

Research Article

The Local Scour Impact Around a Cylindrical Bridge Pier for Two Different Abutment Models

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Article Info	Abstract
Article History	Local scour, the erosion of sediment around hydraulic structures caused by flowing water, is a major factor contributing to bridge failure, particularly near piers and abutments. While scour mechanisms around individual structural components have been widely studied, limited attention has been given to the interactive effects of abutment geometry and spacing relative to piers. This study investigates the influence of two abutment shapes (wing-wall and trapezoidal) on the size and formation of scour holes around a cylindrical pier. Fifty laboratory experiments were conducted in a flume under clear-water conditions, testing two pier–abutment distances (22.5 cm and 17.5 cm) across varying hydraulic parameters. Results indicate that, at a fixed spacing, scour depth around the pier decreases with increased flow depth but increases with higher Froude numbers and flow intensity. When the abutment is positioned closer to the pier, flow convergence intensifies, causing individual scour holes to merge and form a larger scour hole. The presence of abutments increased the scour depth by up to 41.56% for the wing-wall and 52.04% for the trapezoidal model at a 22.5 cm spacing, with a further increase observed at 17.5 cm spacing. Empirical scour prediction models developed using IBM SPSS 30 demonstrated high accuracy, yielding coefficients of determination (R^2) of 93.6% and 91.6% for the wing-wall and trapezoidal configurations, respectively.
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1. Introduction

Bridges are vital components of transportation infrastructure, providing essential connectivity between regions and supporting economic and social development. Despite their importance, bridges are frequently vulnerable to scour-related failures, which occur when flowing water removes sediment from riverbeds and banks, causing localized erosion around hydraulic structures. Such erosion can undermine foundations, compromise structural stability, and even lead to collapse, making scour a significant concern in civil engineering [1].

Among the different types of scour, local, contraction, and general, local scour near bridge piers and abutments poses the most immediate threat, as it can develop rapidly under high-velocity flows and

complex vortex patterns. Empirical studies indicate that local scour is responsible for approximately 64% of bridge failures. Surveys, such as the 1973 Federal Highway Administration (FHWA) report, note that 25% of bridge failures during floods were caused by pier damage, while 75% were due to abutment failures [2]. In addition, scour has been identified as the principal cause of more than 60% of bridge failures in the United States [3, 4] and nearly 70% in the United Kingdom [3].

The development of local scour is driven by intricate hydraulic phenomena, including flow separation, recirculation zones, and vortex formation around structural elements. Horseshoe vortices form around the base of piers and abutments due to stagnation pressure on the upstream face, while wake vortices develop downstream, intensifying sediment removal and producing highly variable scour patterns [4, 5]. Although the mechanisms responsible for scour around piers and abutments are fundamentally similar, the interaction between a pier and a nearby abutment is not yet fully understood. Existing predictive models typically address pier or abutment scour individually and fail to capture the effects that arise when both structures are in proximity, highlighting a significant knowledge gap.

To address this gap, the present study investigates the influence of abutment geometry on local scour development near bridge piers. Using scaled experimental models, the research examines how different abutment shapes affect scour depth and patterns around adjacent piers under controlled flow conditions. The findings aim to improve understanding of pier–abutment interactions, support the development of more accurate predictive models, and inform safer hydraulic design practices. By providing insights into the complex interplay between abutments and piers, this study contributes to enhancing the stability and resilience of bridge structures against scour-related hazards.

2. Literature Review

Accurate prediction and mitigation of local scour are critical for ensuring the structural integrity and longevity of bridges. Local scour around bridge structures has been extensively studied through experimental, numerical, and empirical approaches, resulting in numerous predictive formulas that consider flow characteristics, sediment properties, pier and abutment geometry, pile shapes, and debris accumulation [6-16]. These studies offer valuable insights into the mechanisms driving scour and the key factors that influence scour depth. Research can be broadly grouped into three themes. The first theme focuses on the hydraulic and geometric effects of abutments and piers.

Melville, et al. [17] demonstrated that increasing abutment length in a contraction zone modifies local turbulence and generates an equilibrium scour hole downstream. Similarly, Ben Mohammad Khajeh and Vaghefi [18] observed that in curved channels, an inclined pier adjacent to an abutment intensifies scour at the upstream face of the outer abutment. These studies highlight the significance of abutment geometry in modifying flow patterns and turbulence, yet they primarily address isolated or simplified configurations.

The second theme covers advancements in predictive modeling and data-driven approaches. Traditional empirical formulas and soft computing methods have limitations in accuracy and generalizability. A recent study by Oğuz and Bor [19] introduced a hybrid data-driven methodology that combines hierarchical clustering and genetic programming, analyzing over 40 prior studies to generate cluster-specific predictive equations. This approach achieved high accuracy ($R^2 > 0.8$) while mitigating overfitting, and its practical applicability was enhanced through a web-based interface. This demonstrates a clear advancement in predictive capability but still relies on aggregated datasets rather than exploring physical interactions in detail. The third theme addresses pier–abutment interactions and spacing effects. While local scour around individual piers or abutments is well understood, fewer studies have examined the influence of pier–abutment proximity. Memar, et al. [19] showed that tandem piers can exacerbate scour at abutments, whereas a single pier may have minimal or mitigating effects. Muhsen and Khassaf [20] and Fakhimjoo, et al. [21] further demonstrated that decreasing the spacing between a pier and an abutment increases scour around the pier but reduces scour at the abutment. The maximum scour depth occurs at the minimal spacing, indicating that proximity significantly influences the overall volume of the scour hole. These findings underline the importance of pier–abutment interactions but leave gaps regarding the role of abutment geometry itself. While previous research has examined multiple piers near abutments, pier shape effects, combined impacts on clear-water scour, and interactions between different abutment lengths and piers [19]. The influence of abutment geometry on local scour around a single pier remains relatively unexplored. Specifically, the effects of different abutment shapes, such as wing-wall and trapezoidal configurations, on the spatial distribution, depth, and development of scour around adjacent piers have not been fully investigated. Addressing this gap, the present study seeks to quantify how abutment geometry alters scour patterns around a single bridge pier, providing insights that build upon and extend previous work on pier–abutment interactions. By synthesizing existing findings and identifying gaps, this review establishes the rationale for the current research, highlighting the need to explore abutment geometry as a critical factor in local scour prediction and mitigation.

3. Materials and Methods

3.1. The Experimental Flume and Bed Material

All experiments were conducted in a closed recirculating system featuring a rectangular channel with dimensions of 9.1 m in length, 0.70 m in width, and 0.50 m in height, along with head and basin tanks for testing. The system comprises three main sections. The first section includes a 1.4 m long, 0.7 m wide, and 0.8 m deep head tank, which also contains an inlet tank. To simulate uniform and steady flow conditions, a comprehensive flow conditioning system was implemented.

Two stainless steel meshes were placed inside the head tank to dissipate turbulence and align flow

paths. Additionally, a layer of coarse gravel was installed at the upstream of the working section to act as an energy dissipater and flow straightener. A calibrated volumetric flow meter was installed in the inlet pipe leading to the vertical tank to measure discharge, with a control valve attached to regulate the pump flow. The pump was positioned before the flow meter.

The second section comprises a rectangular experimental channel, supported by a steel frame with transparent polyethylene sidewalls. A steel plate is fixed to the channel bed. This section is divided into three zones: the upstream zone, the working section, and the downstream zone. The working section features a 2.5 m long, 0.7 m wide, and 0.22 m deep sediment bed composed of non-cohesive material ($d_{50} = 0.716$ mm), with a geometric deviation of less than 1.3, which minimizes armoring and ripple formation [5]. The characteristics of experimental sediments are illustrated in Table 1.

