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Quantitative Synthesis and Integrated Prediction of Bridge Pier Scour in Straight and Curved Channels Incorporating Curvature and Shape Effects

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Abstract: Local scour around bridge piers is one of the primary causes of hydraulic and structural failure, particularly in curved channels where secondary flow circulation intensifies bed erosion. Despite extensive previous experimental investigations, available findings remain fragmented across different hydraulic, sediment, and geometric conditions, limiting the generalization of scour prediction approaches. This study presents a quantitative review and analytical synthesis of previously published scour data in straight and curved channels and develops an integrated predictive framework incorporating both curvature amplification and pier-shape efficiency.Analysis of compiled datasets shows that channel curvature increases equilibrium scour depth by 23–42%, with an average amplification factor of 1.36 relative to straight-channel conditions. Regression results indicate that scour depth scales with discharge according to a near-quadratic relationship, $d_s \propto Q^{1.8-1.9}$, in both channel types, confirming that curvature amplifies scour magnitude without altering hydraulic scaling behavior.Pier geometry significantly affects vortex formation and scour intensity. Streamlined configurations reduce equilibrium scour depth by 30–60% compared with rectangular piers. These reductions are generalized through a shape efficiency factor ranging from 0.40 to 0.70, enabling integration into predictive models. Sensitivity analysis of common scour equations identifies pier width as the dominant geometric parameter, exerting 30–35% greater influence than flow depth.An integrated curvature–shape modified formulation is proposed, providing a practical framework for scour prediction and bridge foundation assessment in both straight and curved channels.

Keywords: Local scour, bridge pier, scour mitigation, curved channel, straight channel .

1. Introduction

Bridge pier scour is one of the most serious hydraulic problems affecting the safety and long-term performance of bridges worldwide[1], [2]. It occurs because of the complex interaction between flowing water, sediment transport, and bridge foundations, leading to the gradual removal of bed material around the pier base[3], [4]. This process becomes particularly critical during flood events, when increased flow velocity and turbulence intensify erosion[3]. Numerous documented bridge failures have demonstrated that local scour is often a dominant factor in structural instability, underscoring the need for a comprehensive understanding of scour mechanisms[5]

The impacts of bridge pier scour extend beyond structural damage alone. Scour-related failures can cause significant economic losses due to repair and reconstruction costs, disrupt transportation networks, and, in severe cases, result in loss of human life[4], [6]. Inadequate estimation of scour depth during the design stage may expose foundations, reduce load-carrying capacity, and ultimately lead to bridge collapse[6]. Consequently, controlling and predicting local scour around bridge piers has become a major concern in hydraulic and bridge engineering[7].

Over the past several decades, extensive research efforts have been devoted to investigating local scour around bridge piers. Experimental studies have explored the influence of key parameters such as flow conditions, sediment size, pier diameter, pier shape, and foundation geometry[4]. Many researchers have focused on modifying pier geometry, including nose shape and cross-sectional form, as well as applying various scour countermeasures such as riprap, collars, bed sills, and bed shelves to reduce scour depth[8]. In parallel, numerous empirical and semi-empirical equations have been developed to estimate maximum scour depth based on laboratory observations, while recent advancements have introduced numerical and computational fluid dynamics (CFD) models to simulate flow–sediment interactions[9].

Despite the large volume of available studies, notable gaps still exist in the literature. A considerable volume of previous investigations has concentrated on scour around single piers in straight channels, whereas relatively limited attention has been given to curved channels[10], where secondary flows and transverse velocity components can significantly alter scour characteristics. Furthermore, many studies investigate individual parameters in isolation, making it difficult to draw generalized conclusions or directly compare results across different experimental conditions[11], [12]. Existing scour prediction equations also show considerable variability in their accuracy, often producing inconsistent results when applied beyond their original experimental ranges[13].

Considering these limitations, the present work is conducted as a review and analytical study based on previously published experimental and empirical data concerning bridge pier scour in straight and curved channels. The study provides a comprehensive and comparative synthesis of previous investigations addressing the effects of pier geometry, pier position, sediment properties, flow conditions, channel curvature, and pier shape on local scour behavior. In addition, commonly used scour prediction equations and various scour countermeasures are critically evaluated to assess their applicability and limitations. By identifying prevailing trends, research gaps, and unresolved issues, the study aims to support future research efforts and contribute to the development of more reliable and integrated scour prediction and mitigation approaches.

