics and Scour:** A strong correlation was established between tailwater conditions and scour morphology. The results indicate that the maximum scour depth (Z_{max}) and longitudinal jet length (L_{jet}) are highly sensitive to the tailwater Froude number (Fr_t).
- **Geometric Influence:** The cross-sectional geometry plays a pivotal role in energy dissipation. The rectangular configuration (traditional shape) exhibited the lowest hydraulic efficiency, resulting in the most aggressive scour profiles.
- **Superiority of the Triangular Section:** Among the primary shapes tested, the triangular compound weir (127°) proved to be the most effective in minimizing downstream erosion compared to rectangular, trapezoidal, and semicircular designs.
- **Optimization of the Apex Angle:** The apex angle is a critical design parameter. Reducing the angle significantly enhances hydraulic control; the **85° angle** recorded the absolute minimum scour depth (4.8 cm), achieving a **36% reduction** compared to the 127° section.
- **Design Implications:** To ensure adequate bed protection, the stilling basin length must be proportionally adjusted based on the predicted jet length, which increases with higher Froude numbers.

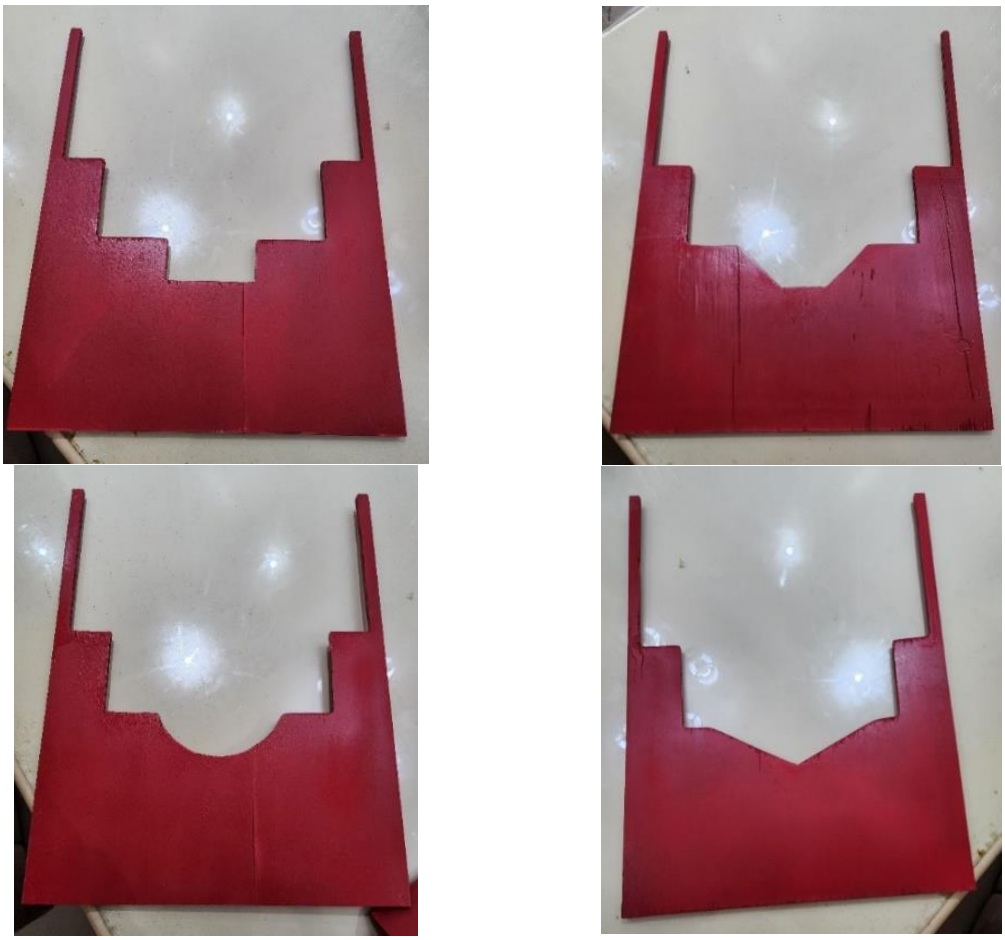


Figure 8. Different models of compound weirs



Figure 9. Different shapes of experimental works

6. Recommendations for Future Research

- While this study optimizes the geometric shape of compound weirs, the following areas are suggested for further exploration:
- **Sediment Diversity:** Evaluating these optimized geometries in cohesive soils and graded sediment beds to assess the universality of the 85° apex angle.
- **Hybrid Mitigation Measures:** Investigating the combined effect of the 85° triangular weir with floor jets or baffle blocks to further enhance scour reduction.
- **Numerical Modeling (CFD):** Utilizing 3D Computational Fluid Dynamics (CFD) to visualize the complex turbulence structures and vortex dynamics, facilitating the scaling of these results to full-scale prototypes.

Declarations

- **Conflict of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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- **Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.
- **Authors' Contributions:** All authors contributed equally to the conceptualization, methodology, and writing of the original draft

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