Experimental Investigation of Local Scour Around Twin Cylindrical Bridge Piers: Effects of Pier Spacing and Skew Angle

AmirHossein Topal [1], Morteza Shokri [*,1], Majid Fazli [1]

1. Department of Civil Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran.

***Corresponding Author:**
Morteza Shokri

Email: M.Shokri@basu.ac.ir
Received: 2026.04.26
Accepted: 2026.07.06
J. Hydraul. Struct., 2026; 12(4):75-90
DOI: 10.22055/jhs.2026.51968.1382

ABSTRACT

Local scour around bridge piers is a major cause of bridge instability in alluvial rivers, particularly when the approaching flow is skewed relative to the bridge alignment. This experimental study investigates the effects of pier spacing and skew angle on local scour development around twin cylindrical bridge piers. A total of 42 experiments were performed in a laboratory flume (15 m long, 0.6 m wide, and 0.6 m deep) under clear-water conditions. The sediment bed consisted of uniform sand with a median grain size of d_{50} = 1.6 mm. The flow discharge was maintained at 28 L/s with a water depth of 13.5 cm, corresponding to a Froude number of approximately 0.29. Two cylindrical piers with a diameter of D = 4 cm were tested at spacing ratios of S/D = 1–6 and skew angles ranging from 0° to 90°. The results show that the scour response strongly depends on both pier spacing and flow skewness. At close spacings (S/D = 1 and 2), increasing the skew angle intensifies the maximum scour depth and enlarges the scour-hole dimensions around both piers. At intermediate spacings (S/D = 3 and 4), the upstream pier experiences an increase in scour depth and scour length, while scour width decreases; in contrast, the downstream pier shows a non-monotonic variation, with scour parameters initially increasing and then decreasing. At wider spacings (S/D = 5 and 6), the upstream scour parameters continue to increase with skew angle, whereas the downstream maximum scour depth exhibits a rising–falling trend. In addition, the height of the deposition mound increases and then decreases as the skew angle rises for all tested spacings. These findings demonstrate that skew angle and pier interaction are key parameters governing local scour around twin bridge piers. The results provide useful quantitative guidance for bridge foundation design, scour prediction, and the assessment of river engineering measures under oblique-flow conditions.

KEYWORDS
Flow interference; Local scour; Pier spacing; Sediment mound; Skew angle; Twin bridge piers.

1. Introduction

Bridge piers significantly disturb the approaching flow and often become the focal point of local bed erosion in alluvial channels. Among the various hydraulic factors affecting bridge safety, local scour around piers has long been recognized as one of the primary causes of bridge damage and collapse worldwide. Numerous post-failure investigations have shown that a large proportion of bridge failures are associated with excessive scour at foundations, leading to severe economic losses and disruption of transportation networks.

Consequently, improving the understanding and prediction of pier scour has become a major focus in hydraulic and bridge engineering research [1–4].

Local scour develops when the approaching flow encounters a pier and generates complex three-dimensional flow structures near the bed. The downward flow in front of the pier and the formation of the horseshoe vortex system increase the local bed shear stress and promote sediment entrainment, gradually forming a scour hole around the foundation. Under clear-water conditions, the equilibrium scour depth is governed by several interacting parameters, including flow depth, flow intensity, sediment characteristics, and pier geometry. Because of this complexity, numerous experimental studies and predictive relationships have been proposed to estimate scour depth and evaluate the stability of bridge foundations, many of which continue to be widely used in engineering practice [5–8].

In practice, however, bridges are commonly supported by multiple piers. Flow interference between adjacent piers significantly alters vortex dynamics, scour-hole geometry, and sediment deposition patterns. Earlier studies primarily examined longitudinal (tandem) or transverse (side-by-side) spacing effects separately [9,10]. More recent experimental investigations have expanded this knowledge: side-by-side configurations under varying spacing [11], tandem and staggered arrangements of compound piles [12], non-uniform twin piers [13], staggered groups in gravel beds [14], and scour evolution around staggered double-cylinder piers [15]. Additional works have addressed side-by-side piers in curved channels under ice-covered conditions [16] and angled square pier groups [17]. These studies collectively demonstrate that pier interference can either amplify or reduce scour depending on spacing, alignment, and flow conditions, and have led to new predictive equations for specific configurations [11,18].

Despite these valuable contributions, a critical literature gap persists: few, if any, systematic experimental studies have simultaneously varied center-to-center spacing from $1D$ to $6D$ and skew angle from 0° (aligned) to 90° (transverse) for identical cylindrical twin piers under identical clear-water conditions. Most recent works focus on either fixed-spacing tandem/side-by-side setups or limited angle ranges, and rarely provide high-resolution three-dimensional scour topography or volumetric analysis across the full parameter space. This limitation restricts the understanding of horseshoe- and wake-vortex interaction mechanisms and reduces the applicability of findings to real multi-pier bridge design, where piers are often placed at oblique angles due to river morphology or structural constraints.

The present experimental study directly addresses this gap. Forty-two clear-water scour tests were conducted in a recirculating flume using identical cylindrical piers (diameter D). Twin cylindrical piers with diameter D were tested at six longitudinal spacings, characterized by a normalized spacing ratio S/D ranging from 1 to 6, and skew angles θ relative to the approach flow ranging from 0° to 90°. Equilibrium scour topography was measured at high spatial resolution with a point gauge and processed into three-dimensional surfaces using Surfer software to quantify maximum scour depth (upstream and downstream holes), hole dimensions (length and width), sediment mound characteristics, affected area, and scour volume.

Beyond the study of isolated piers, recent experimental efforts have increasingly focused on the complexities introduced by pier configurations, bed morphology, and environmental obstructions. For instance, the scour behavior around roughened pile groups have been investigated, particularly in the presence of material harvesting pits, highlighting how flow intensity and surface conditions influence the resulting bed topography [19]. Further research has explored the morphological evolution downstream of scour holes, specifically noting how upstream debris accumulation

significantly accelerates dune formation [20]. In addition, detailed mapping of scour evolution around grouped bridge piers under controlled hydraulic conditions has provided insights into the spatial distribution of bed erosion [21]. Recent studies have also evaluated the efficacy of mitigation measures, such as bed sills, in controlling the intensified scour caused by debris obstructions, demonstrating the sensitive balance between structural interventions and local flow dynamics [22]. These advancements underscore the importance of accounting for multi-pier interactions and external obstructions in scour prediction.

