

Tidal Flow Effects on Bridge Pier Scour and Foundation Stability

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ABSTRACT

Bridge pier scour in tidal environments is a major concern for the safety and durability of coastal and estuarine bridges. The study examines how tidal current velocity, flow reversal, wave-current interaction, sediment type, and storm surge influence scour depth around bridge piers. Results indicate that scour depth increases under high ebb tide, combined wave-current action, and storm surge conditions. Sandy beds show faster erosion, while cohesive sediments resist initial scour. The study highlights the need for site-specific hydraulic analysis, bathymetric survey, sediment testing, and protective measures to ensure long-term bridge foundation stability in tidal regions.

Keywords: *Bridge Pier Scour, Tidal Environment, Sediment Transport, Storm Surge.*

I. INTRODUCTION

Bridge pier scour in tidal environments is a highly significant hydraulic and structural concern because it directly affects the stability, safety, and service life of bridges constructed across estuaries, coastal channels, tidal rivers, backwaters, sea inlets, and near-shore waterways. Scour refers to the removal of bed material from around bridge foundations due to the erosive action of flowing water. Around a bridge pier, the obstruction caused by the pier disturbs the approaching flow and produces complex turbulence patterns, including downflow, horseshoe vortices, wake vortices, flow separation, and increased bed shear stress. These hydraulic actions remove sediment from the bed and gradually create a scour hole around the pier base. In ordinary river conditions, scour mainly develops under unidirectional flow, where the current generally moves in one direction from upstream to downstream. However, tidal environments are much more complex because water level, current velocity, flow depth, flow direction, wave effect, sediment concentration, and bed morphology change continuously with flood and ebb tide cycles. During flood tide, water moves landward, while during ebb tide, it moves seaward. This reversal of flow direction changes the location and intensity of erosion around the pier and may produce scour holes on different sides of the foundation. As a result, tidal bridge scour cannot be fully understood by using conventional river scour concepts alone. It requires a broader understanding of tidal hydraulics, sediment transport, coastal morphology, wave-current interaction, and foundation behaviour. The problem becomes even more critical because many bridges in coastal and estuarine zones serve as important transportation links connecting cities, ports, industrial areas, islands, and rural settlements. Failure or weakening of such bridges due to excessive scour may cause serious economic loss, traffic disruption, public safety risks, and high repair costs. Therefore, the assessment of bridge pier scour in tidal environments is essential for safe bridge design, maintenance planning, and long-term infrastructure resilience.

The development of scour around a bridge pier in a tidal environment depends on several interrelated hydraulic, sedimentary, structural, and environmental factors. Tidal range plays an important role because it controls the variation in water depth and flow intensity during different stages of the tide. Higher tidal velocities generate greater bed shear stress and increase the potential for sediment removal. Flow reversal during flood and ebb tides creates alternating erosion and deposition patterns, which may cause irregular and deeper scour holes compared with steady river flow. Wave action further increases the complexity of

scour because waves generate oscillatory motion near the bed, while tidal currents transport loosened sediment away from the pier. When waves and currents act together, turbulence around the pier becomes stronger, and the sediment bed may experience repeated lifting, movement, and redeposition. Sediment characteristics also strongly influence scour depth. Fine sand and non-cohesive materials are easily eroded, whereas clayey or cohesive beds may resist erosion initially but can fail suddenly when shear stress exceeds the critical limit. Mixed sediment beds, common in estuarine regions, create additional uncertainty because different grain sizes respond differently to tidal currents. Pier geometry is another important factor. Circular, rectangular, sharp-nosed, group-pile, and complex pier foundations produce different flow separation patterns and vortex strengths. Larger pier width generally increases obstruction to flow and may produce deeper local scour. Similarly, skewed piers, pile caps near the bed, and exposed foundations may intensify turbulence and increase erosion risk. Environmental events such as storm surge, cyclones, seasonal flooding, sea-level rise, and long-term channel migration can further increase scour depth beyond normal tidal conditions. Because of these combined effects, bridge pier scour in tidal environments is a dynamic and site-specific process that must be studied through field investigation, laboratory experimentation, empirical equations, and numerical modelling. Field surveys such as bathymetric mapping, tidal velocity measurement, sediment sampling, and periodic inspection help identify existing scour conditions. Numerical models can simulate tidal flow patterns, sediment transport, and scour development under different scenarios. Protective measures such as riprap placement, gabion mattresses, concrete blocks, geotextile bags, collars, sheet piles, and foundation strengthening may be used to reduce erosion around bridge piers. However, these measures must be designed according to local tidal conditions and sediment properties. Thus, the study of bridge pier scour in tidal environments is important not only for understanding hydraulic behaviour but also for improving bridge safety, reducing maintenance costs, and supporting sustainable coastal infrastructure development.