The present quantitative synthesis was developed using previously published experimental and numerical investigations concerning local scour around bridge piers in both straight and curved channels. The reviewed studies were selected based on their relevance to scour prediction, pier geometry effects, hydraulic flow conditions, and channel curvature influence. Greater emphasis was placed on studies providing quantitative scour measurements under clear-water conditions along with adequate hydraulic and sediment characteristics. Comparative assessment and regression-based analysis were carried out using the reported equilibrium scour depths and corresponding hydraulic parameters extracted from the selected studies.

2. Physical Mechanisms of Local Scour Around Bridge Piers

Local scour around bridge piers is governed by complex three-dimensional interactions between the approaching flow, sediment transport, and pier geometry. When flow encounters a bridge pier, a stagnation point develops at the upstream face, generating a downward jet that impinges on the bed surface[14]. This downflow initiates sediment erosion at the pier base and contributes to the formation of a horseshoe vortex system wrapping around the pier foundation, as illustrated in Fig. 1. In addition, flow separation at the sides of the pier produces wake vortices downstream, which further enhance sediment entrainment and transport[15].

The intensity and development of these vortical structures are strongly influenced by flow velocity, flow depth, sediment size, and pier geometry. As scour progresses, a scour hole forms and gradually deepens until an equilibrium condition is reached, where sediment removal is balanced by sediment inflow[9]. Experimental studies have shown that the rate of scour development is initially rapid, then gradually slows as the scour hole enlarges and the flow of energy dissipates within it. Understanding these physical mechanisms is fundamental for evaluating scour behavior under different hydraulic and geometric conditions and for developing effective mitigation strategies.

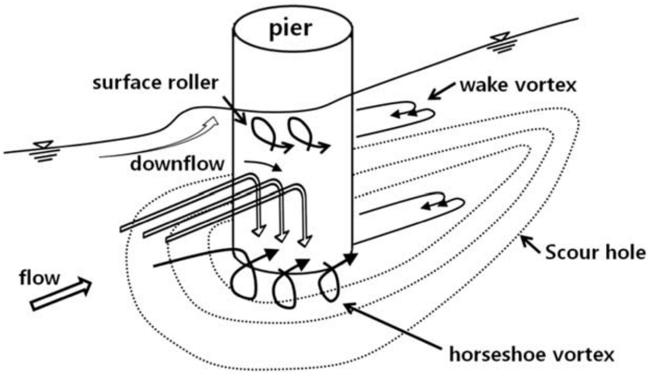


Figure 1: schematic of the scour process [16]

3. Countermeasure of the bridge local scour effect

Although a wide range of countermeasures has been proposed to mitigate local scour around bridge piers, these measures differ significantly in terms of effectiveness, constructability, cost, and long-term performance. Existing countermeasures can generally be classified into structural, hydraulic, geometric, and sediment-based approaches. Structural and hydraulic solutions, such as riprap protection[17], collars, and guide banks, have been widely applied in practice; however, they often require additional construction, regular maintenance, and may be vulnerable to failure under extreme flow conditions. Consequently, recent research has increasingly focused on geometric modification of bridge piers and sediment-based countermeasures ,[1] [19] ,[18] ,[12] ,[10], as these approaches aim to reduce scour by directly influencing flow–structure interaction or increasing bed resistance to erosion without the need for extensive external protection. Therefore, the present review primarily emphasizes geometric countermeasures and soil-related approaches, highlighting their mechanisms, effectiveness, and applicability in both straight and curved channels. It was examined that the influence of soil particle size on reducing local scour around bridge piers in curved channels using a laboratory flume with a 30° shown in Figure 2, under clear-water conditions[1]. The results showed that scour depth in curved channels is strongly controlled by soil particle size. The maximum scour reduction was achieved for a hexagonal pier at a 2.5° rotation angle, with relative soil diameters (D50/B) ranging from 5.8×10^{-4} to 2.2×10^{-3}, resulting in reductions of up to 55%. Oblong piers were the least effective, and soil particle sizes of 0.1–1.4 mm were recommended for scour mitigation[4]