Local scour around bridge piers located in channel bends has attracted considerable attention in recent years because of the complex flow structures generated by channel curvature and secondary currents. In curved channels, the interaction between centrifugal forces, secondary flow, and the horseshoe vortex system around the pier can considerably intensify the scour process, particularly near the outer bank of the bend. Several recent experimental studies have investigated the influence of flow intensity, pier position, and pier arrangement on scour characteristics in sharp bends. Vaghefi et al. (2025) experimentally examined the effect of variations in the velocity ratio (U/Uc) on scour holes around vertical-inclined piers positioned within a sharp 180° bend [23]. Safaripour et al. (2025) analyzed streamlines around single and double piers with submerged vanes in a sharp U-shaped flume and demonstrated the significant influence of flow structures on scour development [24]. Furthermore, Eghbalnik et al. (2023) investigated the effects of triplex inclined-vertical group pier arrangements on scour hole characteristics in a sharp bend, while Moghaddassi et al. (2024) studied the combined effects of pier position and critical velocity ratio on scour patterns in two consecutive bends under clear-water conditions [25,26]. These studies emphasize the importance of bend-induced flow complexity in determining local scour behavior around bridge foundations.

Based on the limitations identified in previous studies, the present research provides several important contributions to the existing literature.

The main novelties of this study are as follows:

- Simultaneous investigation of skew angles (0°–90°) and spacing ratios (S/D = 1–6), whereas previous studies mostly examined these parameters separately.
- Three-dimensional analysis of scour morphology, including scour hole length, bed deformation, and deposition mound characteristics in addition to maximum scour depth.
- Providing new experimental evidence on the influence of skewed flow on scour intensity and erosion–deposition patterns around bridge piers.

Recent studies have provided further insight into hydraulic behavior, sediment transport, and local scour processes under different flow conditions and hydraulic configurations [27-30]. Despite these advances, the combined effects of skew angle and pier spacing on the three-dimensional morphology of scour around bridge piers have not yet been comprehensively investigated. Therefore, the present study experimentally examines the evolution of scour geometry under varying skew angles and spacing ratios.

The specific objectives are: (1) to quantify the combined influence of pier spacing and skew angle on the magnitude and three-dimensional geometry of local scour holes around twin cylindrical piers; (2) to elucidate the underlying vortex interaction mechanisms responsible for observed trends; (3) to generate a high-resolution dataset suitable for numerical model validation and development of improved design equations; and (4) to provide practical recommendations for optimal pier placement in new and existing bridges.

Results reveal strong non-linear interactions: at close spacings (1D-2D), increasing skew angle dramatically

amplifies scour through merged vortices, while at larger spacings, the effect of angle differs markedly between upstream and downstream piers. These findings extend and complement recent literature [11,15] and have direct implications for resilient bridge design under complex hydraulic conditions.

2. Materials and Methods

2.1. Experimental Facility

The experimental investigation was carried out in a recirculating rectangular laboratory flume. The flume is a concrete structure with a length of 15 m, a width of 0.6 m, and a depth of 0.6 m. The side walls of the flume are constructed of transparent materials to facilitate continuous side-view observation of the scour process and flow dynamics. A test section, specifically designed for sediment placement, was located approximately in the middle of the channel, allowing for a 4 m upstream approach length to ensure a fully developed turbulent flow. The test section itself was 2 m long and spanned the entire width of the flume. In order to minimize the influence of side-wall effects on the flow field and scour development, the piers were installed along the centerline of the flume. The channel width was selected to be sufficiently larger than the pier diameter, providing a large width-to-diameter ratio and reducing the possibility of wall-induced flow distortion. This configuration allowed the main flow structures responsible for local scour, including the horseshoe vortex and wake vortices, to develop properly around the piers.

A 4 m upstream distance was provided between the flow entrance and the test section to allow the approach flow to develop before reaching the model piers. Given the flume width of 0.6 m, this length corresponds to approximately 6.7 times the channel width, which is generally considered sufficient to achieve a reasonably developed turbulent flow in laboratory flumes [31,32]. Preliminary runs also indicated that the approaching flow was stable and uniform before entering the test section.

Flow discharge was supplied by a pump and was determined using a volumetric method. A tailgate situated at the downstream end of the flume was utilized to precisely control the flow depth.

The experiments were conducted in a rectangular flume. The schematic view of the experimental setup, including the arrangement of the twin piers, flow direction, and measurement grid, is illustrated in Figure 1.

The experiments were conducted under constant hydraulic and geometric conditions throughout all test runs. The flume dimensions, sediment characteristics, discharge, flow depth, and clear-water scour condition were maintained unchanged during the experiments. Therefore, Table 1 in section 2.3 summarizes only the principal experimental variables and measured scour parameters.

In the present study, a single flow condition and a uniform sediment size were selected to isolate the effects of skew angle and pier spacing on local scour characteristics. Keeping the hydraulic and sediment conditions constant allowed a clearer interpretation of the influence of the

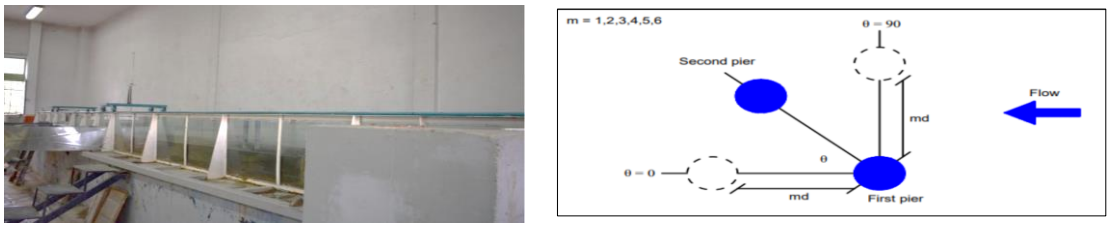


Figure 1.Schematic of the experimental setup showing the flume and twin cylindrical piers at variable spacing S and skew angle θ, flow direction.

investigated parameters on scour morphology. Although different flow intensities and sediment properties may affect the absolute scour dimensions, the observed trends are expected to remain qualitatively similar under comparable clear-water scour conditions. Future studies may extend the experiments to multiple flow and sediment conditions to further evaluate the general applicability of the results.

2.2. Sediment Characteristics

The working section of the flume was filled with a uniform, non-cohesive natural sand bed with a thickness of 13.5 cm. The physical properties of the sediment were determined through standard sieve analysis. The median grain size (d_{50}) was 1.6 mm. The geometric standard deviation of the particle size distribution, defined as $\sigma_g = \sqrt{d_{84}/d_{16}}$, ranged between 1.29 and 1.5. Since the sediment size distribution ($\sigma_g < 1.5$) the sediment was classified as uniform, effectively eliminating the influence of dynamic bed armoring during the scour process [7]. The specific gravity of sediment particles (G_s) was 2.65.

