

## Local Scour Analysis and Mitigation for Tidal Bridge Piers

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### ABSTRACT

Bridge piers in tidal and coastal environments face complex hydraulic forces, leading to local scour, which erodes sediment around foundations. Scour intensity is influenced by nonlinear interactions among waves, currents, tides, and wind, as well as pier geometry, debris accumulation, and environmental factors like salinity and ice cover. Traditional empirical models often fail to predict these dynamics accurately. Recent advancements include structural countermeasures—riprap, collars, and sacrificial vanes—and predictive modeling using machine learning algorithms such as XGB with SHAP interpretation. Integrating multi-physics interactions remains a challenge, requiring further research for adaptive, reliable scour mitigation.

**Keywords:** *Local Scour, Tidal Environments, Bridge Piers, Hydraulic Forces, Machine Learning.*

### I. INTRODUCTION

Bridge piers constructed in tidal and coastal environments are continuously exposed to highly complex hydrodynamic forces that arise from the interaction of waves, currents, tides, and sometimes wind-driven effects. Among the most critical hydraulic problems affecting such structures is local scour, which refers to the erosion of sediment around bridge foundations due to accelerated flow separation and vortex formation. In tidal regions, the scour process becomes even more severe and unpredictable because flow direction and velocity vary periodically, leading to cyclic sediment transport and bed instability. Research has shown that hydrodynamic loading around bridge piers is not governed by a single force component but by a nonlinear coupling of multiple environmental factors such as wave height, wave period, current velocity, and wind action (Yang et al., 2026). These coupled interactions significantly amplify local flow velocities and shear stresses, thereby increasing scour potential beyond that predicted by traditional single-factor models. Furthermore, Guo and Weng (2026) emphasized that marine and sea-crossing bridge foundations are particularly vulnerable due to wave–current interactions, which accelerate sediment removal and delay equilibrium conditions. In tidal river and estuarine systems, the situation is further complicated by salinity gradients and sediment heterogeneity, making scour prediction a highly challenging geotechnical and hydraulic problem. Therefore, understanding scour behavior in tidal environments is essential for ensuring the safety, durability, and serviceability of bridge infrastructure subjected to dynamic coastal conditions.

The mechanics of scour around bridge piers in tidal environments are strongly influenced by flow structure modifications such as horseshoe vortices, wake vortices, and shear layer separation. These flow features intensify bed shear stress, leading to sediment entrainment and progressive formation of scour holes. Studies have demonstrated that pier geometry plays a crucial role in controlling vortex intensity and scour depth, where streamlined shapes such as sharp-nosed or lenticular piers significantly reduce scour compared to rectangular or square piers (Baranwal et al., 2023; Al-Jubouri et al., 2024). In addition, debris accumulation around piers further complicates flow patterns, resulting in localized turbulence amplification and increased scour variability. Al-Jubouri et al. (2024) observed that debris thickness and shape could alter scour depth by several centimeters, depending on flow conditions and pier configuration.

Similarly, Bento et al. (2023) confirmed through CFD simulations and laboratory calibration that sediment transport processes around oblong piers are highly sensitive to shear stress distribution, with numerical models achieving less than 3% error when properly validated. The presence of ice covers in cold-region tidal environments has also been shown to significantly modify scour dynamics, increasing near-bed turbulence and enhancing scour depth under partially developed ice conditions (Sirianni et al., 2022). These findings collectively indicate that scour in tidal environments is governed by a combination of structural, hydraulic, and environmental variables that interact in a nonlinear and time-dependent manner. As a result, conventional empirical equations often fail to capture the full complexity of scour processes under real tidal conditions, necessitating more advanced predictive and experimental approaches.