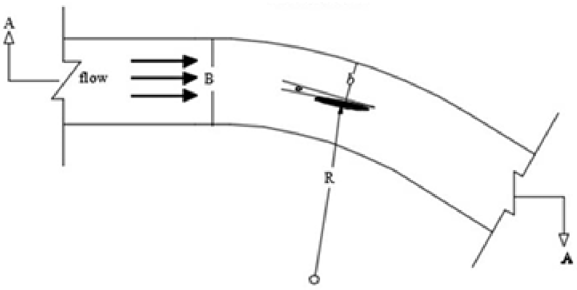


Figure 2: the used flume[10]

A series of laboratory experiments have been carried out to study the local scour appearing around the bridge pier of different shapes. It was investigated about how bridge pier nose shape and nose properties influence local scour using laboratory experiments in a straight rectangular recirculating flume under clear-water conditions [20]. Three pier nose shapes (rectangular, oblong, and triangular) were tested with solid noses and gabion noses on a uniform sand bed ($d_{50} \approx$ 0.52 mm). Results showed that triangular noses produced the lowest scour depths, while rectangular noses caused the greatest scour due to stronger vortex development. Adding a gabion nose further weakened the vortices and reduced the maximum scour depth by about 46–50% compared with solid noses. Overall, optimizing the nose geometry and porosity is an effective, practical countermeasure for reducing local scour at bridge piers. The recommended procedure for countermeasure design involves identifying the mechanisms responsible for scouring, selecting an appropriate countermeasure concept, and choosing a suitable construction method for its implementation.

4. Scour Behavior in Straight and Curved Channels: Quantitative Synthesis

Most early investigations of bridge pier scour were conducted in straight channels [12], where the flow field is relatively uniform and symmetrical. Under such conditions, scour holes typically develop symmetrically around the pier, and maximum scour depth is primarily controlled by approach flow velocity, sediment properties, and pier geometry. As a result, many empirical scour prediction equations have been derived based on straight-channel experiments.

In contrast, scour behavior in curved channels is significantly more complex due to the presence of secondary flows and centrifugal forces. Channel curvature induces transverse velocity components and spiral flow motion, causing a non-uniform velocity distribution across the channel width. These effects lead to asymmetric scour patterns, with deeper scour often occurring near the outer bank of the channel bend. Experimental studies have demonstrated that bridge piers located within curved sections experience greater scour depths compared to those in straight reaches under similar flow conditions. It was studied that local scour at a cylindrical bridge pier located in a straight channel and within a 180° channel bend as shown in fig. 3 [21]. The results showed that scour depth and scour hole dimensions increase with discharge at all pier locations, while scour in curved channels is significantly greater than in straight channels, as shown in Figure 4. In the bend, maximum scour consistently occurred near the outer bank, with the deepest scour observed at 60° along the bend, whereas the minimum scour occurred in the straight reach. These patterns were attributed to secondary (spiral) flow and centrifugal effects, which shift erosion toward the outer bank and deposition toward the inner bank, demonstrating that straight-channel scour assumptions underestimate scour in channel bends.

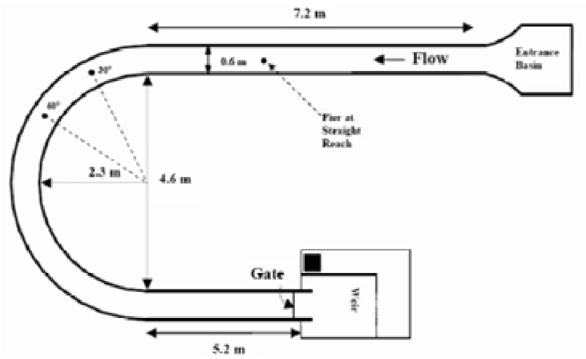


Figure 3. Schematic view of Laboratory channel[21]

Table 1 shows that maximum scour depth increases with discharge in both straight and curved channels, while remaining consistently greater in the curved flume across all flow rates. At 30 L/s, scour in the curved channel is about 42% higher than in the straight channel, with a comparable difference of approximately 39% at 42 L/s. These results demonstrate the intensifying influence of channel curvature on local scour and the limitations of straight-channel-based scour estimates in curved reaches.