2.3. Pier Geometry and Test Configuration

Two identical cylindrical pipes with an external diameter of $D = 40$mm (0.04 m) were used as the bridge pier models. A pier diameter of 4 cm was adopted based on the flume dimensions and hydraulic conditions to ensure reliable development of local scour while minimizing wall interference effects. The selected diameter also allowed accurate measurement of scour geometry and was consistent with commonly used laboratory-scale pier dimensions reported in previous scour studies. The pier diameter was selected such that the flume width-to-pier diameter ratio ($B/D = 15$) was greater than 10, ensuring that flow contraction and side-wall boundary effects on the local scour development were practically eliminated.

To systematically investigate the interference effects, the twin piers were tested under various spatial configurations. The center-to-center spacing between the piers, S, was varied in increments of one pier diameter, corresponding to $S/D =$ 1,2,3,4,5,and 6. For each spacing, the skew angle (θ) of the twin-pier arrangement relative to the longitudinal direction of the approach flow was adjusted to $\theta \in \{0°, 15°, 30°, 45°, 60°, 90°\}$. The spacing ratios investigated in this study ranged from 1D to 6D in order to capture the transition from strong hydraulic interaction between adjacent piers to conditions approaching isolated-pier behavior. Spacing smaller than 1D was avoided because the two piers effectively act as a single obstruction, whereas at spacing ratios larger than 6D the interaction effects become considerably weaker and the scour characteristics tend toward those of isolated piers. A single isolated pier test was also conducted under the same hydraulic conditions to serve as a baseline for comparison. In total, 42 experimental runs were executed for the twin-pier configurations, plus additional tests for calibration and isolated pier conditions.

Under clear-water scour conditions, with the flow intensity set at the threshold of sediment motion, $V/V_c = 1$ to investigate the effect of spacing and skew angle on

Table 1.Main experimental variables and measured scour parameters

Parameter type	Symbol / Parameter	Values / Description
Independent variable	Longitudinal pier spacing, L/D	1, 2, 3, 4, 5, 6
Independent variable	Pier skew angle, θ (deg)	0, 15, 30, 45, 60, 75, 90
Response parameter	Maximum scour depth, ds	Measured after each experiment
Response parameter	Scour-hole length, Ls	Measured after each experiment
Response parameter	Scour-hole width, Ws	Measured after each experiment
Response parameter	Deposition mound height, Hd	Measured after each experiment

local scour around twin cylindrical piers. The experiments were conducted in a rectangular concrete flume with a uniform sediment bed having a median particle diameter of d_{50} = 1.6mm. The approach flow conditions corresponded to a Froude number of $Fr \approx 0.29$. The experiments were conducted in a rectangular laboratory flume with fixed geometric and hydraulic conditions. The flume dimensions, channel slope, sediment properties, and scour regime were kept constant throughout the experiments and are described in this section. Table 1 summarizes only the main experimental variables and parameters considered in the present study.

Table 1 summarizes only the main experimental variables and response parameters. Constant hydraulic and geometric conditions, including the flume dimensions, channel slope, sediment size, discharge, flow depth, and scour regime, are described in the Experimental Facility section.

2.4. Hydraulic Conditions

The experiments were conducted under clear-water scour conditions, which occur when the approach flow velocity is close to the critical velocity for sediment motion. The critical velocity (V_c) corresponding to the initiation of sediment movement was estimated based on sediment characteristics and flow conditions.

The flow velocity in the flume was gradually increased until the bed material showed the onset of particle movement, indicating the threshold condition for sediment entrainment. The approach velocity was then adjusted so that the velocity intensity ratio remained approximately equal to unity ($V/V_c \approx 1$), representing clear-water scour conditions near the threshold of sediment motion.

Maintaining this condition ensured that the observed scour was primarily generated by the flow–structure interaction around the bridge piers rather than by general sediment transport within the channel.

All experiments were conducted under clear-water scour conditions at the threshold of sediment motion. Clear-water scour conditions were ensured by maintaining the approach flow intensity below the threshold for initiation of sediment motion, consistent with the criterion $V/V_c < 1$, where V is the mean approach velocity and V_c is the critical velocity for the bed material [33,1]. The selected hydraulic conditions were defined with respect to the sediment size used in the experiments ($d_{50} = 1.6$ mm), so that no general bed transport occurred upstream of the test section. In addition, preliminary observations confirmed that sediment motion was absent in the approach reach and remained limited to the vicinity of the pier during the tests. Therefore, all experiments were conducted under clear-water scour conditions. To maximize the local scour depth without inducing general bed movement, the approach flow velocity (V) was systematically adjusted until it equaled the critical velocity for sediment entrainment (V_c). Thus, the velocity intensity was set precisely to $V/V_c \approx 1$. The flow depth (y_0) was maintained constant at 13.5 cm for all tests.

The experiments were carried out under clear-water scour conditions, i.e., the approach flow velocity was kept below the threshold of sediment motion. In each run, the sediment bed was initially at rest, so scour developed solely due to the local hydraulic action around the piers. The hydraulic conditions were selected to ensure that general bed movement did not occur during the tests.

In the present experiments, the Froude number was used as the primary hydraulic similarity parameter because it represents the balance between inertial and gravitational forces in open-channel flows. The experiments were conducted under a constant flow condition in order to isolate the effects of pier spacing and skew angle on local scour characteristics. Other parameters such as flow depth, sediment properties, and pier geometry were kept constant to maintain comparable clear-water scour conditions throughout the tests.

2.5. Experimental Procedure

Prior to each experiment, the sediment bed in the test section was carefully leveled to ensure a uniform initial condition. The twin cylindrical piers were then installed at the desired center-to-center spacing (S/D = 1–6) and skew angle relative to the approach flow (θ = 0°, 15°, 30°, 45°, 60°, and 90°).

Water discharge was gradually increased until the target hydraulic conditions were achieved. The flow depth was maintained constant at y = 0.135 m using an adjustable tailgate located at the downstream end of the flume.

All experiments were conducted under clear-water scour conditions at the threshold of sediment motion. Once the desired flow condition was established, the experiment was allowed to run continuously until the equilibrium scour state was reached.

Equilibrium scour conditions were assumed to be reached when the temporal variation in scour depth became negligible. In this study, equilibrium was defined as the condition in which the change in the maximum scour depth during a 24-hour observation period was less than or equal to 5% of the pier diameter (0.05D).