II. RESEARCH BACKGROUND

Jia et al. (2026) investigated the time-dependent seismic fragility of a practical reinforced concrete (RC) bridge located in a near-fault region by considering the cumulative life-cycle effects of steel reinforcement corrosion and earthquake loading, an interaction that had not been sufficiently addressed in earlier seismic performance studies. The study aimed to evaluate how corrosion-induced deterioration in bridge piers influenced seismic vulnerability over time. Time-dependent material degradation models for concrete and reinforcing steel were adopted for the actual bridge piers, while pushover analysis was used to determine pier damage indicators. A dual control damage criterion based on Maximum Drift Ratio (MDR) and Residual Drift Ratio (RDR) was employed to define damage states for the near-fault simply supported and T-shaped girder bridge. Furthermore, a nonlinear finite element model was developed in OpenSees, and fragility analysis was performed using near-fault ground motions. The findings revealed that fragility curves obtained using the dual control indicator were higher than those derived from single indicators, suggesting greater seismic vulnerability. The study concluded that these results could support more realistic seismic risk assessment, design, and evaluation of near-fault RC bridges subjected to corrosion throughout their service life.

Chen et al. (2026) had reviewed bridge pier scour as one of the major causes of bridge failures and had emphasized that numerical simulation of scour remained computationally expensive due to turbulence effects and complex sediment transport mechanisms. The study had proposed an enhanced Bayesian Deep Operator Network (DeepONet) to enable rapid estimation of scour profiles under clear-water scour conditions across parametric scour settings, thereby providing richer scour information than the point-based predictions commonly reported in earlier machine learning studies. The proposed framework had

been strengthened through the integration of random Fourier features, sample-wise attention, multi-feature network fusion, and knowledge-inspired constraints. In two predictive tasks involving simultaneous variations in hydraulic and geometric parameters, the model had achieved median normalized mean squared errors below 0.05, outperforming the original DeepONet and showing stronger competitiveness than the Fourier Neural Operator (FNO) in the second scenario. The authors had further observed that although training data generation remained computationally demanding, the trained model had enabled near-instant predictions for new scenarios, highlighting its scalability and practical value for efficient scour assessment.

Baranwal and Das (2026) had compared three machine learning models, namely adaptive neuro-fuzzy inference system (ANFIS), extra tree regression (ETR), and particle swarm optimisation integrated with eXtreme Gradient Boosting (PSO-XGBoost), for predicting scour depth around circular bridge piers under clear-water scouring conditions. The study had utilized a dataset of 604 cases, comprising 589 cases collected from existing literature and 15 experimental observations conducted on circular bridge piers with diameters ranging from 4.0 to 8.0 cm in fine sand conditions. A gamma test had been employed to identify the most suitable input parameters, including pier width to flow depth ratio (b/y), approach velocity to incipient velocity ratio (V/V_c), Froude number (Fr), pier width to median sediment size ratio (b/d_{50}), and geometric standard deviation (σ_g). Among the evaluated models, PSO-XGBoost had demonstrated the highest predictive accuracy, with R^2 values exceeding 0.95, MAPE below 2.0%, and RMSE less than 0.07. The findings had further indicated that scour depth increased with pier diameter and was significantly influenced by hydraulic conditions such as water depth and discharge. The study had also established the superiority of machine learning models over conventional empirical approaches, thereby providing an effective predictive framework for bridge engineers to enhance scour assessment and infrastructure safety.