Table 1. Comparison of Maximum Scour Depths in Straight and Curved Channels for Various Discharges

	Straight flume	Curved flume
Discharge (L/s)	Scour depth (m)	Scour depth (m)
30	0.03990	0.05677
35	0.07325	0.10076
40	0.09939	0.12215
42	0.10633	0.14760

Figure 4 presents the relationship between equilibrium scour depth and discharge under both straight- and curved-channel conditions. The results indicate that scour depth increases progressively with increasing discharge, while curved channels consistently exhibit larger scour depths as a result of curvature-induced secondary flow and transverse velocity effects.

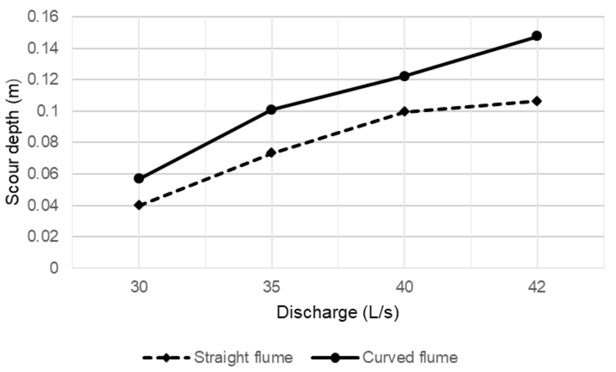


Figure 4: Variation of equilibrium scour depth with discharge in straight and curved channels

Most previous investigations compared scour depth in straight and curved channels descriptively. However, the experimental data summarized in Table 1 enable quantitative extraction of curvature effects and hydraulic scaling behavior.

4.1 Curvature Amplification Effect

Quantitative synthesis of the reviewed datasets was conducted through comparative analysis and power-law regression of the reported scour depths and discharge conditions. Curvature amplification ratios were calculated as the ratio between scour depth in curved channels and the corresponding scour depth under comparable straight-channel conditions. Regression relationships were obtained using logarithmic fitting of scour depth versus discharge data.

To quantify the influence of channel curvature on equilibrium scour depth, a curvature amplification ratio is defined as:

$$R_c = \frac{d_{s,\text{curved}}}{d_{s,\text{straight}}} \quad (1)$$

Using the values presented in Table 1, the computed amplification ratios range between 1.23 and 1.42, with an average value:

$$R_{c,\text{avg}} \approx 1.36 \quad (2)$$

This indicates that channel curvature increases equilibrium scour depth by approximately 36% under comparable hydraulic conditions.

Accordingly, scour depth in curved channels may be expressed as:

$$d_{s,\text{curved}} \approx 1.36\, d_{s,\text{straight}} \quad (3)$$

This relationship provides a practical curvature multiplier for preliminary design evaluation.

4.2 Discharge–Scour Scaling Relationship

Regression analysis of the straight-channel data reveals a power-law relationship between discharge and scour depth:

$$d_{s,\text{straight}} \approx 1.6 \times 10^{-4}\, Q^{1.88} \quad (4)$$

Similarly, for the curved channel:

$$d_{s,\text{curved}} \approx 2.3 \times 10^{-4}\, Q^{1.82} \quad (5)$$

The exponent values (≈1.8–1.9) indicate that scour depth scales nearly quadratically with discharge. Notably, channel curvature primarily increases the coefficient rather than significantly modifying the exponent, demonstrating that curvature intensifies scour magnitude without fundamentally altering hydraulic scaling behavior.