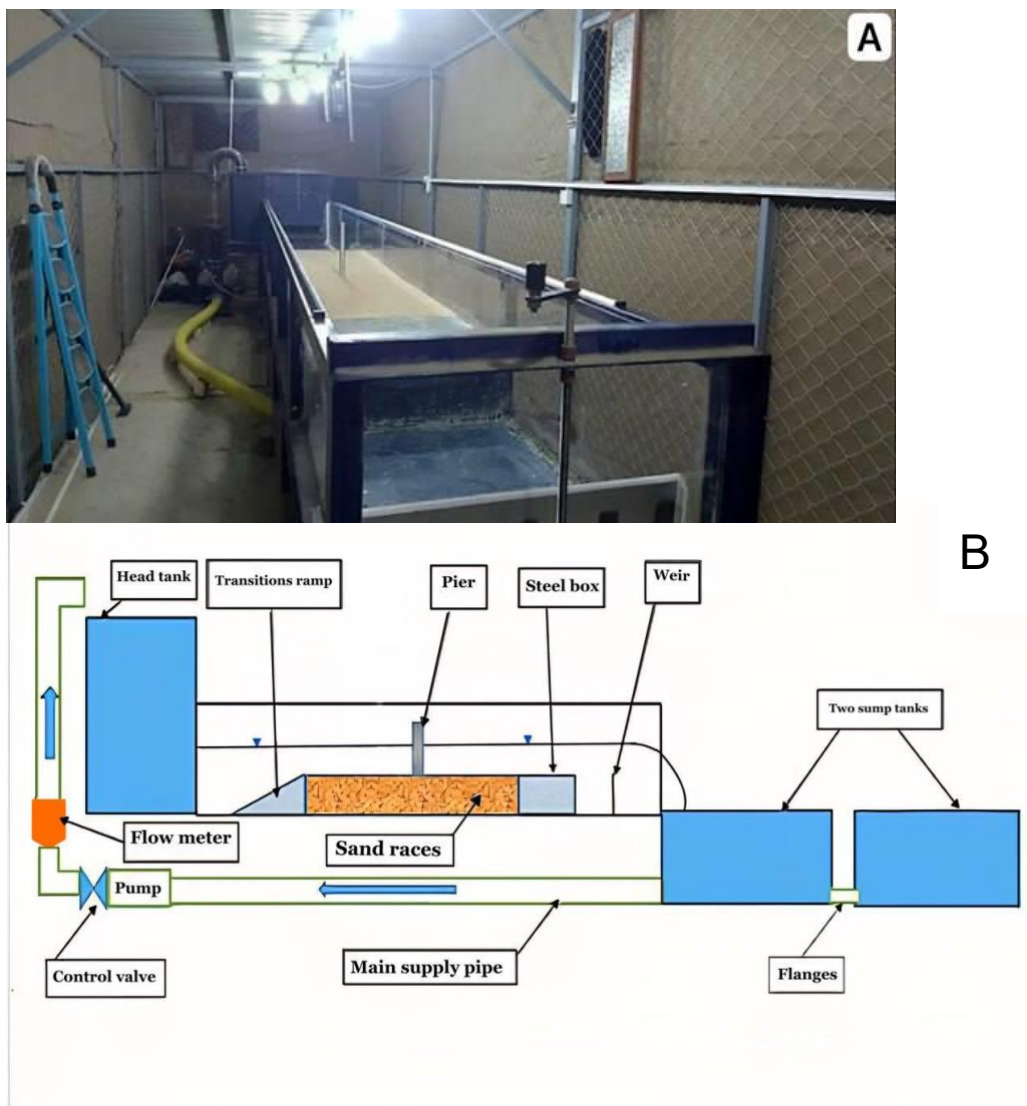


Figure 1. The flume setup for (A) experimental setup, (B) schematic

A cylindrical aluminum platform, 3.1 cm in diameter, was placed at the mid-distance length (1.25 m) of the working section. The third section represents the downstream part of the channel, featuring a water

gate at the end to control water depth. Additionally, two sump tanks provide a water supply to an electric pump with a maximum discharge capacity of 25 L/S. These sump tanks measure 1.6 m in length, 1.36 m in width, and 0.7 m in depth (Figure 1)

Table 1. Sediment characteristics

Material	d_{50} (mm)	d_{84} (mm)	d_{16} (mm)	$\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{0.5}$	$\frac{\rho_s - \rho}{\rho}$
Sand	0.716	0.85	0.516	1.283	1.596

where d_{50} =Median particle diameter, d_{84} =Sediment size for which 84% of particles are finer, d_{16} =Sediment size for which 16% of particles are finer, σ_g = Geometric standard deviation, ρ_s = Sediment density, ρ = Water density.

3.2. The Laboratory Models

The model used in the experiments was manufactured from a wooden block with a smooth surface to represent a simulation of the bridge abutment (Figures 2 and 3), and a cylindrical aluminum model representing the bridge pier with a diameter of 3.1 cm (Figure 4).

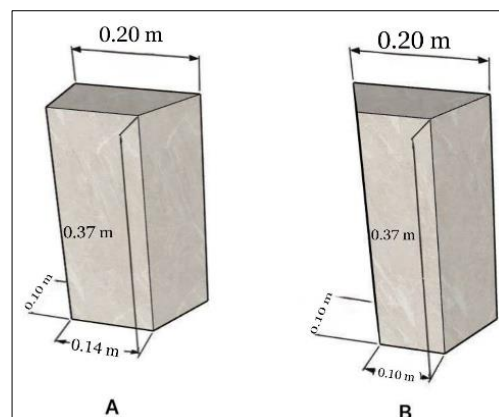


Figure 2. Sketch of abutment models with dimensions (A) trapezoidal, and (B) wing-wall.



Figure 3. Wooden abutment models (A) trapezoidal, and (B) wing-wall.



Figure 4. Cylindrical aluminum pier model.

3.3. Experimental Procedures

A total of fifty experiments were conducted and classified into three main groups. The first group consisted of a series of tests specifically designed to investigate the local scour depth associated with a single bridge pier. The second group focused on wing-wall abutment models and was further divided into two subgroups, each comprising ten experiments. In the first subgroup, the face-to-face distance between the pier and abutment was set at 22.5 cm, corresponding to the center of the working section. In the second subgroup, the spacing was reduced to 17.5 cm to assess the effect of reduced separation on scour behavior.

The third group mirrored the experimental design of the second group but substituted the wing-wall abutment with a trapezoidal abutment, as illustrated in Figure 5. These experiments aimed to analyze the interaction effects between the bridge pier and various abutment geometries. Hydraulic conditions, including flow depth, flow intensity, Froude number, and discharge, were systematically measured across all experimental groups. All tests were conducted under clear-water conditions.

Based on the variability reported in previous studies regarding the time required to reach equilibrium scour depth, it was determined that a three-hour test duration would be sufficient for this investigation. For instance, Barkdoll, et al. [22] reported that scouring depth could reach between 50% and 80% of the equilibrium depth depending on flow intensity, with approximately 10% of the total time required to reach equilibrium.

The experimental procedure began with adjusting the flowmeter to set the discharge, followed by setting the flow depth. The working section was leveled before the pump was activated. Upon initiating flow, water was gradually introduced into the flume until the desired flow depth was achieved. Observations indicated that scour developed rapidly within the initial 30 minutes of flow initiation, with the rate of development decreasing substantially thereafter. Peak scour depth was typically observed at approximately

90 minutes, beyond which incremental increases in depth were minimal.

Scour development was monitored until equilibrium conditions were reached, as defined by the criterion proposed by Ettema, et al. [23], where the scour depth was considered to be at equilibrium when additional increases did not exceed 1 mm. After each test (lasting three hours), the pump was shut off, and the channel was slowly drained via a bottom drainage system to preserve the morphology of the scour hole. Measurements of the scour dimensions were then recorded, including the maximum scour depth (d_s), the longitudinal length (L_s), and the transverse width (W_s), as depicted in Figure 6. A point gauge mounted on a wheel-based traversing system spanning the flume walls was employed to obtain accurate measurements of the maximum scour depth (d_s).