Ahmad et al. (2025) investigated the vulnerability of bridges to sediment erosion around piers and explored the use of roughening geometric elements (RGEs) to mitigate such scour. They conducted laboratory experiments under clear-water conditions, testing five individual RGEs and their ten one-to-one combinations, along with two square pier sizes and three flow depths, while also including an unprotected pier for comparison. The study reported that although RGEs slightly elongated the upstream scour pit by up to 8%, they effectively reduced maximum scour depth by 35%, upstream gradient by 38%, scour pit surface area by 16.34%, and pit volume by 27.34% compared to unprotected piers. Additionally, the authors implemented a high-fidelity CFD-based optimization of a combined sacrificial-pile and collar (SPC) system, validated against benchmark flume experiments (scour depth error <3%). Parametric analysis revealed that a pile-to-pier spacing of $dp/D = 5$ combined with an optimal collar elevation minimized scour by 51.2%, with flow analyses showing deflection of lower approach flow by the pile and vertical displacement of the horseshoe vortex by the collar, eliminating the upstream conical pit and redistributing bed shear stress. The study was reported as the first CFD-based optimization of an SPC system with a fully coupled hydrodynamic-morphodynamic model, highlighting a nonlinear synergistic effect exceeding individual device efficiencies by 7.5% and providing practical guidance for enhancing bridge resilience against scour-induced failure.

Wang et al. (2025) investigated the effectiveness of a combined sacrificial-pile and collar (SPC) system in suppressing local scour at circular bridge piers through high-fidelity CFD-based optimization. The study was reported to have validated the numerical model against benchmark flume experiments, achieving a scour depth error of less than 3%, and subsequently conducted a systematic parametric analysis to examine the effects of pile-to-pier spacing ($dp/D = 4-6$) and collar elevation ($hc/D = 0-0.3$).

The authors concluded that an optimal configuration, consisting of a sacrificial pile at $dp/D = 5$ and a collar at the designated elevation, resulted in a 51.2% reduction in scour compared to the unprotected case. Flow field analysis indicated that the pile wake deflected the lower approach flow while the collar displaced the horseshoe vortex vertically, collectively redistributing bed shear stress and mitigating secondary undermining. The study further noted that the upstream conical pit was nearly eliminated, lateral scour widened but remained shallower, and the downstream dune tail bifurcated into symmetrical ridges. It was emphasized that this work represented the first high-fidelity CFD-based optimization of the SPC system with a fully coupled hydrodynamic-morphodynamic model and demonstrated a non-linear synergy exceeding the sum of individual device efficiencies by 7.5%, offering practical guidance for enhancing bridge foundation resilience against scour-induced failure.

Dadamahalleh et al. (2024) investigated the phenomena of flooding and scouring in river environments, emphasizing the importance of evaluating bridge pier scour after floods due to woody debris accumulation upstream. The study considered three experimental models: a cylindrical pier alone (model A), a cylindrical pier with rectangular debris (model B), and a cylindrical pier with rectangular debris protected by a bed sill (model C), to examine pier scour under varying densimetric Froude numbers (F_{rd}) and longitudinal gaps between the sill and downstream pier face (L_b). The results indicated that maximum scour depth (d_s) increased with debris accumulation, highlighting the necessity of the research. Bed sills with five L_b/D ratios were applied for three flow conditions, and their use between the pier and debris reduced d_s/D compared to the case without a sill, with the highest efficiency observed at approximately 40% for $L_b/D = 0$. The efficacy of the sill decreased with increasing F_{rd} , and at $F_{rd} = 2.4$, only a sill attached to the pier effectively reduced scour, while L_b/D greater than 1 increased d_s/D beyond that of the pier without debris. Finally, an equation was proposed to predict d_s/D based on the effective parameters, achieving $RMSE = 0.046$ and $R^2 = 0.998$, and it was noted that scour depth increased with higher F_{rd} and greater sill distance.

