A Review on Local Scour Protection Measures for Bridge Piers: State of the Art and Future Directions

Bin Chen[1], Zihao Ren[1], Chengquan Wang[1,*], Xiangjun Yan[2], Jianwei Wang[2], Ruirui Qian[1]
[1]School of Engineering, Hangzhou City University, Zhejiang Hangzhou, China
[2]Hangzhou Municipal Facilities Management Center, Zhejiang Hangzhou, China
**Corresponding Author*

Abstract: This review systematically examines the current state of local scour protection measures for bridge piers. It summarizes the underlying mechanisms and influencing factors of scour, compares the advantages and disadvantages of existing countermeasures, and identifies limitations in current research to provide theoretical support for the optimization of protective technologies. Based on a comprehensive literature review and analysis of experimental data, the study consolidates various protection strategies, research methodologies, and predictive formulas for scour depth. Key issues highlighted include the limited development of combined protection devices, insufficient computational fluid dynamics (CFD) analysis of flow fields around protected piers, and a scarcity of reliable prediction models under protective conditions. The findings offer a technical basis and reference for the design, construction, and maintenance of cross-river and cross-sea bridges, contributing to the mitigation of pier scour—a widespread challenge in hydraulic engineering. Future research should prioritize the evaluation of impact resistance, development of new connection technologies, functional recoverability in design, integration of physical and numerical simulations, and comprehensive disaster prevention strategies. These advances are expected to further stimulate innovation in prefabricated and assembled bridge engineering, introducing new concepts and methodologies to the field.

Keywords: Bridge piers; Local scour; Scour protection; Scour mechanism; Countermeasures

1. Introduction

With the increasing demand for socio-economic and transportation construction, super long cross river and cross sea bridges such as Taizhou Bay Bridge, Hangzhou Bay Cross sea Bridge, and Hong Kong Zhuhai Macao Bridge are constantly being built. As the core infrastructure of water transportation, the safe operation of bridges is crucial for political and economic development. However, global warming exacerbates hydrological extreme events, coupled with a surge in the number of cross river and cross sea bridges, and frequent bridge water damage accidents, which have become key issues threatening the safety of bridge structures. According to statistical data, among the 1716 collapsed bridges worldwide from 1807 to 2021, hydrological factors accounted for 46.69% of the total. Among hydrological factors, erosion contributed the most, accounting for 31.53%, which is more than twice that of floods and far exceeds other factors such as collisions and overloading. Many serious accidents both domestically and internationally have been caused by erosion, such as the collapse of the foundation of the Qinglian Panjiang Bridge in Jiangyou, Mianyang in 2013 due to flood erosion, and the collapse of the Thruway Bridge in New York in 1987 due to pier erosion, resulting in 10 deaths. In addition, China has built over one million bridges and the United States has added 2500 bridges annually, further amplifying the risk of erosion and highlighting the urgency and necessity of research on local erosion protection of bridge piers and columns.

Based on the above cases and statistical data, it can be seen that local erosion has become the core bottleneck restricting the safe operation of bridges. Thoroughly analyzing the erosion mechanism, improving scientific research methods, and constructing accurate prediction models are not only the core research directions that urgently need to be broken through in the field of bridge engineering, but also the practical and urgent needs to ensure the safe operation of transportation infrastructure and reduce economic losses caused by disasters. They have both important theoretical research value and significant engineering practical significance.

2. Classification and Research Progress of Protective Technologies

Local erosion of bridge piers is a long-term problem in bridge operation and maintenance, and scholars at home and abroad have conducted extensive research. Li Bing and his son in China were the first to propose the flow field phenomenon of "fish swimming in the water, water splitting on both sides" through observation, providing experience for subsequent research; Melville [1] conducted classical flume experiments in the 1980s to study the flow around a cylinder, laying the foundation for flume experiments abroad. This section provides an overview of the current status of erosion protection measures, research methods, and erosion depth calculation formulas.

The measures to reduce local erosion of bridge piers are mainly divided into two categories: changing the flow field protection and changing the riverbed protection. The former works by weakening the descending water flow and horseshoe vortex intensity that causes erosion [2], while the latter sets up physical barriers around the bridge pier foundation to enhance the anticorrosion ability of the riverbed.

Flow field change measures can be divided into four categories based on shape and performance: bridge pier openings, bridge pier attachments, riverbed attachments, and other measures. The following is a detailed analysis.

2.1 Flow Field Change Protection Technology

2.1.1 Bridge pier opening technology

By installing internal connecting pipes on the bridge piers, using pier groups or slotting on the piers, some water flow is allowed to pass through or divert, reducing the impact of water flow in front of the piers. For example, Abd El Razek et al. [3] found that the inclined pipeline inside the bridge pier has a reduction efficiency of 39% under optimal parameters; the full pier group proposed by Vitta et al. [4] can reduce the maximum scour depth by 39%; Moncada-M et al. [5] and Grimaldi et al. As shown in Figure 1.