To determine the approximate equilibrium time, a preliminary long-duration experiment was conducted for a single isolated pier under the same hydraulic conditions. The results indicated that the rate of scour development significantly decreased after approximately 9 hours. Therefore, all experiments in the present study were conducted for a minimum duration of 9 hours to ensure that the scour process approached equilibrium conditions. Each experiment was continued until the scour process approached equilibrium conditions. Equilibrium scour was assumed when no noticeable change in scour depth was observed during an extended observation interval and the scour rate became very small. The temporal variation of scour depth generally exhibited a rapid initial increase followed by gradual stabilization, indicating the approach toward equilibrium conditions.

The selected test duration was based on a preliminary long-term experiment conducted under the same hydraulic conditions as the main tests, namely clear-water flow in a recirculating flume with a discharge of 28 L/s, a flow depth of 13.5 cm, and a Froude number of approximately 0.29. The bed material was uniform sand with $d_{50} = 1.6$mm. In this preliminary test, the rate of scour development decreased markedly after about 9 h, indicating that the scour process was approaching equilibrium. Accordingly, the main tests were conducted for at least 9 h. The equilibrium condition was defined as a 24 h change in the maximum scour depth not exceeding 5% of the pier diameter.

After completion of each test, the flow was slowly stopped and the bed topography around the piers was measured using a point gauge. The bed elevations were recorded over a measurement grid covering the scour hole and the surrounding deposition area.

After completion of each test, the flow was slowly stopped and the bed topography around the piers was measured using a point gauge. The bed elevations were recorded over a measurement grid covering the scour hole and the surrounding deposition area. To better illustrate the spatial characteristics of the scour hole and the deposition dune formed around the twin bridge piers, the measured bed elevations were interpolated using Surfer software to generate two-dimensional contour maps and three-dimensional surface plots of the bed morphology.

The collected data were then processed to generate three-dimensional representations of the scour morphology using Surfer software.

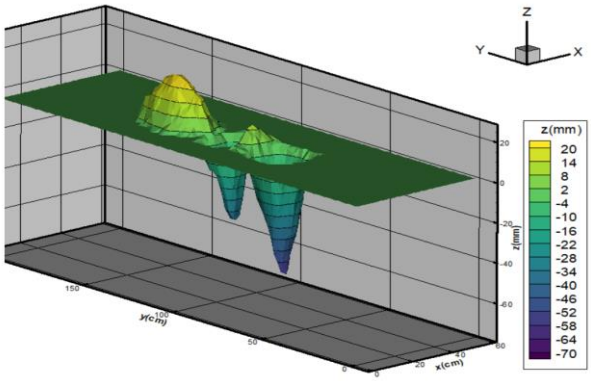


Figure 2.Three-dimensional bed morphology showing the scour hole and downstream deposition dune around the twin bridge piers under skewed-flow conditions.

The Figure 2 illustrates the spatial development of the scour hole and the downstream deposition dune for a representative experimental condition.

2.6. Dimensional analysis

To identify the governing parameters affecting local scour around the twin bridge piers, a dimensional analysis was performed using the Buckingham π theorem. The

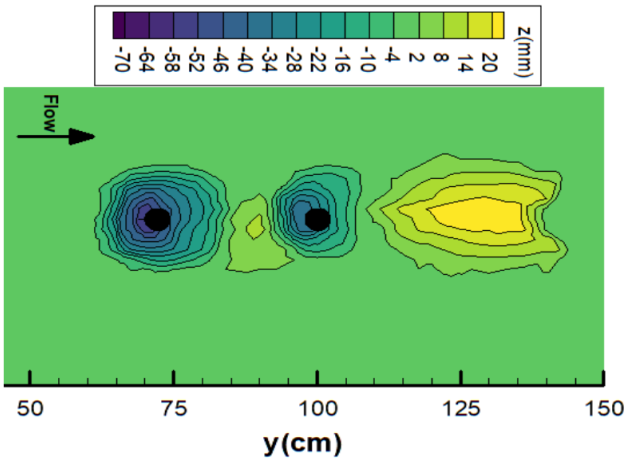


Figure 3.Two-dimensional contour map of bed elevation around the twin bridge piers generated from measured bed-profile data.

The contours lines (Figure 3) represent the bed elevation obtained from the measured bed profiles and interpolated using Surfer software, highlighting the scour hole and deposition patterns.

The use of contour and three-dimensional morphology visualization is consistent with previous scour investigations reported in the literature, such as studies on scour morphology around bridge piers subjected to debris accumulation [34].

equilibrium scour depth $d_s$can be expressed as a function of flow characteristics, sediment properties, and pier geometry:

$$d_s = f(U, y, \rho, \rho_s, g, d_{50}, D, S, \theta) \qquad (1)$$

where $U$is the approach flow velocity, $y$is the flow depth, $D$is the pier diameter, $S$is the spacing between the piers, $d_{50}$is the median sediment size, and $\theta$is the flow attack angle.

Applying dimensional analysis yields the following dimensionless relationship (2):

$$\frac{d_s}{D} = f\left(\frac{y}{D}, \frac{U}{\sqrt{gD}}, \frac{d_{50}}{D}, \frac{S}{D}, \theta\right) \quad (2)$$

In the present experiments, the pier diameter and sediment characteristics were kept constant, while the spacing ratio (S/D)and flow angle (θ)were systematically varied to investigate their effects on scour depth and bed morphology. In the present study, the spacing ratio (S/D) and flow attack angle were selected as the primary varying parameters.

3. Results & Discussion

This section presents the experimental results concerning the variations in scour topology around twin cylindrical piers. The quantitative analysis focuses on the maximum scour depth (d_s), scour hole geometry (length and width), and sediment deposition mound, evaluated across different pier spacings (S/D) and skew angles (θ).

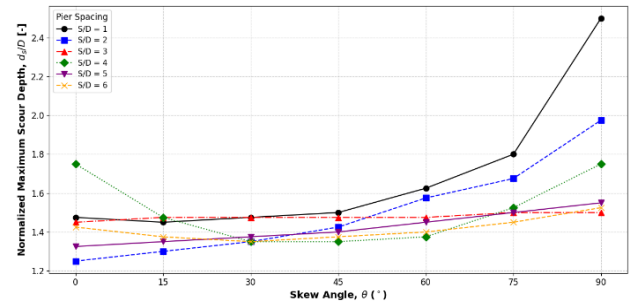
3.1. Maximum Scour Depth Analysis

The absolute maximum scour depth is a critical parameter for bridge safety. In twin-pier configurations, flow interference significantly alters the scouring capacity compared to a single pier.