5. Effect of Pier Shape on Local Scour: Development of a Shape Efficiency Framework

Pier geometry is one of the most influential factors affecting local scour depth and scour hole development. Experimental investigations have consistently shown that bluff or sharp-edged pier shapes, such as rectangular or square sections, tend to generate stronger flow separation and more intense vortical structures, resulting in deeper scour holes. In contrast, streamlined or rounded pier shapes reduce flow disturbance and weaken horseshoe vortex formation, leading to smaller scour depths. It was examined that the effect of pier shape on local scour through laboratory experiments conducted in a straight rectangular flume under clear-water conditions. Ten pier shapes (rectangular, circular, octagonal, chamfered, hexagonal, elliptical, sharp-nose, Joukowsky, oblong, and streamlined) were tested while keeping flow depth and bed material constant [12]. The results showed that blunt shapes, particularly rectangular piers, generated strong flow separation and vortices, leading to the maximum scour depth, whereas streamlined shapes allowed smoother flow alignment and reduced scour depth by up to 60%. It was investigated that the effect of bridge pier shape on local scour depth was numerically using CFD simulations (Flow-3D) conducted in a straight rectangular flume under clear-water conditions with non-cohesive sediment. Six pier shapes (circular, rectangular, square, octagonal, elliptical, and lenticular) were analyzed while varying flow intensity, flow depth, and pier width. The model was validated against laboratory data, showing good agreement (≈10% error) [22], [23]. Results indicated that rectangular piers produced the greatest scour, whereas lenticular piers yielded the minimum scour depth, achieving about 40% reduction compared with rectangular shapes. Scour depth increased with flow intensity, flow depth, and pier width, with pier width identified as the most influential parameter. Overall, the findings highlight pier shape optimization, particularly streamlined forms, as an effective approach to mitigate local scour. It was examined that the effect of bridge pier shape on local scour using laboratory tests conducted in a straight open-channel flume under clear-water conditions. Four uniform pier shapes (square, circular, oval, and octagonal) were tested on a uniform sand bed ($D_{50} \approx 0.28$ mm) at three discharges (≈16–29.5 L/s) [24]. Results showed that square piers produced the maximum scour, while octagonal piers yielded the minimum scour, achieving about a 33% reduction compared with square piers; circular and oval shapes exhibited intermediate scour depths. Overall, the findings confirm that pier geometry significantly influences local scour in straight channels.

Studies examining circular, elliptical, hexagonal, lenticular, and oblong pier shapes have demonstrated that reducing the exposed frontal area and smoothing the upstream nose significantly decreases scour intensity. In curved channels, the influence of pier shape becomes even more pronounced, as streamlined geometries can partially align with the curved flow path, thereby reducing adverse flow–structure interaction. It was evaluated that local scour around bridge piers in a 30° curved channel under clear-water conditions, using four pier geometries [10]. As in Figure 5, the results showed that channel curvature increased scour intensity and shifted the maximum scour toward the outer bank, with the curved lenticular pier achieving the greatest scour reduction (≈44%) and the hexagonal pier performing best among conventional shapes, confirming the effectiveness of curvature-aligned pier geometry in scour mitigation.

Although modifying pier geometry is an effective passive strategy for reducing local scour, its application may be limited by structural, constructional, and economic constraints. Therefore, investigating the combined effects of pier shape and other scour mitigation measures remains an important research direction.

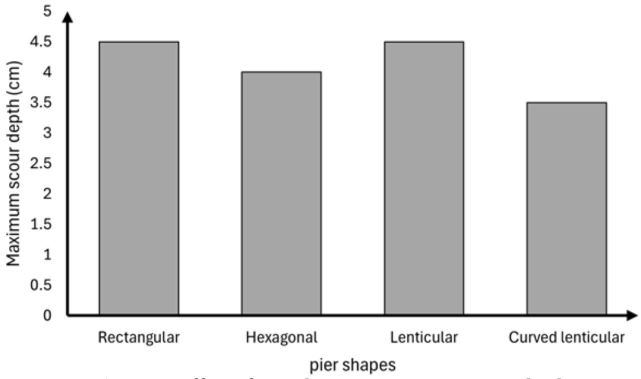


Figure 5. Effect of pier shape on maximum scour depth

Table 2 presents the pier shapes considered in this review together with their corresponding plan-view schematics, providing a clear geometric classification of the investigated configurations.