2.1.2 Bridge pier attachment technology

Install spiral coils, collars, or flat plates on the surface of bridge piers to interfere with the flow field. Research shows found that the three wire spiral coil can weaken horseshoe shaped eddy currents and reduce thrust by 46%; Richardson et al. proposed the optimal arrangement of multiple rings to reduce impact by 30%, and Kumar et al. As shown in Figure 2.

2.1.3 Riverbed attachment technology

Install sacrificial piles, vertical deflectors, or sleeves on the riverbed to alter the boundary layer flow field. Someone proposed a triangular sacrificial pile with a 50% reduction in scour, while he found a 44% reduction in scour when three piles were arranged in the field test; Another found that the anticorrosion efficiency of the internal angle guide plate is as high as 90%, and the soil erosion can be ignored and proposed that the sleeve should be equipped with an annular plate to prevent external erosion. As shown in Figure 3.

2.1.4 Innovative measures

A certain scientist tested the antifouling method of bridge pier suction by drilling holes on the lower wall of the pier and pumping water at a rate of about 5 gallons per minute. The results showed that there was no scouring of the riverbed, only a small depth of scouring hole was formed downstream of the pier. Research has shown that there is a strong horseshoe shaped vortex system on the upstream surface of circular bridge piers, while pointed bridge piers such as triangles, parabolas, and ellipses can weaken the strength of submerged water flow and horseshoe shaped vortices by reducing water flow obstruction. The shape coefficient Ks can be reduced to below 0.7, and the influence of pier shape on scour depth will be analyzed in detail in Chapter 2.

Riverbed alteration measures reduce local erosion by enhancing the anticorrosion ability of the riverbed around the pier. Typical measures include stone throwing protection, concrete formwork, and overall bottom protection. Among them, stone throwing protection has become the most widely used form in engineering due to its simple operation and easy material selection - by throwing large particle stones around bridge piers, increasing the roughness of the riverbed to reduce flow velocity, and increasing the energy of sediment initiation to reduce sediment initiation. Liang and Qi [6] conducted experiments to study the effects of the thickness, particle size, range, and particle size of the stone throwing layer on the protective effect.

Although the existing anticorrosion measures for bridge piers can improve the foundation's anticorrosion ability, they have their own limitations, such as the waterway impact and aesthetic issues of sacrificial piles pointed out by Parker et al. On the basis of summarizing the advantages and disadvantages of existing measures, this article proposes a combination of anticorrosion measures for specific water flow conditions, aiming to reduce the risk of local erosion of bridge piers and improve the safety performance of bridges through a series of studies. As shown in Figure 4.

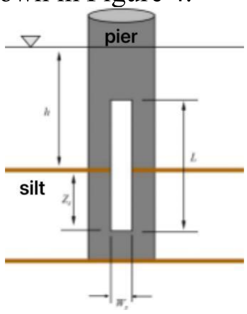

Figure 1. Schematic Diagram of Pier Opening

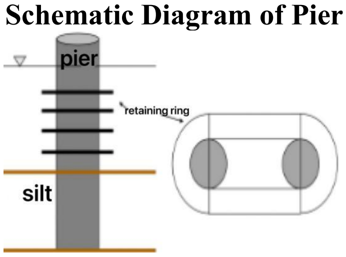

Figure 2. Schematic Diagram of Multi Ring Bridge Pier

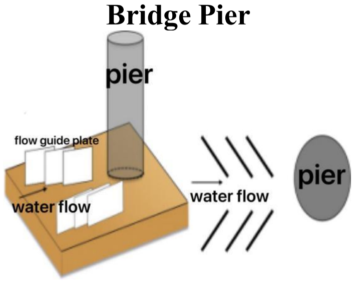

Figure 3. Schematic Diagram of Surface Guide Plate

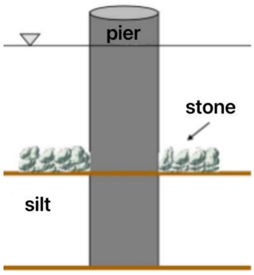

Figure 4. Schematic Diagram of Stone Throwing Protection

2.2 Progress in Research Methods

2.2.1 In situ testing

In situ testing refers to the use of fixed and portable instruments to monitor the local erosion of the foundation at the original site of the bridge. It can effectively observe the changes in the erosion situation over time and the development of the flow field. Li et al. [7] conducted an 8-month on-site monitoring experiment during the construction of the Haiyan Bridge and bridge piers to study the impact of new bridge piers on existing seawater flow and local erosion phenomena under deep-sea environmental conditions. Based on the analysis of hydrogeological conditions, the experiment found that bridge piers were mainly affected by upstream runoff and tides under deep-sea conditions. Sohn et al. [8] used Fiber Brain Signals sensors for in-situ monitoring of local scour on bridges. However, in deep water environments, the spatial resolution of the sensor is greatly reduced. Lagasse et al. [9] conducted in-situ monitoring of local scour on bridge foundations using magnetic sliding rings.