Recent advancements in scour mitigation and predictive modeling have focused on both structural countermeasures and data-driven approaches to improve bridge safety in tidal environments. Structural solutions such as riprap layers, collars, sacrificial vanes, and multi-layer protection systems have been widely investigated to reduce local scour intensity. For instance, Guo and Weng (2026) demonstrated that a 2 m thick multi-layer riprap system could reduce maximum scour depth by up to 89%, while Valela et al. (2022) reported that improved collar designs reduced scour volume by more than 75%, highlighting the effectiveness of modifying near-bed flow structures. Similarly, Singh et al. (2026) showed that sacrificial vanes can reduce scour depth by more than 60% by weakening horseshoe vortex formation, while Sultana et al. (2025) concluded that oblong collar configurations provide superior performance compared to circular and octagonal designs. On the predictive side, machine learning models such as eXtreme Gradient Boosting (XGB) combined with SHAP interpretation have emerged as powerful tools for estimating scour depth under uncertain hydraulic conditions, achieving high accuracy and interpretability (Kim et al., 2024). Despite these advancements, challenges remain in integrating multi-physics environmental interactions such as wind–wave–current coupling into predictive frameworks and in scaling laboratory findings to real tidal field conditions. Moreover, Harasti et al. (2021) noted that protective measures such as riprap can sometimes alter local hydraulics and unintentionally shift erosion patterns downstream, indicating the need for holistic design approaches. Therefore, further research is required to develop integrated hydrodynamic–sediment transport models and adaptive scour protection systems that can reliably operate under the complex and variable conditions characteristic of tidal bridge environments.

## II. RESEARCH BACKGROUND

**Yang et al. (2026)** presented a fully coupled computational fluid dynamics model to investigate the hydrodynamic characteristics around a bridge pier under combined wind–wave–current conditions. The study had been validated against Morison theory and was reported to have accurately captured wave propagation and force generation. A total of 15 simulation scenarios had been conducted to examine the influence of wave height, wave period, current velocity, and wind speed on hydrodynamic loading. The findings indicated that peak wave forces had increased in a quasi-linear manner with wave height but tended to saturate after the onset of wave breaking. It was further observed that every 0.1 m/s increase in current velocity had amplified positive force peaks by nearly 3% while reducing negative peaks by approximately 2.9%. The study also revealed that a critical wind-speed threshold, close to wave celerity, had caused a significant rise in positive forces and a reduction in negative forces. Moreover, nonlinear coupling effects had produced a peak synergy coefficient of 1.23, showing that linear superposition had underestimated design loads by more than 20%. The study emphasized the importance of incorporating wind–wave–current coupling in reliability-based marine bridge pier design.

**Guo and Weng (2026)** examined scour as a major source of structural vulnerability in bridge engineering and investigated methods for mitigating local scour around sea-crossing bridge foundations through systematic experimental and numerical analyses. The study had numerically simulated 11 pile-group configurations to evaluate the scour protection performance of riprap under wave–current coupling, with particular emphasis on the influence of riprap geometry. It was reported that square riprap had provided superior scour protection compared with elliptical riprap, and that a 2 m thick square riprap layer had reduced the maximum scour depth by 89%. Based on these findings, the authors had proposed two advanced protection strategies, namely multi-layer riprap and sacrificial pile combined with riprap. Furthermore, seven sets of physical model tests had been conducted under realistic engineering conditions to assess five different protection methods. The physical test results had been found consistent with the numerical simulations and standard predictive formulas, while also showing that riprap protection had shortened scour equilibrium time. Ultimately, the 2 m thick multi-layer square riprap had demonstrated the best performance by minimizing maximum scour depth and preserving structural stability, thereby offering valuable guidance for practical scour protection design under wave–current coupling.

**Singh et al. (2026)** had examined the problem of scour around hydraulic structures in alluvial rivers, backwaters, and estuarine environments, where progressive riverbed lowering often exposed bridge pier foundations and increased the risk of structural failure. The study had presented a comprehensive experimental investigation into the effectiveness of sacrificial vanes installed upstream of bridge piers as a scour mitigation measure. These vanes, termed sacrificial because they were themselves prone to scouring, had been shown to modify the local flow regime and weaken horseshoe vortex formation, thereby reducing local scour intensity. Their performance had been assessed using parameters such as vane angle, number of vane arrays, distance of the first array from the pier, and vane height above the bed. Preliminary experiments with vane angles from 10° to 75° had identified 10° and 15° as the most effective, reducing scour depth by 52% and 63%, respectively, compared to an unprotected pier. Furthermore, a multivariate regression model had been developed to predict equilibrium scour depth, and it had shown strong agreement with observed results, indicating its usefulness for scour prediction and bridge pier design, particularly in sea backwater regions where tidal currents and sediment transport intensified scour around marine piers.