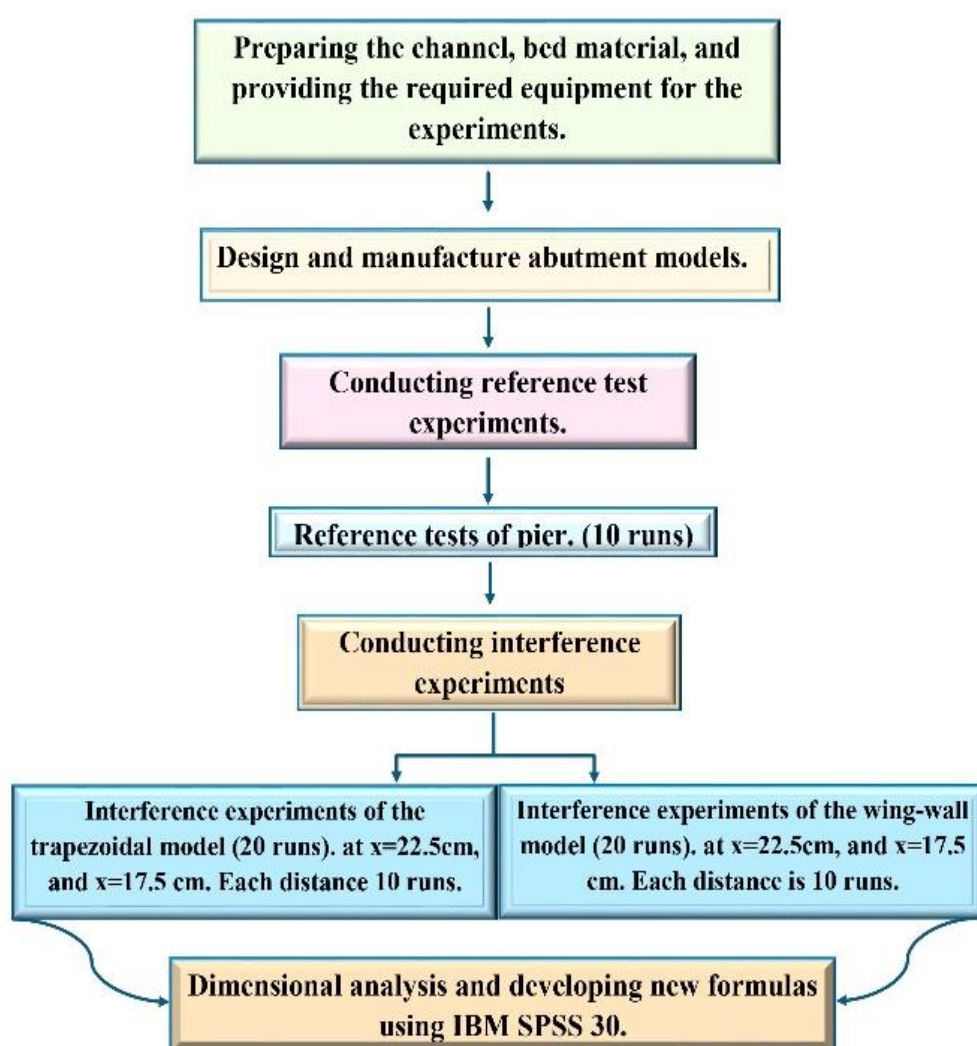


Figure 5. Flow chart of the methodology of the study.

4. Results and Discussions

The experimental investigation compared two abutment geometries, a trapezoidal model and a wing-wall model, under conditions where the abutment-pier distance was constant, first at 22.5 cm and second at 17.5 cm. Tables 2 and 3 illustrate the impact of each configuration on the development of local scour around

the bridge pier as hydraulic parameters (flow depth, discharge, Froude number, and flow intensity) vary. All laboratory experiments were conducted under clear water conditions when $v/v_c < 1$, where v =average flow velocity (L/T), and v_c =critical flow velocity (L/T) for steady and subcritical flow. The velocity profile's logarithmic form can be used for determining the critical velocity [5].

$$\frac{v_c}{u_{*c}} = 5.75 \log \left(5.53 \frac{y}{d_{50}} \right) \quad (1)$$

where u_{*c} = critical shear velocity based on the d_{50} size, the Shields diagram for the appropriate size is used to calculate the shear velocity. For quartz sediments in water at 20°C, a useful approximation of the Shields diagram is:

$$u_{*c} = 0.0115 + 0.0125d^{1.4} \quad , 0.1 \text{ mm} < d < 1 \text{ mm} \quad (2)$$

where (u_{*c}) is in m/s and (d_{50}) , (y) are in mm.

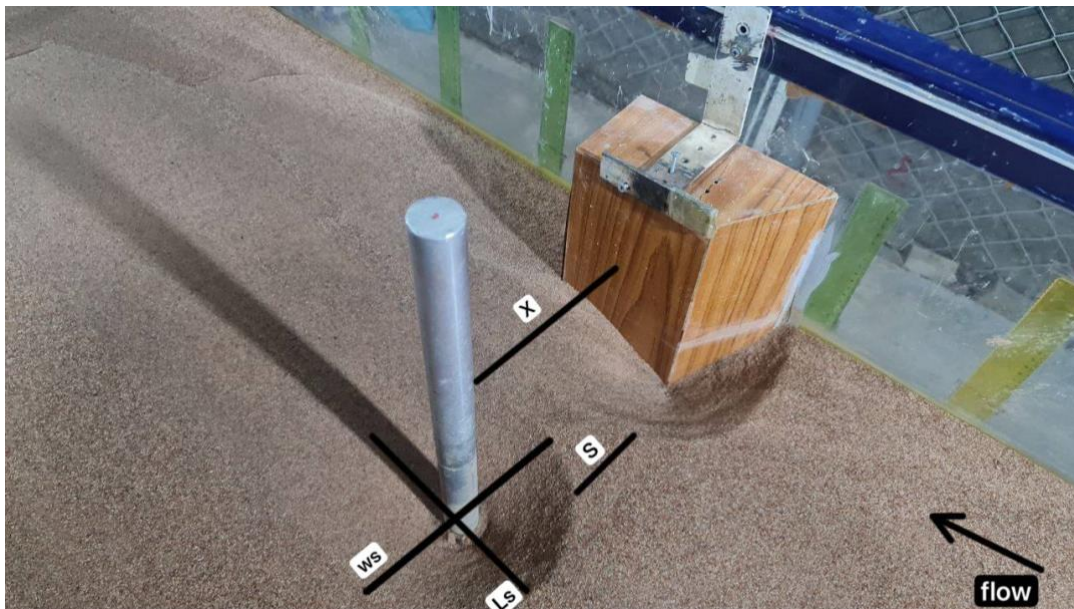


Figure 6. Scour hole dimensions of the pier.

4.1. Flow intensity (v/v_c) and Froude number (Fr) effects on scour depth(ds/y)

A series of flow velocity experiments was conducted to investigate the development of scour depth around a cylindrical pier under varying flow velocities and constant flow depth conditions. Specifically, four velocity tests were conducted at a constant flow depth of $y = 7$ cm to assess the effect of incremental increases in flow velocity under shallow water conditions.

As presented in Figure 7, the resulting scour depth curves exhibit a consistent increasing trend, indicating a marked increase in scour depth as the flow velocity approaches and nears the critical threshold. These findings corroborate the Froude number relationship ($Fr = v/\sqrt{gy}$), where increases in flow velocity led to higher Froude numbers, subsequently contributing to the formation of larger scour holes. This behavior is principally attributed to intensified flow disturbances around the pier, particularly the strengthening of horseshoe vortex systems.

Table 2. Results of the interface between pier and abutment face-to-face distance $x = 22.5$ cm

Scour depth of the pier only							Pier scour affected by the trapezoidal model							Pier scour affected by the wing-wall model							
RUN	y (cm)	Q (l/sec)	Fr	x/y	V(m /sec)	V/V C	ds (cm)	L/y	ds (cm)	ds/y	Ws (cm)	Ls (cm)	S (cm)	P.I%	L/y	ds (cm)	ds/y	Ws (cm)	Ls (cm)	S (cm)	P.I%
1	7	8.33	0.18	3.21	0.15	0.5	2.27	2	4.3	0.614	12.5	14.5	10	89.4%	1.43	4.04	0.557	16.5	17.5	10.5	77.9%
2	7	9.72	0.24	3.21	0.19	0.65	3.3	2	5.2	0.742	15.5	16.5	5	57.6%	1.43	4.6	0.657	20	21	9	39.4%
3	7	11.11	0.26	3.21	0.21	0.7	3.62	2	6.8	0.971	21	25	3.5	87.8%	1.43	5.6	0.8	20	22	2	54.7%
4	7	13.89	0.33	3.21	0.27	0.9	5.7	2	7.2	1.028	22	31	Intersect	26.31%	1.43	7.6	1.086	24	30.5	Intersect	33.3%
5	9	9.72	0.17	2.5	0.16	0.5	2.68	1.56	3.9	0.433	11	11	8.5	45.5%	1.11	3.11	0.346	10.5	11	13.5	16.04%
6	9	13.89	0.23	2.5	0.22	0.7	4.3	1.56	6.2	0.689	18.5	20	7&Intersect	44.2%	1.11	6.03	0.67	26.5	26.5	Intersect	40.2%
7	9	18.05	0.30	2.5	0.28	0.9	5.5	1.56	8	0.889	23	27	Intersect	45.5%	1.11	7.9	0.878	25	34.5	Intersect	43.6%
8	11	12.5	0.16	2.05	0.16	0.5	2.5	1.27	4.2	0.381	13.5	12	11	68%	0.91	3.7	0.336	12.5	12.5	7	48%
9	11	18.05	0.22	2.05	0.23	0.7	4.8	1.27	5.6	0.509	20	21	5	16.7%	0.91	6.24	0.567	26	30.5	3.5&Intersect	30%
10	11	22.22	0.28	2.05	0.29	0.9	6.1	1.27	8.5	0.772	24.5	39	Intersect	39.34%	0.91	8.08	0.735	24	30	Intersect	32.5%
Mean (x̄)		-	-	-	-	-	4.08	-	5.9	-	18.15	21.7	-	0.52	-	5.69	-	20.5	23.6	-	0.42
Standard deviation (σ)		-	-	-	-	-	1.41	-	1.62	-	4.74	8.92	-	0.24	-	1.80	-	5.7	8.11	-	0.17

where Y=flow depth, Q=discharge, Fr =Froude number, X=constant distance between pier and abutment, V=mean approach flow velocity, V /VC=flow intensity, L=length of abutment model, ds=depth of scour, ws=transfer dimension of scour hole, ls=longitudinal dimension of scour hole, S=distance between scour holes until intersection, P. I.=percentage increase of pier scour, Figure 6.