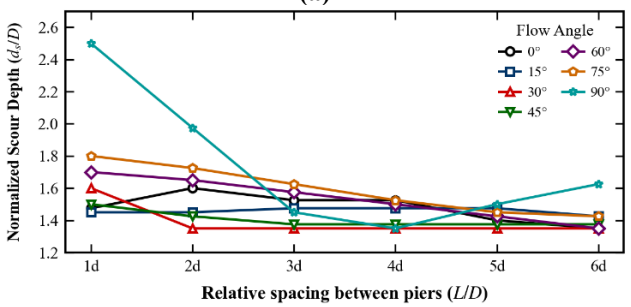
3.1.1. Upstream Pier Scour Characteristics

Figure 4 illustrates the variation of the normalized maximum scour depth (d_s/D) at the upstream pier. For a constant pier spacing, increasing the skew angle from 0° to 90° generally led to an increase in d_s/D. Conversely, at any constant skew angle, increasing the spacing (S/D from 1 to 6) resulted in a gradual decrease in the upstream scour depth.

Discussion: The increase in scour depth with higher skew angles at the upstream pier is primarily due to the broader projected area of the pier group intercepting the flow, which strengthens the primary horseshoe vortex. This observation is consistent with recent findings by Wang, et. Al. [35,44], who demonstrated that greater flow blockage in staggered arrangements amplifies the downflow energy at the leading pier. As spacing increases, the hydrodynamic independence of the upstream pier grows, reducing the "backwater" blockage effect caused by the downstream pier, which explains the slight



(a)



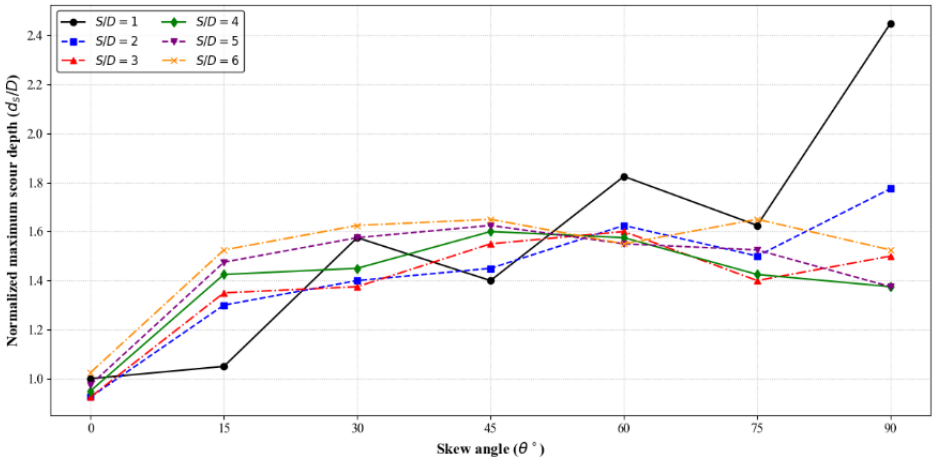
(b)

Figure 4.Variations of the normalized maximum scour depth (ds/D) at the upstream pier: (a) effect of increasing skew angle (θ) at constant pier spacings; (b) effect of increasing pier spacing (L/D) at constant skew angles.

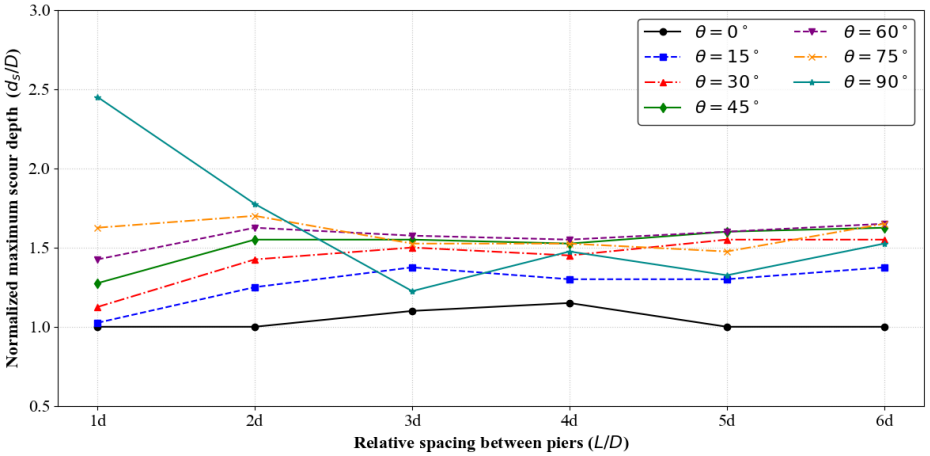
reduction in d_s/D at wider spacings.
For the smallest spacing ratio (S/D = 1), the two piers behave hydraulically as a nearly combined obstruction to the approaching flow. When the flow angle increases toward 75°–90°, the incoming flow directly impinges on the upstream pier while the narrow gap between the piers accelerates the flow and intensifies local turbulence. This condition strengthens the horseshoe vortex system and promotes interaction with wake vortices generated downstream of the upstream pier. The resulting concentration of bed shear stress around the pier base leads to a pronounced increase in scour depth compared with larger spacing ratios.

3.1.2. Downstream Pier Scour and Shielding Effect

The scouring behavior at the downstream pier (Figure 5) was found to be highly non-linear due to complex wake interactions. At tight spacings (S/D=1 and 2) and a 0° angle (tandem arrangement), the downstream pier experienced significantly less scour than the upstream pier due to the shielding effect. However, as the skew angle increased, the downstream pier moved out of the upstream wake region. For spacings larger than $3D$, the scour depth increased with the angle up to 60° but decreased for angles >60°. The non-linear variation of scour depth with spacing ratio indicates that the interaction between adjacent piers changes with pier



(a)



(b)

Figure 5. Variations of the normalized maximum scour depth (d_s/D) at the downstream pier: (a) effect of increasing skew angle (θ) at constant pier spacings; (b) effect of increasing pier spacing (S/D) at constant skew angles.