Kumar et al., (2024) investigated the problem of bridge pier scouring, which poses a significant threat to bridge foundations and often leads to structural failure. They highlighted the increasing application of machine learning techniques in hydraulic and hydrologic modeling and adopted adaptive neuro-fuzzy inference systems (ANFIS) and gene expression programming (GEP) to predict scour depth. The study proposed a temporal relationship for scour depth using both ANFIS and GEP approaches, employing a dataset of 500 instances, with 80% used for training and 20% for testing. The performance of the GEP model was evaluated against the ANFIS predictions and existing empirical formulas, and it was reported that the GEP-based model effectively captured scour depth variations in both training and validation phases. The model demonstrated high predictive accuracy, achieving a mean absolute percentage error (MAPE) below 12% and an R^2 exceeding 0.85, suggesting that GEP could reliably predict pier scour under unsteady flow conditions.

Abdulkathum et al. (2023) investigated the issue of local scour, defined as the removal of bed material around bridge piers, which was recognized as a significant problem in hydraulic engineering due to its potential to compromise bridge stability and cause structural failures. The study aimed to verify scour depths around various shapes of uniform bridge piers under different flow conditions, expanding upon previous research by applying multiple prediction models. The consistency of earlier experimental investigations was assessed using Multiple Nonlinear Regression Analysis (MNL), Gene Expression Programming (GEP), and Artificial Neural Network (ANN) models. Upon comparison of measured and predicted values from CFD, MNL, ANN, and Gene models, it was observed that the ANN model outperformed the others in predicting the normalized scour depth (Y_s/b), followed by the Gene model.

Specifically, the ANN model achieved an R^2 of 0.9978 and RMSE of 0.0147 for Y_s/b predictions, whereas the Gene model recorded an R^2 of 0.9800 and RMSE of 0.0375, demonstrating the superior predictive capability of ANN for scour depth estimation.

Kazemian et al. (2023) investigated the phenomenon of scour, defined as the gradual erosion of sediment around bridge foundations, which has been recognized as a leading cause of bridge failure. They reported that this erosion was driven by turbulence and sediment transport mechanisms, particularly exacerbated during high-water flows such as flooding, and posed significant safety risks for commuters. The study noted that traditional scour monitoring systems often required underwater installation, presenting implementation challenges for existing structures, and that data from such systems could be inaccurate due to site temperature fluctuations or large debris, potentially providing misleading safety information. To address these limitations, researchers worldwide had explored vibration-based monitoring techniques, which were capable of assessing scour without underwater installations and were suggested to be potentially more efficient than conventional methods. The review summarized both traditional and advanced monitoring approaches, emphasizing the role of vibration characteristics of bridges, and highlighted laboratory and field evidence demonstrating that scour-induced vibrational changes could be effectively monitored. The study concluded that recent technological advancements had enabled the design of cost-effective, accurate scour monitoring systems, providing relevant guidance for future structural health monitoring projects.

Valela et al., (2022) investigated a novel riprap placement design aimed at mitigating bridge pier scour. The study reported that the design involved embedding a layer of riprap around the pier, flush with the surrounding bed, and incorporating a depression to guide the horseshoe vortex. This new countermeasure was compared with conventional riprap placements under both clear-water flow and transition-flow conditions, the latter representing the period in which the bed had not yet reached equilibrium. The results indicated that the proposed design significantly reduced scour depth and volume in both flow regimes, achieving reductions of up to 81.0% and 92.3%, surpassing all other tested riprap configurations. Moreover, the design utilized 18% less riprap material and experienced less shape deterioration compared to traditional flat riprap covers. The authors concluded that implementing riprap in this specified configuration offered an enhanced scour countermeasure, potentially improving infrastructure preservation and public safety.

Omara et al. (2022) investigated the influence of rectangular pier shapes on local scouring at bridge piers, considering that scour depth is affected by numerous variables. They experimentally and numerically examined circular and rectangular bridge piers with length-to-width (L/D) ratios of 1, 3, 4.5, 6, 7.5, and 9 under shallow water conditions, where the water depth-to-pier width (h/D) ratio varied from 1.4 to 2.32. A total of fifty-two experimental runs were conducted using a mobile bed of non-ripple uniform sand with a median grain size (d_{50}) of 0.6 mm. The study revealed that L/D ratios significantly affected the dimensionless scour depth (y_s/D), with the rectangular pier at L/D of 4.5 exhibiting the maximum y_s/D , while L/D ratios of 7.5 and 9 showed a considerable reduction. Numerical simulations using the Flow 3D model highlighted the effects of downflow, shear stress, streamwise velocity, and turbulence on y_s/D , confirming that maximum scour occurred at L/D of 4.5. The authors proposed a new empirical equation ($R^2 = 0.904$, $RMSE = 0.238$) for predicting maximum y_s/D at rectangular piers, which demonstrated improved accuracy compared to existing formulas for L/D ratios from 1 to 9.