Table 3. Results of the interface between pier and abutment face-to-face distance $X = 17.5$ cm

Scour depth of pier only							Pier scour affected by the trapezoidal model							Pier scour affected by the wing-wall model							
RUN	Y (cm)	Q (l/sec)	Fr	x/y	V(m/sec)	V/VC	ds (cm)	L/y	ds (cm)	ds/y	Ws (cm)	Ls (cm)	S (cm)	P.I%	L/y	ds (cm)	ds/y	Ws (cm)	Ls (cm)	S (cm)	P.I%
1	7	8.33	0.18	2.5	0.15	0.5	2.27	2	4.3	0.614	10.5	10	4	89.4%	1.43	3.1	0.443	9.5	9	7	36.6%
2	7	9.72	0.24	2.5	0.19	0.65	3.3	2	5.5	0.786	17	16.5	2.5	66.7%	1.43	4.8	0.686	13	14.5	7	45.5%
3	7	11.11	0.26	2.5	0.21	0.7	3.62	2	6.5	0.929	20	20	Intersect	79.6%	1.43	6.6	0.943	21	27	Intersect	82.3%
4	7	13.89	0.33	2.5	0.27	0.9	5.7	2	8.3	1.186	18	29.5	Intersect	45.6%	1.43	6.74	0.963	20	28	Intersect	18.2%
5	9	9.72	0.17	1.94	0.16	0.5	2.68	1.56	3.8	0.422	10	11	4	41.8%	1.11	3.35	0.372	10	11	7	25%
6	9	13.89	0.23	1.94	0.22	0.7	4.3	1.56	5.1	0.567	13.5	20.5	Intersect	18.6%	1.11	6.35	0.706	22	23	Intersect	47.7%
7	9	18.05	0.30	1.94	0.28	0.9	5.5	1.56	8.15	0.906	21	21	Intersect	48.2%	1.11	7.8	0.867	16	23	Intersect	41.8%
8	11	12.5	0.16	1.6	0.16	0.5	2.5	1.27	4	0.363	11	11	2.5	60%	0.91	4.5	0.409	14.5	14	5.5	80%
9	11	18.05	0.22	1.6	0.23	0.7	4.8	1.27	6.8	0.618	21	25	Intersect	41.7%	0.91	6.3	0.573	22	26	Intersect	31.3%
10	11	22.22	0.28	1.6	0.29	0.9	6.1	1.27	8.5	0.773	40	56	Intersect	39.3%	0.91	7.2	0.654	20.5	53	Intersect	18.03%
Mean (x̄)	-	-	-	-	-	-	4.08	-	6.1	-	18.2	22.05	-	0.53	-	5.67	-	16.58	22.85	-	0.43
Standard deviation (σ)		-	-	-	-	-	1.41	-	1.82	-	8.8	13.52	-	0.21	-	1.63	-	4.89	12.7	-	0.23

As the flow velocity increases, the strength of these vortices increases, allowing greater sediment entrainment from the bed material. Consequently, the scour zone experiences raised sediment loss, resulting in deeper and more expansive scouring formations. Notably, the trapezoidal abutment exhibited higher scour depths compared to the wing-wall abutment under identical flow intensity conditions. This difference is ascribed to the more pronounced flow contraction and the generation of stronger horseshoe vortices associated with the trapezoidal geometry.

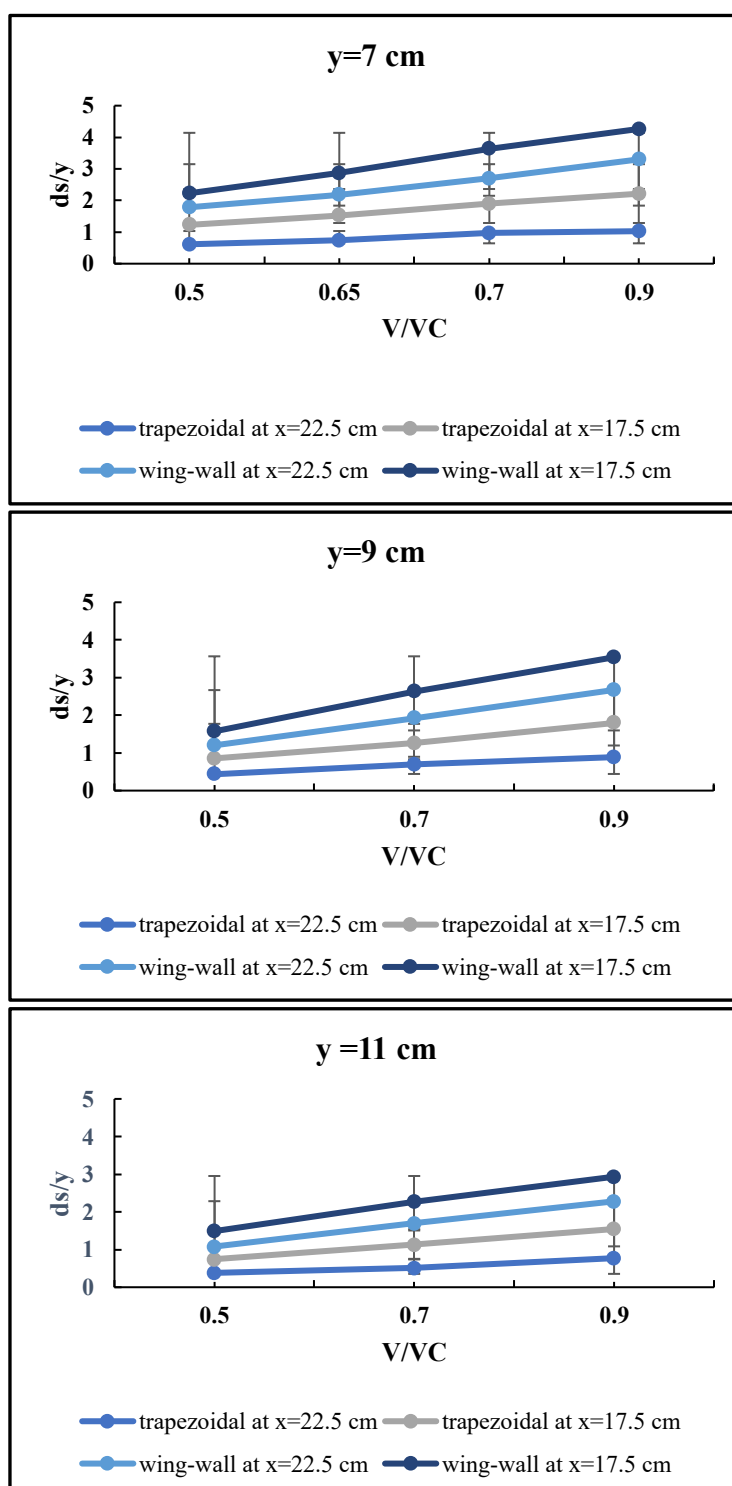


Figure 7. Impact of flow intensity on scour depth for two abutment models at flow depths $y = 7, 9$, and 11 cm

Figure 8 illustrates the combined influence of elevated flow intensity and pier–abutment interaction on the development of local scour around the pier. The data confirm that scour depth increases with increasing flow intensity across all abutment configurations. However, the geometry of the channel and the geometric arrangement of the structural elements influence both the rate of scour development and the ultimate scour depth, as varying separation distances and sediment transport mechanisms manifest differently across the configurations. These results support proven theories of local scour by highlighting the critical role of near-threshold velocities and vortex formation in driving sediment removal processes.

Furthermore, the findings are consistent with the conclusions of Dheyab and Günal [24], which emphasized the importance of the Froude number in estimating local scour depth. By integrating flow velocity, water depth, and sediment characteristics, Fr serves as a comprehensive parameter for evaluating scour potential under varying hydraulic conditions.



Figure 8. The development of scour hole according to effect of high flow intensity $v/v_c=0.9$ and $y=11$ cm at (A) pier only, (B) interface between trapezoidal shape and pier at $x=22.5$ cm (C) Trapezoidal at $x=17.5$ cm (D) wing-wall at $x=22.5$ cm (E) wing-wall at $x=17.5$ cm. All scour hole dimensions in cm.

Figure 7 illustrates error bars representing the range of ± 1 standard deviation from the mean scour depths obtained in repeated experiments. They evaluate data variations and indicate whether scour occurs

consistently across different currents. For y values of 7 cm, 9 cm, and 11 cm, the majority of sessions exhibited minimal error bars, suggesting that the scour measurement remained consistent throughout the trials. The wing-wall model at $x = 17.5$ cm exhibits a wider margin of error, particularly at elevated v/v_c values (specifically when $v/v_c = 0.9$), indicating that local scour may experience more significant variations in areas of pronounced flow piercing.