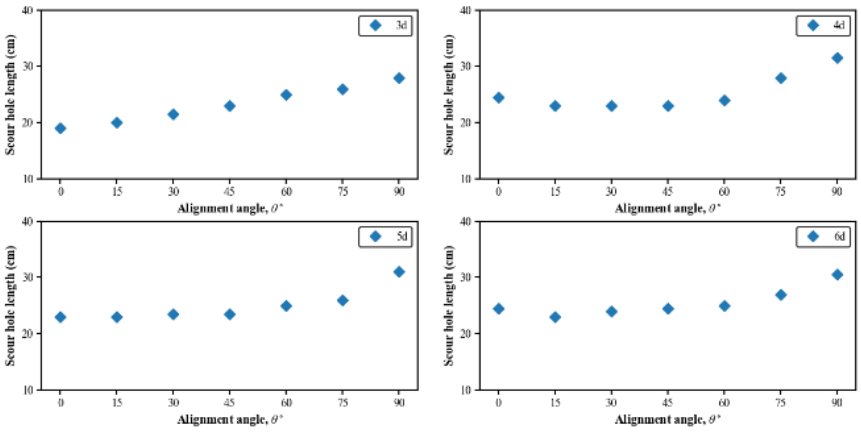
spacing. At smaller spacing ratios, stronger interaction between vortex systems enhances local turbulence intensity and sediment entrainment, increasing scour depth. Beyond a certain spacing, the interference effect weakens and the flow field progressively resembles that around isolated piers, resulting in reduced scour intensity.

Discussion: At intermediate angles (e.g., 15° to 45°) and wider spacings (S/D> 3), a critical flow phenomenon occurs: the flow accelerates as it is channeled between the gap of the twin piers. authors [36,37] recently highlighted this "gap flow channeling" effect, noting that the shed vortices from the upstream pier are swept directly toward the downstream pier, eroding its base more aggressively. This explains why, in the current study, the location of the absolute maximum scour shifted from the upstream pier to the downstream pier at intermediate angles and wider spacings.

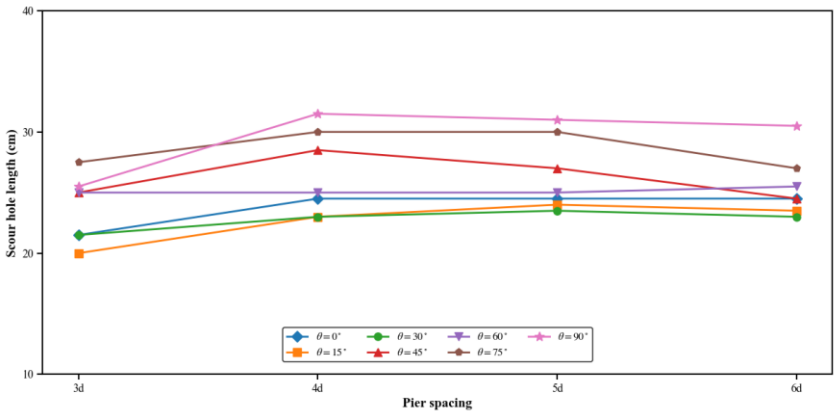
3.2. Scour Hole Morphology (Length and Width)

The spatial extent of the scour holes provides insight into the volume of eroded material. As shown in Figure 6, at narrow spacings ($S/D = 1$ and 2), the individual scour holes of the twin piers completely merged into a single, massive depression. The length and width of this combined hole increased continuously as the skew angle approached 90°.

Discussion: The merging of scour holes at $S/D \leq 2$ indicates that the horseshoe vortex of the downstream pier and the wake vortices of the upstream pier combine into a unified, highly turbulent erosive system. Recent experimental works by Majid and



(a)



(b)

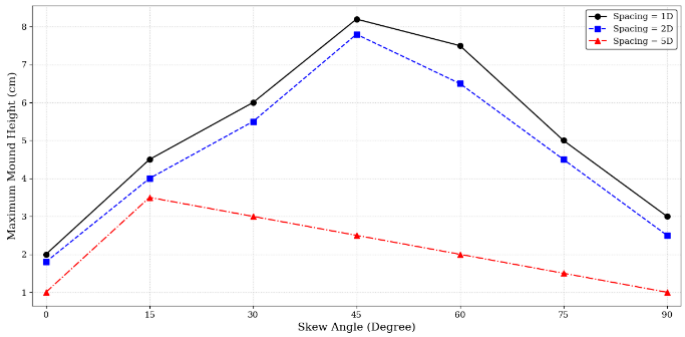
Figure 6.a) Variation of the upstream pier scour hole length with pier spacing for various skew angles. b) Variation of the upstream pier scour hole length with skew angle for different pier spacings.

Ahmad [38] corroborate this, showing that overlapping vortex systems at close proximity exponentially increase the scour hole dimensions. For wider spacings ($S/D \geq 4$), the holes separated, and the upstream scour hole dimensions became relatively stable, indicating diminished interference.

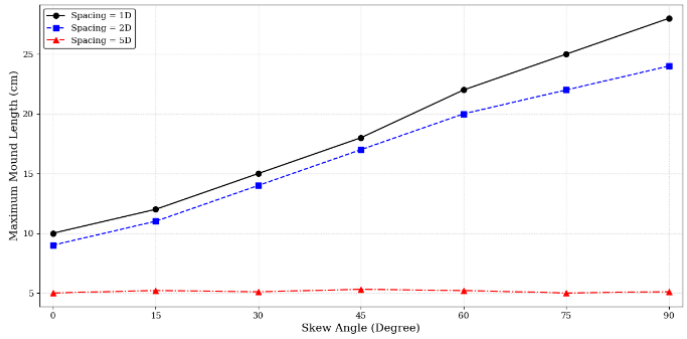
3.3. Sediment Deposition Mound Characteristics

The eroded sediment from the scour holes is transported and deposited downstream, forming a deposition mound (Figure 7). The experimental data revealed that the maximum height of the deposition mound consistently decreased with an increasing skew angle. However, the spatial extent (length and width) of the mound expanded with the skew angle up to intermediate spacings ($4D$ to $5D$).

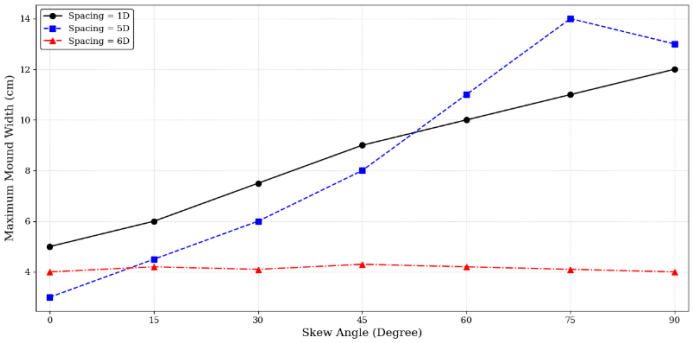
Discussion: The reduction in mound height at higher skew angles suggests a wider distribution of turbulent kinetic energy, which scatters the bedload material over a larger area rather than piling it into a steep dune. The absolute maximum mound dimensions were observed at extreme interference states (e.g., max length at S/D=1, Θ= 90°), underscoring the direct correlation between maximum flow



(a)



(b)



(c)

Figure 7. Variations of maximum sedimentation mound dimensions as a function of skew angle for different pier spacings ($S = 1D, 2D, 5D$: (a) height, (b) length, and (c) width.

blockage and maximum sediment displacement volume, a trend recently discussed in sediment transport models by Yao et al. [39].