Tables 3 and 4 collectively summarize the reviewed studies, presenting their experimental and numerical configurations, measured scour parameters, and key findings. Together, these tables facilitate comparison of study conditions and highlight the relative performance of different pier shapes in reducing local scour under clear-water conditions in both straight and curved channels

Table 2. Used pier shapes

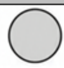
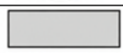
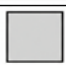
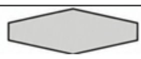
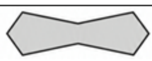
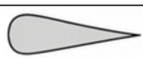
Pier shape	Plan view (schematic)
Circular	
Rectangular	
Square	
Hexagonal	
Octagonal	
Chamfered	
Elliptical	
Oblong	
Sharp-nose	
Triangular-nose	
Streamlined	
Joukowsky	
Lenticular	
Lenticular (curved)	

Table 3. Summary of selected recent research showing study characteristics and experimental conditions:

Author (Year)	Study Type	Channel Type	Pier Shapes	Flow Condition	Hydraulic Conditions	Sediment Properties
Al-Shukur & Obeid [12]	Experimental	Straight channel	Circular, Rectangular, Octagonal, Chamfered, Hexagonal, Elliptical, Sharp nose, Joukowsky, Oblong, Streamline	Clear-water, steady	h = 12.00 cm, Q = 10.00–18.00 L/s, Fr = 0.16–0.27	Uniform sand, D50 = 0.71 mm
Ahmed et al. [10]	Experimental	Curved channel (30° bend)	Elliptical, Hexagonal, Lenticular, Lenticular (curved)	Clear-water, steady	Q = 13.89–30.64 L/s, h = 13.50 cm, Fr ≈ 0.15–0.35	Uniform non-cohesive sand
Murtaza et al. [24]	Experimental	Straight channel	Square, Circular, Oval, Octagonal	Clear water, steady subcritical flow	Q = 16.10–29.50 L/s	Uniform sand, D50 = 0.28 mm
Rasaei et al. [25]	Experimental	90° curved channel	Cylindrical, cubic	Clear water	Fr = 0.10–0.19, h = 10.00 cm	Uniform sand, D50 = 1.00 mm
Jalal et al. [22]	Numerical	Straight (modelled)	Circular, Square, Rectangular, Octagonal, Elliptical, Lenticular	Clear-water, subcritical	V/Vc = 0.55–1.00, Fr < 1	Non-cohesive sand, D50 = 0.38 mm
Elshahat & Elniakhely [20]	Experimental	Straight channel	Rectangular, oblong, triangular (solid & gabion noses)	Clear-water, steady	v = 0.17–0.27 m/s, Fr = 0.20–0.40	Uniform sand, D50 = 0.52 mm

Table 4. Summary of selected recent research showing measured parameters and key findings:

Author (Year)	Measured Parameters	Key findings
Al-Shukur & Obeid [12]	Equilibrium scour depth, patterns	Streamlined pier reduced scour by ~60% relative to a rectangular pier
Ahmed et al. [10]	ds, ds/y, scour-hole length	Curved-lenticular pier achieved the highest reduction (~44%); The hexagonal best among conventional shapes
Murtaza et al. [24]	Longitudinal scour profiles	Octagonal pier reduced scour by ~32.3% vs square
Rasaei et al. [25]	Scour depth, volume, and topography	Maximum scour at ~75° bend; cylindrical piers reduced scour by ~21%
Jalal et al. [22]	ds, ds/b, morphology	The rectangular pier showed maximum scour. The lenticular pier reduced scour by ~40%; good agreement with lab data
Elshahat & Elniakhely [20]	ds vs velocity, bed contours	Triangular and gabion noses reduced scour up to ~50%. Scour increased with velocity

Experimental findings summarized in Tables 3 and 4 consistently demonstrate that pier geometry significantly influences equilibrium scour depth. To generalize these reductions analytically, a shape efficiency factor is introduced:

$$\eta_s = \frac{d_{s,\text{shape}}}{d_{s,\text{rectangular}}} \quad (6)$$

Based on the reviewed studies:

- Streamlined pier: $\eta_s \approx 0.40$
- Triangular nose: $\eta_s \approx 0.50$
- Lenticular pier: $\eta_s \approx 0.60$
- Octagonal pier: $\eta_s \approx 0.67$
- Rectangular pier: $\eta_s = 1.00$

Accordingly, scour depth for any optimized shape can be expressed as:

$$d_s = \eta_s \, d_{s,\text{rectangular}} \quad (7)$$

This formulation converts qualitative reduction percentages into a usable geometry correction factor applicable within predictive equations.