**Pasha et al. (2025)** examined the persistent challenge of scour around bridge piers in hydraulic engineering, noting its threat to the structural integrity and safety of bridge infrastructure globally. They highlighted that collar systems had emerged as a prominent countermeasure due to their ability to modify near-bed flow structures and reduce the intensity of horseshoe vortices at pier bases. The review synthesized contemporary research on collar systems, emphasizing their hydrodynamic mechanisms, performance under varied flow conditions, and influential design parameters. Both empirical and numerical investigations were reported to indicate that circular collars, particularly when installed at or slightly below the bed level, could markedly decrease local scour depth. Additionally, multi-collar arrangements and hybrid systems combining collars with other countermeasures were observed to enhance scour mitigation effectiveness. The study also noted challenges in practical application, including accurate placement in complex hydraulic environments, susceptibility to debris accumulation, and the need for routine inspection and maintenance. Overall, the review systematically assessed these limitations while underscoring the advantages of collars as cost-effective, low-maintenance alternatives and identified research gaps for future exploration.

**Sultana et al. (2025)** conducted a comprehensive review on collar-based countermeasures for local scour around bridge piers, emphasizing that scour-induced instability poses risks to structural safety, economic resources, and the environment. They systematically analyzed literature from 1992 to 2025, highlighting 12 collar shapes and detailing their positions, normalized dimensions, and reported percentages of scour

reduction. The study examined effective elevations of oblong collars ( $H = -1.0b$  to  $1.0b$ ) and circular collars ( $H = -1.0b$  to  $1.3b$ ), summarizing prior researchers' findings and limitations. Formulas developed in previous studies for temporal ( $ds$ ) and maximum ( $dsm$ ) scour depths at collar-pier configurations were discussed, alongside key parameters such as flow intensity ( $U/U_c$ ), flow shallowness, collar width ( $bc$ ), and elevation ( $H$ ). Comparative analyses from the reviewed studies indicated that oblong collars reduced scour below the bed most effectively ( $H = -0.1b$ ,  $bc = 3b$ ), whereas circular and octagonal collars achieved less maximum scour reduction at bed level ( $H = 0$ ,  $bc = 4.5b$  and  $2b$ , respectively). Overall, the review concluded that oblong collars offered superior performance in mitigating scour holes around rectangular piers, providing valuable guidance for engineers and researchers.

**Kim et al. (2024)** investigated the challenge of predicting scour depth around bridge piers, noting that traditional deterministic models struggled due to the presence of multiple uncertain factors and complex processes. They highlighted that recent approaches employing machine learning (ML) techniques had gained attention for their ability to extract statistical structures from input/output data, although these methods often reduced interpretability as complexity and parameter diversity increased. In this context, the study proposed an interpretable ML model for local scour depth prediction around piers, utilizing the eXtreme Gradient Boosting (XGB) algorithm combined with Shapley additive explanations (SHAP) derived from cooperative game theory. The model reportedly achieved high prediction accuracy ( $R^2: 0.75$ , RMSE: 0.23) compared with existing empirical formulas for pier scour assessment. Analysis of SHAP values demonstrated that the contribution of each input variable aligned with theoretical knowledge on scour-influencing factors, indicating the model's reasonableness. Furthermore, the study recommended design guidance using mean absolute percentage error (MAPE) and a "level of conservatism" metric to provide flexibility in balancing accuracy and conservatism in predicted scour depths.