At larger skew angles, the scour process appears to be influenced by both the modification of the horseshoe vortex system and stronger flow separation around the piers. The lateral approach flow produces asymmetric vortex structures and enhances downstream wake development, resulting in higher local bed shear stresses and increased sediment transport capacity. Consequently, deeper and more elongated scour holes were observed as the skew angle increased. The observed scour morphology is consistent with mechanisms previously reported for skewed bridge-pier flows.

3.4 Validation of the Experimental Results

To assess the reliability of the experimental observations, the obtained scour characteristics were compared with previously published studies and widely accepted scour prediction approaches for cylindrical bridge piers under clear-water conditions. Such comparisons are commonly used to verify the consistency of laboratory measurements with established hydraulic behavior [1,7].

In the present experiments, the normalized maximum scour depth around the upstream pier generally increased with increasing skew angle. This behavior is consistent with the findings of several previous studies which reported that flow obliquity intensifies the horseshoe vortex system and increases the local bed shear stress around bridge piers [32,33]. As the skew angle increases, the approaching flow interacts more strongly with the pier surface, producing stronger vortical structures and consequently deeper scour holes.

Furthermore, the experimental results indicate that increasing the spacing ratio between the twin piers (S/D) reduces the scour depth around the upstream pier. Similar trends have been reported by researchers investigating flow interference between multiple bridge piers, where close pier spacing amplifies turbulence and vortex interaction, while larger spacing weakens these interference effects [41].

The downstream pier exhibited significantly smaller scour depths at low spacing ratios (S/D = 1–2), which can be attributed to the sheltering effect produced by the upstream pier. This shielding phenomenon reduces the effective flow velocity and turbulence intensity reaching the downstream pier, leading to smaller scour holes. Comparable observations have been reported in experimental studies of tandem bridge piers under clear-water scour conditions [42,43].

Overall, the trends observed in the present study including the influence of skew angle, pier spacing, and flow interference show satisfactory agreement with previous laboratory investigations and established scour mechanisms reported in the literature. This agreement confirms the reliability of the experimental setup, measurement procedure, and the obtained scour data.

4. Conclusions

This study experimentally investigated the three-dimensional scour morphology around twin bridge piers subjected to skewed-flow conditions. The results revealed that flow obliquity significantly affects the development of local scour, the interaction of scour holes between adjacent piers, and the associated sediment deposition patterns. Under skewed approach flow, the scour geometry became increasingly asymmetric, while the location of maximum scour depth shifted toward the downstream side of the pier due to the redistribution of near-bed vortical structures and accelerated flow zones.

The contour maps and reconstructed three-dimensional bed surfaces clearly demonstrated the complex interaction between horseshoe vortices, wake vortices, and pier interference effects. The experiments further showed that the mutual interaction of the twin piers modifies the flow field and produces non-uniform scour

development that cannot be adequately represented using isolated-pier assumptions. The outcomes of this research provide useful reference data for improving the hydraulic design of bridge foundations in alluvial rivers. The findings are particularly relevant for bridge crossings where channel alignment, river curvature, or floodplain conditions generate oblique flow attack angles. Incorporating skew-angle effects into scour assessment procedures may therefore improve bridge safety and reduce the risk of foundation failure during extreme hydraulic events.

Future investigations are recommended to examine a broader range of hydraulic and geometric conditions, including different pier spacings, sediment gradations, flow intensities, and larger skew angles. The integration of laboratory measurements with advanced numerical simulations and field observations would further enhance the applicability of the present findings to prototype-scale river systems. Additional studies on scour countermeasures under skewed-flow conditions are also recommended to develop more reliable and cost-effective protection strategies for bridge infrastructure.

Acknowledgments

The authors would like to thank the Laboratory of Hydraulic Engineering at Bu-Ali Sina University for providing the facilities required to conduct this research.

References

1. Richardson EV, Davis SR. Evaluating scour at bridges. Washington (DC): Federal Highway Administration; 2001. Report No.: FHWA-NHI-01-001.
2. Lagasse PF, Zevenbergen LW, Schall JD, Clopper PE. Bridge scour and stream instability countermeasures: experience, selection, and design guidance. 3rd ed. Washington (DC): Federal Highway Administration; 2001. Report No.: FHWA-NHI-01-003.
3. Kim T, Park J, Lee S. Title of the 2025 article on scour or related topic. J Hydraul Eng. 2025;151(1).
4. Cristopher RA, Cook RA. Prediction of scour depth at bridge abutments. J Bridge Eng. 2014;19(5):04014004. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000554
5. Rashno A, Eghbalzadeh A, Naserbegi A. Scour depth prediction around spur dikes using hybrid ANFIS methods. J Hydroinform. 2016;18(5):822-33. https://doi.org/10.2166/hydro.2016.128
6. Tena AF, Martín-Vide JP, Bladé E. Experimental study on the influence of pier shape on local scour. Water. 2021;13(4):490. https://doi.org/10.3390/w13040490
7. Melville BW, Coleman SE. Bridge scour. Highlands Ranch (CO): Water Resources Publications; 2000.
8. Ettema R, Melville BW, Barkdoll B. Scale effect in pier-scour experiments. J Hydraul Eng. 1998;124(6):639-42.
9. Hannah CR. Scour at pile groups. Christchurch (NZ): Department of Civil Engineering, University of Canterbury; 1978. Report No.: 28-3.
10. Keshavarzi A, Hamidifar H, Ball JE. Bed topography and local scour around twin bridge piers. Water. 2018;10(3):329. https://doi.org/10.3390/w10030329
11. Nandi B, Das S. Developing new equations for maximum scour depth near tandem, side-by-side, and eccentric piers. Can J Civ Eng. 2025;52(6):1030-44.
12. Duan B, Wang D, Qin C, Duan L. Local scour around marine structures: a comprehensive review of influencing factors, prediction methods, and future directions. Buildings. 2025;15(12):2125.
13. Ravanfar SM, Mohammadpour R, Sabzevari T. Experimental study of local scour around non-uniform twin piers. Int J River Basin Manag. 2023:1-16. https://doi.org/10.1080/15715124.2023.2167823
14. Anand A, Beg M. Local scour at group of bridge piers founded in gravel bed in