4.2. Discharge (Q) and Flow Depth Effect on Scour Depth (ds/y)

The depth of flow above the channel bed plays a significant role in influencing local scour around bridge foundations. Experimental results consistently demonstrated a prominent effect of flow depth on scour development across all tested scenarios. A non-linear relationship was observed between flow depth and scour depth under constant discharge conditions. Specifically, deeper water was associated with a reduction in scour depth, primarily due to weakened bed shear stress and reduced velocity gradients.

However, under shallow flow conditions ($y=7$ cm), a strong interaction between the pier and abutment zones was evident, resulting in a relative scour depth increase of up to 89%, as illustrated in Figure 9. Across all abutment configurations, greater scour depths at the pier were observed with increasing discharge rates. High discharge increased both flow velocity and bed shear stress, thereby enhancing sediment entrainment and transport processes.

For instance, in tests involving the trapezoidal abutment, when discharge was held constant ($Q = 18.05$ L/s), increasing flow depth from $y = 9$ cm to $y = 11$ cm led to a decrease in scour depth from $ds = 8.0$ cm to $ds = 5.6$ cm, representing a decrease of approximately 16.7%. Similar trends were noted for the wing-wall abutment, where the scour depth decreased from $ds = 7.9$ cm to $ds = 6.24$ cm, reducing the relative increase from 43.6% to 30%, as shown in Figure 10.

The separate hydrodynamic behavior of the trapezoidal abutment can be attributed to its capacity to induce strong flow contraction and generate intense turbulent vortices. Under higher discharge conditions, local scour around the pier was more severe in the presence of trapezoidal abutments due to the amplification of secondary currents. Conversely, wing-wall abutments were observed to mitigate flow separation and reduce the concentration of flow energy, resulting in less severe scour.

Previous experimental studies (e.g., Rezaie, et al. [25]) have shown that the combination of surface roughness elements on abutments can significantly reduce the extent of local scour. These roughness elements disrupt downflow and weaken the strength of primary vortices, thereby limiting the flow's capacity to enlarge the scour hole. Consequently, the choice of abutment geometry, such as wing-wall versus trapezoidal, should consider its impact on the surrounding flow field. Abutments that more effectively divert or dissipate incoming flow energy tend to provide enhanced protection against scour by reducing the strength of the vortices and downflow structures responsible for sediment removal.

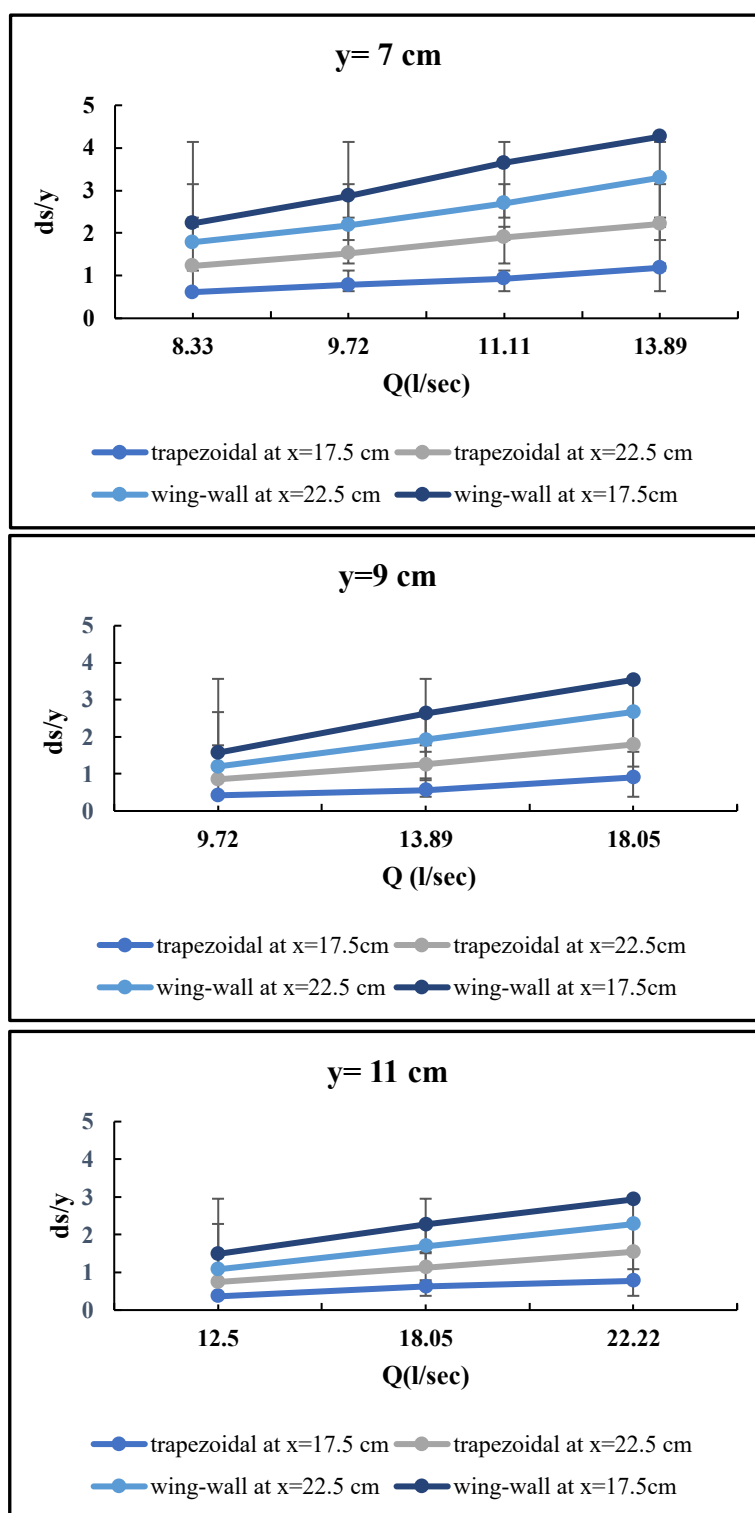


Figure 9. The impact of discharge on scour depth at constant flow depth.

The data represented by the error bars in Figure 9 reflect the level of uncertainty and reliability in the measurements of scour depths. Wing-wall abutments exhibit significantly lower error bars than trapezoidal abutments, indicating that the results from the former are more accurate and reproducible. At a small abutment-pier distance ($X = 17.5$ cm), the trapezoidal abutment exhibits larger error bars, indicating that turbulent flows generated by the pier significantly influence the structure. Larger error bars are observed

with increased discharge (Q) values for both abutment designs, suggesting reduced certainty in predicting scour depth as the flow energy increases. The trapezoidal abutment exhibits a more pronounced effect at a reduced distance of 17.5 cm and an increased water depth of 11 cm, indicating that irregular geometry and flow collectively influence measurement accuracy.



Figure 10. The effect of increased flow depth with constant distance between pier and abutment $x=22.5$ cm, and constant discharge on scour hole development around the pier. (A-C-E) RUN 7 at $y=9$ cm, and (B-D-F) RUN 9 at $y=11$ cm. All scour hole dimensions in cm.

4.3. The Effect of Distance Ratio (x/y) on Scour Depth(ds/y)

Local scour patterns typically develop through the interaction between the bridge pier and its nearby abutment, necessitating a detailed understanding of the influence of pier–abutment spacing. In this study, experiments were conducted by varying the horizontal spacing between the pier and abutment from the flume center ($x = 22.5$ cm) to a reduced separation distance of $x = 17.5$ cm. At each configuration, the pier was aligned relative to the respective abutment model.

As shown in Table 2, the mean of local scour depth around the pier in the presence of the abutment (trapezoidal and wing wall) was 6.1 and 5.67 cm, respectively. Indicating a significant increase in scour intensity compared to the reference case, while the value was identical in Table 3. Experimental results revealed that the reduced spacing of 17.5 cm intensified flow interactions, resulting in an increased maximum scour depth at the pier. Specifically, the relative increase in scour depth increases from 41.56%

to 42.64% for the wing-wall abutment, and from 52.04% to 53.19% for the trapezoidal abutment.

At the larger spacing ($x = 22.5$ cm) and under shallow flow depth conditions ($y = 7$ cm), minimal hydrodynamic interference between the pier and abutment was observed, suggesting a more isolated flow regime. In contrast, the closer proximity of $x = 17.5$ cm promoted flow acceleration between the pier and abutment, which elevated bed shear stress and altered the structure of the horseshoe vortex system.

This interaction was further complicated by the turbulent wake vortices generated by the abutments, which disturbed the vortical flow field around the pier. The combined effects of these interactions led to higher maximum scour depths, as corroborated by the measured percentages. Figure 11 illustrates the morphological differences in dune and scour hole formation resulting from reduced pier–abutment spacing under otherwise identical hydraulic conditions.

These findings are consistent with the work of Akbulut, et al. [26], who indicated that the simultaneous presence of both a pier and an abutment markedly influenced scour hole development within the flow field, particularly in the vicinity of the pier.