**Al-Jubouri et al. (2024)** investigated the influence of various pier shapes and debris interactions on scour patterns to understand risks to bridge stability. They conducted numerical simulations using Flow-3D alongside controlled laboratory experiments, calibrating the model rigorously against physical flume tests with steady-state flow as the initial condition for sediment transport. The study employed the Fractional Area/Volume Obstacle Representation (FAVOR) technique and the renormalized group (RNG) turbulence model to enhance simulation accuracy. Their results suggested that pier geometry was a critical factor in determining scour depth, with square piers exhibiting the most severe scour (up to 5.8 cm) and lenticular piers the least (2.5 cm). The research highlighted the roles of horseshoe, wake, and shear layer vortices, while the Q-criterion analysis revealed debris-induced vortex generation and intensification. Scouring patterns were found to depend on debris amount, thickness, and pier diameter ratio ( $T/Y$ ), with high wedge debris causing maximum scour in square piers at  $T/Y = 0.25$ . The study reported significant fluctuations in scour depth (up to 5 cm) depending on debris form and noted discrepancies between numerical and experimental results ranging from 6% to 32%, particularly for cylindrical piers under complex debris interactions. The work was considered novel for its comprehensive evaluation of pier shapes and debris effects, offering insights into the predictive capability of Flow-3D simulations under varying conditions.

**Baranwal et al. (2023)** investigated the phenomenon of local scouring around bridge piers, emphasizing its significance in the safe and economical design of bridge structures. They defined scouring as the erosion and removal of bed particles around a pier, leading to the formation of scour holes. The study experimentally examined six different pier shapes—rectangular, circular, chamfered, Joukowsky, oblong, and sharp-nosed—to identify the most efficient shape in terms of minimizing scouring. Local scour depths were measured under varying discharges ( $0.0169$ – $0.0355$   $m^3/s$ ) and velocities ( $0.17$ – $0.30$   $m/s$ ). The results indicated that rectangular piers exhibited the largest scour depth due to strong horseshoe vortex formation around the flat frontal area, whereas sharp-nosed piers showed the least scour depth owing to flow

bifurcation and reduced vortex intensity. The study further reported that scour depth was directly proportional to the approach flow velocity and the exposed frontal area. The findings were suggested to support the selection of sharp-nosed piers as the most favorable design among the shapes studied.

**Bento et al., (2023)** investigated the complex flow structures around bridge piers, which had posed challenges for both experimental and numerical studies, and examined the capabilities of Computational Fluid Dynamics (CFD) tools in capturing flow dynamics and sediment entrainment mechanisms in scour holes. They numerically analyzed scour depth around an oblong bridge pier and the spatial–temporal distribution of bed shear stress using the SSIIM (Sediment Simulation In Intakes with Multiblock option) CFD tool. Clear water scour conditions and sand with known granulometric composition were considered, following prior experimental studies. Laboratory data on scour around a 0.11 m wide oblong pier were used to calibrate and validate the numerical model. The averaged form of the Navier–Stokes equations was employed to simulate turbulent flow over extended time scales. Their findings indicated that the calibrated CFD model was able to reproduce measured laboratory scour depths with high accuracy, yielding an average relative error below 3%, particularly for oblong bridge piers.

**Sirianni et al. (2022)** investigated the effects of partially developed ice covers on bridge pier scour, noting that prior research had primarily focused on fully developed ice jams. They conducted experiments simulating floating ice jams at various development stages under a constant flow rate, testing multiple channel-spanning ice cover lengths and one circular localized cover, and compared the resulting pier scour to free-surface flow conditions. Five downstream-initiated ice cover lengths were examined, with upstream lengths of 0, 0.63, 1.33, 2.66, and 5.32 m, while the local cover had a diameter of 0.27 m, three times that of the pier. Their findings indicated that the 2.66 m ice cover produced the greatest scour depth and near-bed Reynolds stress, with increases of 46.9% and 238%, respectively, compared to free-surface flow, whereas the localized cover resulted in the smallest increase, highlighting the significant influence of ice cover configuration on pier scour development.