5.1 Geometry–Curvature Interaction

To evaluate the combined influence of curvature and pier geometry, a Geometry–Curvature Interaction factor is defined:

$$\text{GCI} = \frac{R_c}{\eta_s} \quad (8)$$

If $\text{GCI} > 1$, curvature effects dominate. If $\text{GCI} < 1$, geometric mitigation dominates.

For example:

- Curved rectangular pier:

$$\text{GCI} = \frac{1.36}{1.00} = 1.36$$

- Curved lenticular pier:

$$\text{GCI} = \frac{1.36}{0.60} = 2.27$$

Although streamlined shapes significantly reduce scour, curvature effects remain influential. This demonstrates that geometric optimization reduces but does not entirely eliminate curvature-induced amplification.

6. Prediction of Equilibrium Scour Depth: Analytical Evaluation and Modification

6.1 Sensitivity Analysis of the Breusers Equation

The Breusers equation is given by:

$$Y_{se} = 1.35 K_i b^{0.7} y^{0.3} \quad (9)$$

Sensitivity analysis shows:

If pier width doubles:

$$Y_{se} \propto 2^{0.7} = 1.62$$

If flow depth doubles:

$$Y_{se} \propto 2^{0.3} = 1.23$$

Thus, pier width has approximately 32% stronger influence than flow depth in this formulation.

6.2 Sensitivity Analysis of the CSU Equation

Under clear-water and uniform sediment conditions, the CSU equation simplifies to:

$$y_{se} = 2K_1 y^{0.35} b^{0.65} Fr^{0.43} \quad (10)$$

The relative importance of governing parameters follows the exponent magnitude:

$$S_b : S_{Fr} : S_y = 0.65 : 0.43 : 0.35 \quad (11)$$

This confirms that pier width is the dominant geometric parameter influencing equilibrium scour depth.

6.3 Proposed Integrated Curvature–Shape Modified Equation

To incorporate both curvature amplification and geometric mitigation, the CSU formulation may be extended as:

$$d_s = 2K_1 y^{0.35} b^{0.65} Fr^{0.43} R_c \eta_s \quad (12)$$

Where:

- $R_c = 1.36$ for curved channels
- $R_c = 1.00$ for straight channels
- η_s is the shape efficiency factor

This integrated expression provides a unified predictive framework combining hydraulic intensity, channel curvature, and pier geometry.

6.4 Comparison with Traditional Predictive Equations

Conventional scour prediction equations, including the Breusers and CSU formulations, were mainly derived from laboratory investigations performed under simplified hydraulic conditions, particularly in straight channels with conventional pier geometries. Although these equations remain widely used in engineering practice, they generally neglect the influence of channel curvature, secondary flow structures, and detailed pier-shape effects. To clarify the differences between traditional formulations and the proposed integrated approach, Table 5 presents a comparative assessment of the considered predictive equations in terms of applicability, incorporated parameters, advantages, and limitations. In contrast to conventional equations, the proposed integrated formulation incorporates both curvature amplification and geometric efficiency factors, enabling a more comprehensive evaluation of scour behavior in both straight and curved channels. Nevertheless, like many existing empirical formulations, the proposed approach remains constrained by the limited availability of field-scale validation data and the predominance of steady, clear-water laboratory conditions.

Table 5. Comparison with traditional predictive equation

Equation / Model	Curvature Effect	Pier shape effect	Hydraulic scaling	Advantage	Main Limitations
Breusers Equation	Not included	Limited	Included	Simple and widely used	Developed mainly for straight channels
CSU Equation	Not included	Partially considered	Included	Practical for engineering estimation	Ignores secondary flow and bend effects
Proposed Integrated Model	Included through amplification factor	Included through shape efficiency factor	Included	Applicable to straight and curved channels	Limited field validation

6.5 Dimensionless Reformulation

For broader applicability, the equation can be expressed in dimensionless form:

$$\frac{d_s}{b} = C\, Fr^{0.43} \left(\frac{y}{b}\right)^{0.35} R_c \eta_s \tag{13}$$

where:

$$C = 2K_1$$

This dimensionless representation facilitates comparison across laboratory scales and field conditions.