Figure 11. The scour hole development at the same conditions, $y=9$ cm and $v/v_c=0.7$, for the trapezoidal model (A, at $x=22.5$ and B, at $x=17.5$ cm) and the wing-wall model (C, at $x=22.5$ and D, at $x=17.5$ cm)

Further analysis is presented in Figure 12, which includes six subplots illustrating the variation in maximum scour depth as a function of the spacing ratio (x/y) under three different flow intensity conditions ($V/V_c = 0.5, 0.7$, and 0.9) and flow depths ($y = 7, 9$, and 11 cm). The experimental findings clearly illustrate an inverse correlation between the relative spacing x/y (the distance between the abutment and pier) and the relative scour depth ds/y . As the distance x/y reduces, the scour depth surrounding the pier significantly increases across all evaluated flow intensities ($V/V_c = 0.5, 0.7$, and 0.9).

This impact is especially significant at elevated flow velocities ($V/V_c = 0.9$), where minimal spacing yields the maximum scour depth, particularly with the trapezoidal abutment. This behavior results from amplified hydraulic interaction between the abutment and pier at reduced distances, causing more complex flow patterns and intensified vortices that facilitate sediment removal around the pier. The wing-wall

abutment consistently produces reduced scour depths, demonstrating that abutment design significantly influences flow dynamics and local scour formation.

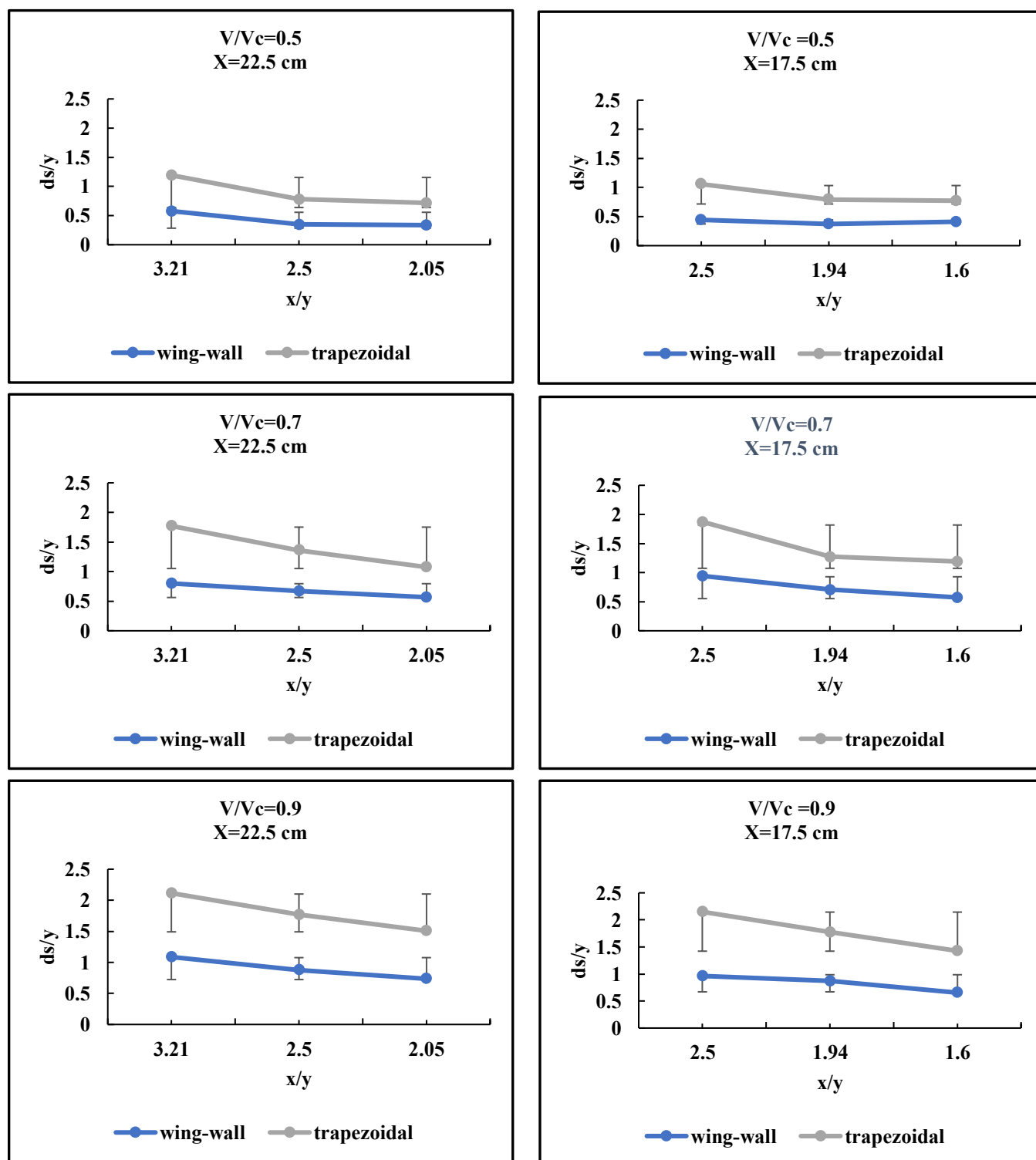


Figure 12. The impact of reducing the distance between the pier and the abutment on the scour depth around the pier at different flow velocities

The error bars in the graphs indicate the variability of the scour depth measurements. These bars denote the standard deviation or confidence intervals surrounding the observed values and function as

indicators of the data's stability. In most instances, the trapezoidal abutment demonstrated extended error bars, indicating greater variability in scour behavior, which is likely attributable to the more irregular and turbulent flow patterns generated by its form.

Moreover, augmenting the flow intensity (V/V_c) leads to greater scour depths and extended error bars, indicating amplified hydraulic disturbances and enhanced sensitivity of the scour process to minor variations in experimental circumstances. These findings suggest that abutment shape and the space between the abutment and the pier are crucial design criteria for assessing local scour risks. Their cumulative impact directly and quantifiably affects the extent of scour around bridge piers, necessitating careful consideration in the design of hydraulic structures within riverine settings.

5. Dimensional Analysis and Development of New Formulas

Dimensional analysis is a powerful method for formulating problems and illustrating the relationships between various physical quantities by identifying their dimensions. A clearer understanding of the physical mechanisms behind local scour around bridge piers can be achieved by defining suitable dimensionless parameters that describe the phenomenon. The factors influencing the maximum scour depth around bridge piers and abutments include flow variables, fluid properties, bed sediment characteristics, pier features, abutment geometry, flume properties, and time. These factors are represented in terms of mass (M), length (L), and time (T), as detailed in Table 4.

Since this study examined two different models of abutments and one model of the pier, each model will have a specific functional relationship to predict scour depth around the pier. The dimensional analysis technique employed in this study is the Buckingham π -theorem, which expresses the maximum scour depth under clear-water conditions as a function of the following variables:

$$d_{smax} = f(\rho, v, \mu, \gamma, g, d_{50}, \sigma_g, \rho_s, v_c, D, B, S, W, L, X, \theta) \quad (3)$$

$$\therefore f_1(d_{smax}, \rho, v, \mu, \gamma, g, d_{50}, \sigma_g, \rho_s, v_c, D, B, S, W, L, X, \theta) = 0 \quad (4)$$

Given that there are seventeen variables ($n = 17$) and three repeating variables ($m = 3$), the number of dimensionless groups according to Buckingham's π -theorem is calculated as $(n - m) = (17 - 3) = 14$. Therefore, there are 14 dimensionless groups, as flowing.

$$f_2(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \dots \dots \pi_{14}) = 0 \quad (5)$$

The repeated variables for this analysis were taken as (ρ, v, γ), then the functional representation of each π for maximum scour depth will be as follows:

$$\begin{aligned} \pi_1 &= \rho^{a1} v^{b1} \gamma^{c1} d_s, & \pi_2 &= \rho^{a2} v^{b2} \gamma^{c2} \mu, & \pi_3 &= \rho^{a3} v^{b3} \gamma^{c3} d_{50}, & \pi_4 &= \rho^{a4} v^{b4} \gamma^{c4} D, & \pi_5 &= \rho^{a5} v^{b5} \gamma^{c5} v_c, \\ \pi_6 &= \rho^{a6} v^{b6} \gamma^{c6} g, & \pi_7 &= \rho^{a7} v^{b7} \gamma^{c7} B, & \pi_8 &= \rho^{a8} v^{b8} \gamma^{c8} L, & \pi_9 &= \rho^{a9} v^{b9} \gamma^{c9} \rho_s, & \pi_{10} &= \rho^{a10} v^{b10} \gamma^{c10} X, \\ \pi_{11} &= \rho^{a11} v^{b11} \gamma^{c11} W, & \pi_{12} &= \rho^{a12} v^{b12} \gamma^{c12} \sigma_g, & \pi_{13} &= \rho^{a13} v^{b13} \gamma^{c13} \theta, & \pi_{14} &= \rho^{a14} v^{b14} \gamma^{c14} S \end{aligned}$$