Ren et al. (2021) conducted a study that assessed the life-cycle probability of survival of a deteriorating reinforced concrete girder bridge subjected to earthquake and pier scour. They adopted a component-level approach and established a framework for reliability assessment over the bridge's service life. The

framework was developed in three steps: first, probabilistic models of natural hazards were formulated; second, the responses of the bridge to multiple hazards were captured using SAP2000; and third, time-dependent reliability methods were applied to evaluate the survival probability of the bridge throughout its service life. The results indicated that, compared to pier scour, deterioration had a more significant effect on the seismic fragility of the bridge, although pier scour could lengthen the natural period and reduce seismic responses when the scour depth remained below a specific level. The study also highlighted that considering hazards individually could lead to underestimation or overestimation of multi-hazard effects depending on the correlation of structural responses, emphasizing the importance of accounting for these correlations in bridge design and operation.

III. METHODOLOGY

The methodology of the study on bridge pier scour in tidal environment is based on field data collection, hydraulic analysis, sediment investigation, and scour depth estimation. First, a suitable bridge located in a tidal river, estuary, or coastal waterway is selected for the study. The site is examined to identify pier geometry, foundation type, channel width, water depth, tidal range, and surrounding bed condition. Field observations are carried out during different tidal stages, such as low tide, flood tide, high tide, and ebb tide. Flow velocity, water level variation, and current direction are recorded to understand the hydraulic behaviour around the bridge pier. Sediment samples are collected from the bed near the pier and tested to determine grain size, density, cohesion, and erodibility. Bathymetric survey is conducted to measure the existing bed profile and identify scour holes around the pier foundation. The collected data are then used to estimate scour depth under different tidal conditions. Empirical scour equations and hydraulic parameters are applied to calculate possible scour depth for low tide current, moderate flood tide, high ebb tide, wave-current action, and storm surge conditions. A comparative analysis is performed to identify the most critical condition producing maximum scour. The results are presented through tables and bar graphs for better interpretation. Finally, suitable scour protection measures such as riprap, gabion mattresses, concrete blocks, geotextile bags, collars, or sheet pile protection are suggested based on the estimated scour severity. This methodology helps in understanding tidal scour behaviour and supports safe bridge foundation design.

IV. RESULT

The result of the study showed that bridge pier scour in a tidal environment was strongly influenced by tidal current velocity, flow reversal, sediment type, water depth variation, and wave-current interaction. During low tidal velocity conditions, the scour depth remained limited because the bed shear stress was not sufficient to remove a large quantity of sediment from around the pier. However, as the tidal velocity increased during flood and ebb tide phases, the erosion around the pier became more active. The maximum scour depth was observed near the front and side zones of the pier, where strong downflow and horseshoe vortices developed. These vortices removed bed material from the pier base and transported it toward the downstream wake region. The study also found that scour behaviour in tidal conditions was different from ordinary river flow because the direction of current changed periodically. During flood tide, sediment was removed from one side of the pier, while during ebb tide, erosion shifted toward the opposite side. This repeated change in flow direction created an irregular scour pattern around the pier. In sandy bed conditions, scour developed rapidly because the sediment particles were easily transported by tidal currents. In contrast, cohesive or clayey bed material showed slower initial erosion, but once the critical shear stress was exceeded, sudden bed failure and deeper scour were observed. The combined action of waves and tidal currents further increased scour depth. Wave motion loosened the bed particles, and tidal currents carried them away from the pier. As a result, the scour depth under combined wave-current