**Valela et al. (2022)** conducted a study that focused on comparing bridge pier collars to mitigate scour and introduced a novel design, termed Collar Prototype Number 3, which was developed based on the concept of an equilibrium scour hole and aimed to control the horseshoe vortex. They employed numerical modeling to investigate the flow field and bed shear stress resulting from the use of Collar Prototype Number 3. Additionally, experimental comparisons were carried out by constructing physical models of both Collar Prototype Number 3 and a flat plate collar under varying flow conditions. The study found that Collar Prototype Number 3 effectively reduced scour, decreasing the maximum depth downstream of the pier and the overall scour volume by up to 69.7% and 75.7%, respectively, in some scenarios. It was also reported that Collar Prototype Number 3 outperformed the flat plate collar, particularly because it avoided undermining, a problem observed in the flat plate design.

**Harasti et al. (2021)** investigated the effects of scour countermeasures on bridge piers located in large rivers, focusing on the use of launchable stone, such as riprap sloping structures, for protection against scouring. They noted that although these measures were effective in safeguarding piers, they altered flow conditions within the bridge opening by inducing overtopping flow and flow contraction, which in turn deflected the formation of downstream scour holes and exposed the riverbed to additional erosion. The study provided a comprehensive review of existing methods for estimating bridge pier scour when riprap sloping structures were installed, analyzing empirical approaches and the corresponding formulae for comparable structures, including complex pier formulae and those for river training works. The authors summarized relevant equations applicable to piers with such scour countermeasures and highlighted potential directions for future research aimed at improving bridge scour estimation and understanding the hydrodynamic impacts of these protective interventions.

## III. KEY FINDINGS FROM STUDY

Author (Year)	Study Type	Methodology	Key Findings	Relevance to Tidal Scour
Yang et al. (2026)	Numerical (CFD)	Fully coupled wind–wave–current simulation validated with Morison theory	Wave forces increase with wave height; current increases positive forces (~3% per 0.1 m/s); nonlinear coupling leads to underestimation (>20%) if linear models used	Critical for realistic tidal loading on bridge piers under combined environmental forces
Guo & Weng (2026)	Experimental + Numerical	Riprap protection analysis under wave–current interaction	2 m square multi-layer riprap reduced scour by 89%; improved equilibrium time	Effective scour mitigation strategy for coastal/tidal bridge foundations
Singh et al. (2026)	Experimental	Sacrificial vanes tested with varying angles and configurations	Scour depth reduced up to 63%; optimal vane angles (10°–15°) most effective	Useful for estuarine and tidal river scour control
Pasha et al. (2025)	Review	Systematic analysis of collar systems	Circular collars reduce scour significantly; multi-collar systems improve performance	Provides design basis for low-cost tidal scour protection
Sultana et al. (2025)	Systematic Review	Analysis of 1992–2025 literature on collar shapes	Oblong collars most efficient; up to ~1 m below bed gives best performance	Offers optimized design parameters for tidal environments
Kim et al. (2024)	Machine Learning	XGB model with SHAP interpretability	$R^2 = 0.75$ ; key hydraulic variables aligned with physical theory	Enables predictive scour estimation under uncertain tidal conditions
Al-Jubouri et al. (2024)	CFD + Experimental	Flow-3D simulation with debris interaction	Pier shape strongly affects scour; square piers worst (5.8 cm scour)	Highlights geometry effects in tidal sediment-laden flows
Baranwal et al. (2023)	Experimental	Comparative study of 6 pier shapes	Sharp-nosed piers show minimum scour; rectangular piers maximum scour	Supports hydrodynamic optimization of pier design in tidal zones
Bento et al. (2023)	CFD + Lab Validation	SSIIM model calibration with experiments	Average error < 3%; accurate scour prediction for oblong piers	Confirms reliability of CFD for tidal sediment transport modeling
Sirianni et al. (2022)	Experimental	Ice cover simulation under controlled flow conditions	Partial ice cover increased scour up to 46.9%	Relevant for cold-region tidal bridge scour analysis

Valela et al. (2022)	Experimental + Numerical	Novel collar prototype vs flat plate collar	Scour depth reduced up to 69.7%; volume reduced 75.7%	Advanced scour mitigation technique for tidal bridges
Harasti et al. (2021)	Review	Analysis of riprap sloping structures	Riprap alters flow and may shift erosion downstream	Important consideration for long-term tidal scour management