staggered arrangement. Results Eng. 2024;23:102608.
15. Yu P, Chen J, Xu S, Zhu L, Li J. Local scour evolution characteristics around staggered cylinder piers: numerical simulation based on the self-sustaining model. Ocean Eng. 2025;339:122043.
16. Song F, Wang J, Zhang Z, Cheng T, Li G, Sui J. Local scour around side-by-side double piers in channel bends under ice-covered conditions—an experimental study. Water. 2023;15(13):2317.
17. Yassein HAA, Al-Shukur AHK. Effect of side-by-side bridge pier shape on depth and configuration of local scour. Math Model Eng Probl. 2025;12(6).
18. Devi G, Kumar M, Bhardwaj A. A review on estimation methods of scour depth around bridge pier. In: River dynamics and flood hazards: studies on risk and mitigation. 2022. p. 189-201.
19. Sattariyan M, Daneshfaraz R, Alinejad B, Majedi-Asl M. Laboratory study of scouring around the roughened pile groups in the presence of material harvesting pits and at different Froude numbers. J Hydraul Struct. 2023;8(4):29-44.
20. Mahdian Khalili A, Akbari Dadamahalleh P, Hamidi M. Experimental evaluation of dune formation downstream of pier scour hole with upstream debris accumulation. J Hydraul Struct. 2024;10(1):13-28.
21. Majedi-Asl M, Kouhdaragh M, Fuladipanah M. Mapping scour depth around group bridge pier under controlled conditions. J Hydraul Struct. 2023;8(4):57-72.
22. Dadamahalleh PA, Hamidi M, Khalili AM. Bed sill effect on bridge pier scour with debris obstruction: an experimental investigation. Innov Infrastruct Solut. 2024;9(5):142.
23. Vaghefi M, Ben Mohammad Khajeh S, Safaripour N. Experimental study of the effect of changes in U/Uc on scour hole around vertical-inclined piers in various positions of a sharp 180-degree bend. Model Earth Syst Environ. 2025;11(1):11.
24. Safaripour N, Vaghefi M, Mahmoudi A. Experimental analysis of streamlines around single and double piers with submerged vanes in a sharp U-shaped flume. Adv Bridge Eng. 2025;6(1):13.
25. Eghbalnik L, Vaghefi M, Behroozi AM. Investigation of the effects of the arrangement of triplex inclined-vertical group piers in a sharp bend on the characteristics of scour holes. Iran J Sci Technol Trans Civ Eng. 2023;47(6):3989-97.
26. Moghaddassi N, Vaghefi M, Akbari M. Experimental study: effects of pier position and critical velocity ratio on scour pattern in two consecutive bends under clear water condition. Iran J Sci Technol Trans Civ Eng. 2024;48(5):3761-73.
27. Sattariyan M, Daneshfaraz R, Alinejad B, Majedi-Asl M. Laboratory study of scouring around the roughened pile groups in the presence of material harvesting pits and at different Froude numbers. J Hydraul Struct. 2023;8(4):29-44.
28. Daneshfaraz R, Nezafat H, Abbaszadeh H, Ebadzadeh P, Kuriqi A. Flow-sediment interaction and experimental design of screen plates for scour mitigation downstream of hydraulic structures. Water Pract Technol. 2026;21(2):555-74.
29. Daneshfaraz R, Rezaie M, Aminvash E, Mehrivar E, Sume V, Abraham J, et al. New generation scour control using nano Xanthan-clay composite for bed protection. Innov Infrastruct Solut. 2026;11(1):46.
30. Daneshfaraz R, Mehrivar E, Aminvash E, Rezaie M. Experimental investigation of scouring parameters of the downstream bed of simple and gabion rostral drops. AQUA Water Infrastruct Ecosyst Soc. 2025;74(4):335-48.
31. Chow VT. Open-channel hydraulics. New York (NY): McGraw-Hill; 1959.
32. Raudkivi AJ, Ettema R. Clear-water scour at cylindrical piers. J Hydraul Eng. 1983;109(3):338-50.
33. Melville BW, Coleman SE. Bridge scour. Highlands Ranch (CO): Water Resources Publications; 2000.

34. Khalili AM, Hamidi M, Dadamahalleh PA. Scour morphology around the bridge pier with upstream rectangular debris. In: Proc of 22nd Iranian Conference on Hydraulics; 2023 Nov; Maragheh, Iran. p. 8-9.
35. Wang H, Tang H, Liu X. Flow structure and local scour around tandem and staggered cylindrical piers. Ocean Eng. 2022;245:110464.
36. Zhang H, Chen Y, Li M. Gap flow channeling effect on local scour around twin bridge piers under steady clear-water flow. Coast Eng. 2023;180:104273.
37. Das R, Das S, Mazumdar A. Experimental study on local scour around twin circular piers. J Hydraul Res. 2020;58(4):629-44.
38. Majid ZA, Ahmad S. Experimental study on local scour around staggered and side-by-side bridge piers. J Hydraul Eng. 2021;147(4):04021008.
39. Yao W, Li J, Zhang Y. Sediment deposition and scour hole volume characteristics around complex bridge piers. Water Resour Res. 2021;57(8):e2020WR029415.
40. Vittal N, Kothyari UC, Haghighat M. Clear-water scour around bridge pier group. J Hydraul Eng. 1994;120(11):1309-18.
41. Kothyari UC, Hager WH, Oliveto G. Generalized approach for clear-water scour at bridge foundation elements. J Hydraul Eng. 2007;133(11):1229-40.
42. Hashemi L, Kashefipour SM, Ghomeshi M, Bahrami Yarahmadi M. An experimental investigation of the scour close to twin bridge piers under unsteady flow. Iran J Sci Technol Trans Civ Eng. 2025:1-19.
43. Ataie-Ashtiani B, Beheshti AA. Experimental investigation of clear-water local scour at pile groups. J Hydraul Eng. 2006;132(10):1100-4.
44. Wang C, Yu X, Liang F. A review of bridge scour: mechanism, estimation, monitoring and countermeasures. Nat Hazards. 2017;87(3):1881-906.

© 2026 by the authors. Licensee SCU, Ahvaz, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 International (CC BY 4.0 license) (http://creativecommons.org/licenses/by/4.0/).