Table 4. Definition of dimensional analysis parameters

Variable	Definition	Units	Dimensions
Fluid parameters			
ρ	Water density	Kg/m ³	ML ⁻³
μ	Dynamic viscosity of water	m ² /s	MT ⁻¹ L ⁻¹
g	Gravitational acceleration	m/s ²	LT ⁻²
Flow parameters			
Y	Flow depth	cm	L
V	Flow velocity	m/s	LT ⁻¹
V_c	Critical velocity for sediment motion	m/s	LT ⁻¹
Sediment parameters			
d_{50}	Median particle diameter	mm	L
σ_g	Geometric standard deviation	-	-
ρ_s	Sediment density	Kg/m ³	ML ⁻³
Geometric parameters of the flume			
B	Flume width	cm	L
S	Flume bed slope	-	-
Geometric parameters of the pier and abutment			
D	Pier diameter	cm	L
L	Abutment length	cm	L
W	Abutment width	cm	L
X	Distance between pier and abutment	cm	L
θ	Angle attack of the pier and abutment	-	-

By applying the analysis for each term and solving for π_1

$$M^0 L^0 T^0 = (M L^{-3})^{a_1} (L T^{-1})^{b_1} (L)^{c_1} L$$

$$M: 0 = a_1 \rightarrow a_1 = 0$$

$$L: 0 = -3a_1 + b_1 + c_1 + 1 \rightarrow b_1 + c_1 = -1$$

$$T: 0 = -b_1 \rightarrow b_1 = 0 \text{ \& } c_1 = -1$$

$$\therefore \pi_1 = \rho^0 v^0 y^{-1} ds \Rightarrow \pi_1 = \frac{ds_{max}}{y}, \text{ and by the same way}$$

$$\pi_2 = \frac{\mu}{\rho v y} = Re, \pi_3 = \frac{d_{50}}{y}, \pi_4 = \frac{D}{y}, \pi_5 = \frac{V_c}{V}, \pi_6 = \frac{gy}{v^2} = Fr, \pi_7 = \frac{B}{Y}, \pi_8 = \frac{L}{Y}, \pi_9 = \frac{\rho_s}{\rho}, \pi_{10} = \frac{X}{Y}, \pi_{11} = \frac{W}{Y}, \pi_{12} = \sigma_g,$$

$$\pi_{13} = \theta, \pi_{14} = S, \text{ so the following function is obtained}$$

$$f_3 \left(\frac{ds_{max}}{y}, \frac{d_{50}}{y}, \frac{D}{y}, \frac{V_c}{v}, \frac{B}{y}, \frac{L}{y}, \frac{\rho_s}{\rho}, \frac{X}{y}, \frac{W}{y}, Re, Fr, \sigma_g, \theta, S \right) = 0 \quad (6)$$

To simplify the relationships, assumptions were made to eliminate the influence of related dimensionless parameters. These assumptions involved applying constant parameters and ensuring the necessary conditions for maximum scour depth, these included using a uniform sediment size (d_{50} , σ_g) maintaining a constant relative density (ρ and ρ_s), steady viscosity (μ), constant pier diameter (D), constant width of abutment models (w), constant flume width (B), fixed horizontal slope ($S=0$), pier and abutments aligned to the flow direction ($\theta=0$) the functional relationship can be written as follows:

$$f_4 \left(\frac{ds_{max}}{y}, \frac{V_c}{v}, \frac{X}{y}, \frac{l}{y}, Fr \right) = 0 \quad (7)$$

By applying the properties of dimensional analysis, Eq.7 can be represented in terms of maximum scour depth, such as:

$$\frac{ds_{max}}{y} = f5\left(\frac{v}{vc}, \frac{x}{y}, \frac{L}{y}, Fr\right) \quad (8)$$

Table 5. Predicted, observed scour depths, and residual of pier scour affected by trapezoidal abutment

Run	ds/y (observed)	ds/y (predicted)	Residual	Scour predicted (by formula)
1	0.614	0.59	0.02	0.59
2	0.743	0.80	-0.05	0.80
3	0.971	0.86	0.11	0.86
4	1.029	1.10	-0.07	1.10
5	0.433	0.45	-0.01	0.44
6	0.689	0.67	0.02	0.67
7	0.889	0.88	0.01	0.88
8	0.382	0.36	0.02	0.36
9	0.509	0.57	-0.06	0.57
10	0.773	0.75	0.02	0.75
11	0.614	0.63	-0.01	0.62
12	0.786	0.84	-0.05	0.84
13	0.929	0.90	0.02	0.90
14	1.186	1.16	0.03	1.16
15	0.422	-	-	0.48
16	0.567	-	-	0.72
17	0.906	-	-	0.94
18	0.364	-	-	0.39
19	0.618	-	-	0.62
20	0.773	-	-	0.82

To construct Eq. (8), which shows an equation for the maximum scour depth surrounding the pier affected by abutment geometry, the following non-linear regression analysis was performed using the IBM SPSS Statistics 30 to examine the formula for wing-wall and trapezoidal abutment models:

For wing-wall

$$\frac{ds_{max}}{y} = \exp\left(a + \frac{b}{vc}\right) \cdot \exp\left(c + \frac{d}{Fr}\right) \cdot \left(e + f \frac{x}{y} + g \left(\frac{x}{y}\right)^2 \cdot \left(h \cdot \exp\left(i \frac{L}{y}\right)\right)\right) \quad (9)$$

where: a=0.933, b=-0.014, c=0.514, d=-0.294, e=3.308, f=0.322, g=-0.034, h=0.105, i=0.272.

For trapezoidal

$$\frac{ds_{max}}{y} = \exp\left(a + \frac{b}{vc}\right) \cdot (c + d \cdot Fr) \cdot \exp\left(e + \frac{f}{x}\right) \cdot \left(g \cdot \exp\left(h \frac{L}{y}\right)\right) \quad (10)$$

where: a=0.787, b=0.392, c=-0.306, d=3.321, e=0.35, f=0.587, g=0.12, h=0.353.

The R² value for the wing-wall design reached 0.916, followed closely by the trapezoidal-wall

determination of 0.936. For each model, 70% of the data were used to fit the model, which included 14 out of 20 runs. The remaining six runs, representing 30% of the data, were used to evaluate it, as illustrated in Tables 5 and 6.

Table 6. Predicted, observed scour depths, and residual of pier scour affected by wing-wall abutment

Run	ds/y (observed)	ds/y (predicted)	Residual	Scour predicted (by formula)
1	0.577	0.51	0.07	0.51
2	0.657	0.74	-0.08	0.74
3	0.800	0.81	-0.01	0.81
4	1.086	1.05	0.03	1.05
5	0.346	0.39	-0.05	0.39
6	0.670	0.65	0.02	0.65
7	0.878	0.87	0.01	0.87
8	0.336	0.32	0.02	0.32
9	0.567	0.55	0.01	0.55
10	0.735	0.75	-0.02	0.75
11	0.443	0.49	-0.05	0.50
12	0.686	0.72	-0.04	0.72
13	0.943	0.79	0.15	0.79
14	0.963	1.03	-0.07	1.03
15	0.372	-	-	0.38
16	0.706	-	-	0.64
17	0.867	-	-	0.85
18	0.409	-	-	0.31
19	0.573	-	-	0.54
20	0.654	-	-	0.73

Figures 13 and 14 illustrate the close match between the predicted and observed values of (ds/y). The accurate fit of predicted values supports the use of equations (9) and (10).