#### IV. CONCLUSION

The reviewed literature clearly establishes that bridge pier scour in tidal environments is a highly complex and multidimensional hydraulic problem governed by the combined influence of waves, tidal currents, wind action, sediment characteristics, and structural geometry. It is evident that traditional deterministic approaches are insufficient to accurately capture the nonlinear and time-varying nature of scour development under such dynamic conditions. Studies such as Yang et al. (2026) and Guo and Weng (2026) highlight that coupled hydrodynamic interactions significantly amplify bed shear stress and flow turbulence, leading to accelerated sediment removal and increased scour depth. Moreover, the performance of bridge piers is strongly dependent on their geometric configuration, as streamlined shapes like sharp-nosed and oblong piers consistently demonstrate reduced scour intensity compared to rectangular or square piers (Baranwal et al., 2023; Al-Jubouri et al., 2024). Structural countermeasures such as riprap layers, collar systems, and sacrificial vanes have been widely validated as effective mitigation techniques, with some configurations achieving scour reduction exceeding 70–80% under controlled conditions (Valela et al., 2022; Singh et al., 2026). However, their efficiency is often influenced by local flow variability, sediment transport dynamics, and maintenance constraints, particularly in tidal and estuarine regions where hydraulic conditions change periodically. In addition, recent advancements in computational fluid dynamics and machine learning approaches have improved the predictive capability of scour estimation models, offering better accuracy and interpretability compared to conventional empirical formulas (Kim et al., 2024; Bento et al., 2023). Despite these developments, significant research gaps remain in integrating multi-physics environmental interactions, scaling laboratory findings to real-world tidal systems, and ensuring long-term stability of scour protection measures under extreme hydrodynamic events. Therefore, it can be concluded that future bridge design in tidal environments must adopt an integrated approach combining advanced numerical modeling, data-driven prediction tools, and optimized structural countermeasures to ensure resilience, safety, and sustainability of critical infrastructure subjected to evolving coastal and hydraulic challenges.

#### V. FUTURE SCOPE

The future research on bridge pier scour in tidal environments is expected to advance significantly with the integration of multi-physics modeling, smart prediction techniques, and innovative scour protection systems. One of the most important directions is the development of fully coupled three-dimensional numerical models that simultaneously incorporate wind, wave, tidal current, sediment transport, and turbulence interactions. Current studies, such as those by Yang et al. (2026), have demonstrated the importance of coupled hydrodynamic effects; however, future models need to include real-time tidal variability, sediment heterogeneity, and climate-driven extreme events to improve predictive reliability under field conditions. Additionally, there is a strong need to bridge the gap between laboratory-scale experiments and real-world tidal bridge systems through advanced scaling laws and field-validated datasets. Another promising direction is the application of artificial intelligence and machine learning for

scour prediction and risk assessment. Models such as eXtreme Gradient Boosting (XGB) and hybrid deep learning frameworks can be further enhanced using large-scale hydrodynamic datasets, remote sensing data, and real-time monitoring inputs. Future systems may enable adaptive scour prediction tools that continuously update based on changing tidal conditions, improving decision-making for bridge maintenance and safety management. Integration of explainable AI techniques will also be essential to ensure interpretability and engineering trust in predictive outputs. In the area of scour mitigation, future research should focus on the development of adaptive and smart protective systems, such as morphing collars, self-adjusting riprap layers, and bio-inspired pier designs that dynamically respond to flow conditions. Sustainable materials such as geosynthetics, recycled aggregates, and eco-friendly composites can also be explored to improve durability and reduce environmental impact. Furthermore, hybrid protection systems combining riprap, vanes, and collars may offer enhanced performance under complex tidal flow regimes. Finally, long-term monitoring using Internet of Things (IoT) sensors, underwater drones, and satellite-based bathymetric mapping can revolutionize scour assessment in tidal regions. These technologies will enable continuous observation of scour evolution, early warning systems for structural failure, and data-driven maintenance planning. Overall, the future scope of research lies in developing intelligent, resilient, and environmentally adaptive solutions for bridge pier scour management in increasingly uncertain and dynamic tidal environments.

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