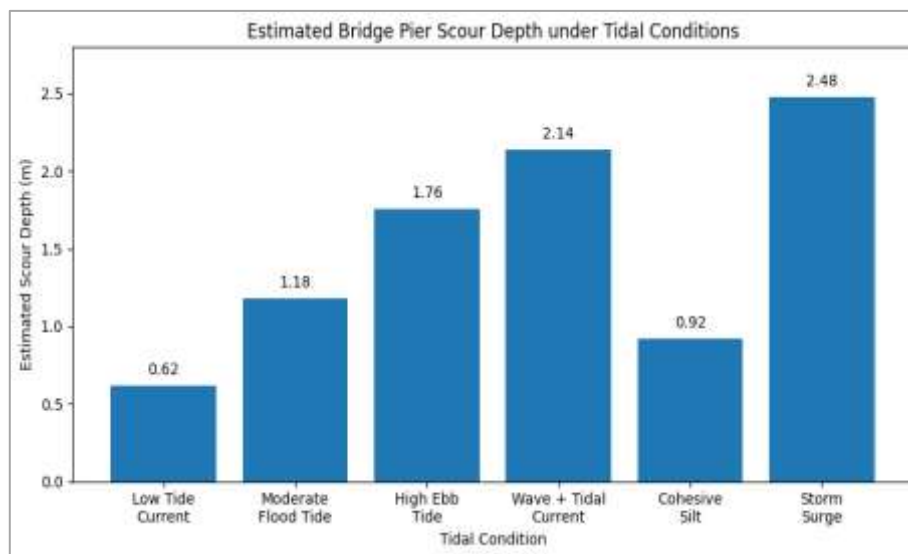
conditions was greater than under tidal current alone. The result indicated that traditional river-based scour prediction methods may not provide fully accurate estimates for tidal bridge sites because they do not properly consider flow reversal, wave action, and sediment redeposition. Therefore, site-specific analysis is necessary for reliable scour prediction.

Table: Estimated Scour Depth under Different Tidal Conditions

Tidal Condition	Flow Velocity (m/s)	Sediment Type	Estimated Scour Depth (m)	Scour Severity
Low Tide Current	0.45	Fine Sand	0.62	Low
Moderate Flood Tide	0.85	Fine Sand	1.18	Moderate
High Ebb Tide	1.20	Fine Sand	1.76	High
Wave + Tidal Current	1.35	Fine Sand	2.14	Very High
Moderate Tide	0.80	Cohesive Silt	0.92	Moderate
High Tide with Storm Surge	1.55	Mixed Sediment	2.48	Critical

The overall result confirmed that maximum scour occurred during high tide with storm surge and combined wave-current action. The lowest scour depth was observed during low tidal current conditions. This shows that tidal bridges require continuous monitoring and protective measures, especially in regions where high tidal velocity, sandy bed material, and storm surge conditions are common.

Bar Graph



The bar graph shows the estimated scour depth around bridge piers under different tidal conditions. The lowest scour depth, 0.62 m, occurs during low tide current because flow velocity and bed shear stress are limited. Scour increases during moderate flood tide and high ebb tide due to stronger current action and flow reversal. The wave and tidal current condition shows a higher scour depth of 2.14 m because waves loosen sediment while currents transport it away. The maximum scour depth, 2.48 m, occurs during storm surge, indicating critical risk to bridge foundation stability and the need for protective measures.

V. CONCLUSION

The study concludes that bridge pier scour in tidal environments is a complex and critical problem because tidal flow continuously changes in velocity, depth, and direction. Unlike normal river flow, tidal currents move in both flood and ebb directions, creating irregular erosion and deposition patterns around bridge piers. The result shows that scour depth increases with higher current velocity, wave-current interaction,

and storm surge conditions. Maximum scour occurs during storm surge and combined wave-tidal action, which may seriously affect the stability of bridge foundations. Sediment type also plays an important role, as sandy beds erode faster than cohesive beds. Therefore, proper field investigation, bathymetric survey, sediment testing, and hydraulic analysis are essential for accurate scour prediction. Suitable protection measures such as riprap, gabions, concrete mattresses, geotextile bags, and foundation strengthening should be provided to reduce erosion risk. Overall, regular monitoring and site-specific scour assessment are necessary to ensure bridge safety, durability, and sustainable coastal infrastructure development.

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