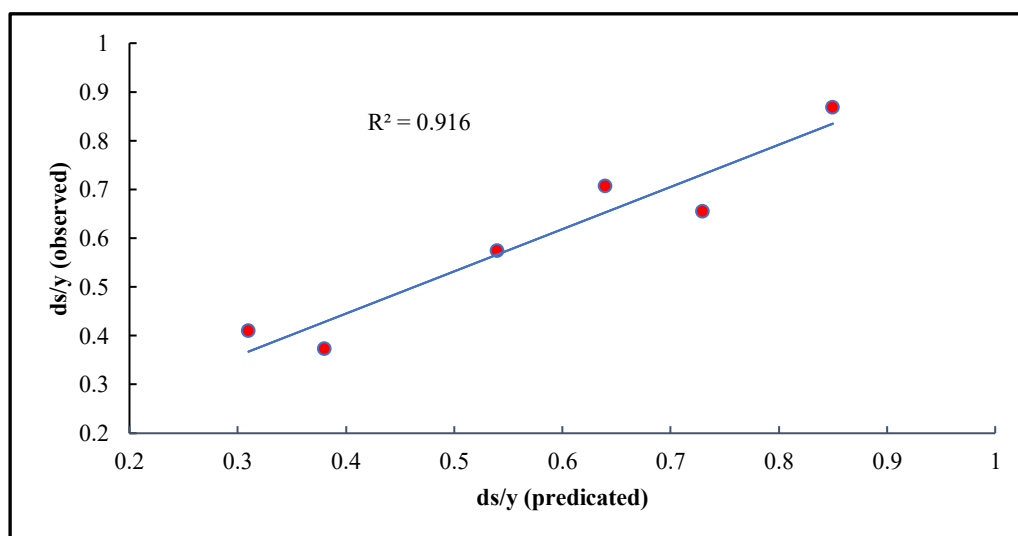


Figure 13. Validation of the wing wall abutment model

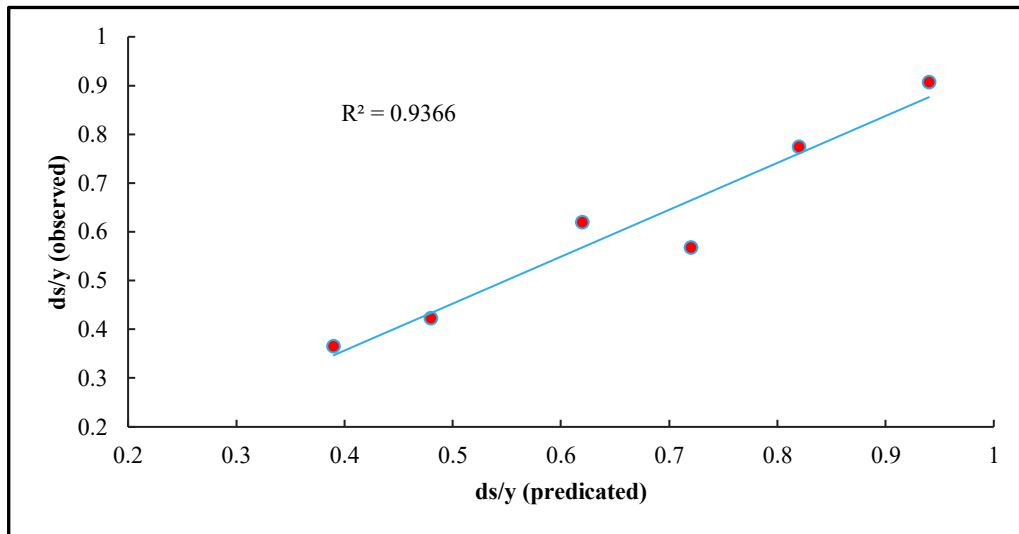


Figure 14. Validation of the trapezoidal abutment model

5.1. Comparison with Existing Empirical Equations

Several empirical equations have been developed in the literature to predict local scour around abutments and piers under various hydraulic conditions. For instance:

Fakhimjoo, et al. [21] conducted experiments in a rectangular flume, comprising 18 primary tests that involved different combinations of pier and abutment types, as well as five control tests using individual piers or abutments. Three types of piers were tested: a rectangular pier with rounded edges, a group of three cylindrical piers, and a single cylindrical pier, along with two abutment types: a wing wall abutment and a semi-circular abutment. A three-dimensional acoustic Doppler velocimetry (ADV) was employed to measure flow characteristics, including streamlines, velocity magnitudes, vertical velocities, and bed shear stress. Results revealed that flow velocity near piers and abutments increased by as much as 80%. The maximum scour depth near the abutment increased by up to 19%, while around the pier it increased significantly, up to 171%. When a pier was located near an abutment, the volume of the resulting scour hole increased by up to 87% compared to an isolated abutment.

Additionally, empirical equations were developed to reliably estimate the maximum scour depth at piers positioned adjacent to abutments, as shown in Eqs. (11) and (12). The following equation was derived from the tests to estimate the scour depth around the pier when influenced by the abutment using the principle of superposition:

$$\frac{d_{sp}}{D} = \frac{d_{sp0}}{D} + \left| \frac{d_{sa0}}{D \tan \varphi} - \left(\frac{X}{D} + \frac{1}{2} \right) \right| \tan \varphi \quad \frac{X}{D} \leq 6 \quad (11)$$

where φ is the angle of repose of the bed materials, d_{sp} and d_{sp0} denoting the maximum scour depths around the pier in the main tests and control tests, respectively. Eq. (11) can estimate the maximum scour depth at a pier located at any distance X away from an abutment, given d_{sp0} , d_{sa0} , and the angle of repose of the bed materials. The following equation can predict the scour depth around a pier near an abutment according to

the shape, type, and arrangement of the pier and abutment:

$$\frac{d_{sp}}{D} = K_{sa} K_{sp} \left[0.19 \left(\frac{X}{D} \right)^2 - \frac{1.8X}{D} + 6.2 \right] \quad (12)$$

where K_{sa} is an abutment shape factor with $K_{sa}=1.14$ for wing-wall abutment and $K_{sa}=1.00$ for semi-circular abutment; and K_{sp} is a pier shape factor with $K_{sp}=0.94$, 0.95 , and 0.88 for a single cylindrical pier, a group of three cylindrical piers, and a rectangular pier with a rounded edge, respectively. This equation accurately estimated the DSP in the vicinity of the abutment with RMSE = 0.12, MAE = 0.10, and $R^2 = 0.98$. The advantage of Eq. (12) is that it can calculate the scour depth given the distance between the pier and abutment and their shapes.

Maatooq [27] describes the scour around the bridge pier near the abutment and offers the findings of a limited experimental program that addressed the issue. The experiments were conducted in a closed system, a water-recirculating flume that was 2 m long, 0.61 m wide, and 0.2 m deep. The maximum discharge used was 3.3 l/s. A layer of sand with a thickness of 8 cm and a median particle size (d_{50}) of 0.575 mm was used as the bottom layer of the working section. There were seven runs, two of which are referred to as pier alone and abutment only. The remaining five runs are provided to illustrate how the distance between a pier and an abutment affects local scour around a pier and its pattern. The findings typically indicate that scour is dependent on the distance between the pier and the abutment. A modification factor deals with this distance, presented as a multiplicative factor used with an empirical predictive formula of scour depth around the bridge pier as follows:

$$\frac{d_s}{b} = \left(0.519 + 2.5 \left(\frac{V}{V_c} - 0.57 \right) y/b \right) k_{dis} \quad (13)$$

It should be noted that the K_{dis} can be taken from the following empirical equation:

$$k_{dis} = 1 - 0.013 \left(\frac{X}{b} \right)^2 + 0.130 \left(\frac{X}{b} \right) \quad (14)$$

where: d_s = maximum scour depth, b = width of pier or abutment, X = spacing between pier and abutment. y = flow depth. K_{dis} = distance coefficient.

6. Conclusions

This experimental study examined the impact of abutment geometry on local scour development around a cylindrical bridge pier under controlled hydraulic conditions. Two abutment configurations, wing-wall and trapezoidal, were tested across varying flow depths and discharges, with fixed durations of three hours per run under clear-water conditions. The results demonstrate that the presence and geometry of abutments significantly influence both the depth and extent of scour around the pier.

Notably, the trapezoidal abutment consistently produced greater scour depths than the wing-wall design, particularly under shallow flow conditions. This effect is attributed to the trapezoidal shape's stronger flow contraction and more direct conveyance of flow energy toward the pier, which enhances

vortex strength and sediment removal. In contrast, the wing-wall abutment facilitated greater flow dispersion, thereby mitigating scour intensity and offering improved protection to pier foundations.

The study also revealed that reducing the pier–abutment spacing amplified scour depth due to intensified flow interactions, particularly at higher flow intensities. Empirical scour prediction models developed for both abutment configurations, using dimensional analysis and non-linear regression (via IBM SPSS 30), demonstrated strong predictive capability, with R^2 values exceeding 0.91.

These findings underscore the significance of abutment design and pier–to–abutment spacing in bridge foundation engineering. Although the results are promising, they are based on idealized laboratory conditions. Further validation in field environments is recommended to account for more complex variables such as live-bed conditions, unsteady flow regimes, and compound channel effects.

6.1. Recommendations for Future Research

The subsequent research directions are proposed to advance the existing work:

1. Validation with Field or Large-Scale Flume Data: This involves comparing the proposed scour equations with empirical data or larger-scale physical models to evaluate their relevance in natural conditions.
2. Extension to Live-Bed and Sediment Transport Conditions: Analyzing the relationship between sediment mobility and abutment geometry.
3. Impact of Compound Channels and Floodplain Geometry: Incorporating intricate geometrical and hydraulic boundaries to represent the conditions at the bridge sites accurately.
4. Investigation of Combined Pier–Abutment Configurations under Skewed Flow: Analyzing the impact of flow angles on scour distribution and structural interaction.
5. Numerical Simulation Coupled with Physical Modeling: Employing computational fluid dynamics (CFD) tools to enhance and broaden experimental results, especially in the analysis of intricate flow patterns and vortex dynamics.

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