7. Conclusion

This study presented a quantitative synthesis of bridge pier scour behavior in straight and curved channels, transforming dispersed experimental findings into a predictive analytical framework. The results confirm that the equilibrium scour depth $d_s$is governed by the coupled interaction of hydraulic intensity, channel curvature, and pier geometry.

Furthermore, sediment properties were identified as an important factor influencing scour development, since sediment size and gradation directly control sediment resistance to erosion and equilibrium scour depth. The reviewed clear-water studies also indicated that non-cohesive bed material characteristics significantly affect the intensity of local scour around bridge piers.

Analysis of the compiled datasets shows that channel curvature increases equilibrium scour depth by 23–42%, with an average amplification factor of 1.36 relative to straight-channel conditions under comparable discharge. Power-law regression indicates that scour depth scales with discharge according to:

$$d_s \propto Q^{1.8\text{–}1.9}$$

in both straight and curved channels. Curvature primarily increases the proportionality coefficient, while the scaling exponent remains nearly unchanged, confirming that curvature amplifies scour magnitude without altering hydraulic similarity behavior.

Pier geometry exhibits equally significant influence. Streamlined configurations reduce equilibrium scour depth by:

- 30–33% for octagonal sections
- 40–44% for lenticular shapes
- 46–50% for triangular or gabion noses
- Up to ≈60% for fully streamlined sections

relative to rectangular piers. These reductions were generalized through a shape efficiency factor η_s, enabling direct integration into predictive equations. However, the Geometry–Curvature Interaction analysis demonstrates that even optimized shapes in curved channels may still experience net scour amplification of 10–20% compared to equivalent straight-channel configurations, indicating that geometry alone cannot fully offset curvature effects.

Sensitivity analysis of the Breusers and CSU equations confirms pier width as the dominant geometric parameter, exerting approximately 30–35% greater influence on predicted scour depth than flow depth in the evaluated formulations. Based on this finding, a curvature–shape modified CSU equation was proposed, integrating hydraulic intensity, curvature amplification $\alpha_c \approx 1.36$, and geometric efficiency $\eta_s = 0.40\text{–}0.70$into a unified predictive framework. The dimensionless reformulation further enhances transferability across scales.

Despite extensive laboratory research, most available data remain limited to steady clear-water conditions and small-scale flumes. Curved channels, unsteady hydrographs, sediment gradation, and prototype-scale validation remain underrepresented in calibration datasets, limiting predictive reliability in field applications.

Overall, this study consolidates experimental evidence into a structured, quantitative, and design-oriented framework. By explicitly incorporating curvature amplification (23–42%), geometric reduction (30–60%), and hydraulic scaling ($Q^{1.8\text{–}1.9}$), the proposed formulation advances scour prediction from empirical comparison toward physically informed integration suitable for engineering design.

Although the integrated analysis provided valuable insights, several limitations of the current study should be considered. Most of the reviewed investigations were conducted under steady, clear-water flow conditions in controlled laboratory flumes. Consequently, the developed synthesis may not completely capture the complex hydraulic behavior of natural rivers subjected to unsteady flow conditions, including floods and rapidly changing discharges. Such unsteady flows can considerably affect vortex formation, sediment transport processes, and the progression of local scour around bridge piers.

Furthermore, most of the available data were obtained from laboratory-scale studies, whereas field measurements for validation remain limited. In natural river environments, several additional factors, including non-uniform sediment characteristics, vegetation, debris accumulation, irregular riverbanks, and complex flow patterns, can influence scour behavior in ways that differ from controlled laboratory conditions.

8. Future research

Future investigations should emphasize validating the proposed integrated curvature–shape formulation using field data from actual bridge locations, particularly in curved river sections subject to varying hydraulic conditions. Further research is also needed to examine the effects of unsteady flows, sediment non-uniformity, debris accumulation, and channel-bed irregularities on the evolution of local scour around bridge piers. In addition, advanced numerical techniques, such as CFD-based flow and sediment transport modeling, should be further developed and calibrated using both laboratory experiments and field observations to enhance the accuracy and applicability of scour prediction models. These efforts would support the development of more robust and physically realistic approaches for evaluating bridge pier scour under practical engineering and environmental conditions.

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