2.2.2 Water tank test

The annular wing anti scouring plate developed by Mou et al. [10] revealed the influence of the size of the circular end bridge pier and the height of the antifouling plate on the antifouling effect by observing the characteristics of the scouring pit and the vertical flow field parameters; The new ring wing bridge pier designed by Cheng et al. [11] verified its weakening effect on the descending water flow in front of the pier, with flow velocity and relative height of the anti-collision plate as variables. Tian et al. [12] used a 1:100 normal model water tank to systematically analyze the effects of skew angle and water flow intensity on the shape of scour pits in multi sand river bridge piers; Hou et al. [13] clarified the scouring characteristics of bridge pier groups in sandy environments by changing the spacing between parallel bridge piers and water flow conditions.

Mou et al. [14] proposed a combination of annular wing shaped anti-collision plates and bridge pier openings, and determined the optimal protection form through parameter optimization; The study of the triangular diversion structure by Ranjbar et al. [15], combined with orthogonal experiments and CFD flow field analysis, obtained the optimal combination of device size, position, and submergence rate. Xiang et al. [16] and Wang et al.

2.2.3 Numerical simulation experiment

A certain scientist presented a systematic review of one-dimensional river numerical simulation algorithms, encompassing both dynamic-bed one-dimensional unsteady flow algorithms and sediment models. Another developed a one-dimensional model for reservoir sedimentation and riverbed evolution based on real-world data. As shown in Table 1.

Table 1. Classification of Research Experimental Methods

Test Method	advantage	disadvantage	Core application scenarios
In situ testing	Real environmental data, long-term continuity	High cost and strong environmental dependence	Bridge operation and maintenance monitoring, extreme working condition verification
Water tank test	Controllable variables, intuitive mechanism analysis	Scale effect, difficult to simulate complex flow fields	Research and development of new devices, and study on the influence of single factors
Numerical simulation experiment	Efficient multi working conditions, adaptable to complex scenarios	Model calibration dependency, computational resource requirements	Fine analysis of flow field and multi-factor coupling prediction

3. Prediction Formula for Scour Depth

The current calculation formulas for local scour depth of bridge piers are mainly divided into empirical formulas and semi empirical and semi theoretical formulas. Due to the complexity of scour, there are differences in the calculation results of each formula, and the prediction formulas under device protection, especially under combined device protection, are relatively scarce. The following is a refined summary of the two types of formulas under individual bridge piers and device protection:

Regarding the calculation formulas for local scour of individual bridge piers, the 65-1 and 65-2 formulas specified in the Code for Hydrological Survey and Design of Railway Engineering are widely used in China. These formulas are based on extensive flume tests and field data, serving as important references for calculating bridge foundation scour in the country. However, they have drawbacks, including inconsistent dimensions, the 65-1 formula ignoring the influence of water flow depth, limited options for pier shape coefficients, and complex relationships between influencing factors. Someone investigated the effect of water flow depth on scour through flume experiments and proposed the Laursen equation, which takes into account water flow depth, bridge pier diameter, and sediment particle size. Somebody argued that the equilibrium scour depth increases as the water flow depth increases. The HEC-18 formula recommended by the U.S. Federal Highway Administration considers a comprehensive set of factors and shows high consistency with field-measured data. For cylindrical bridge piers under clear-water conditions, the scour depth in this formula is proportional to relevant parameters and the Froude number, while being inversely proportional to the sediment particle coarsening correction factor. Nevertheless, it has limitations: the physical meaning of $Fr^{0.43}$ is unclear, and it provides accurate scour depth predictions for wide piers but not for narrow piers or partially transitional piers. Another developed a formula based on experimental data. The improved version introduced the sediment non-uniformity coefficient and the density particle Froude number to describe the temporal variation of scour depth. Another integrated data to derive a formula for clear-water conditions; this formula incorporates three types of interaction correction coefficients and accounts for the relationship between sediment particle size and pier width. However, using only the median particle size D_{50} fails to reflect the influence of non-uniform sediment. Based on the scour mechanism and measured data from multiple countries, by the experiment established a formula that includes parameters such as pier shape coefficient, water flow depth, and pier width. This formula quantifies the impact of various factors on scour depth. As shown in Table 2.

Table 2. Calculation Formula for Local Scour of Individual Bridge Piers

Formula name	considerations	Formula form	Applicable Conditions	margin of error	Engineering Case
China 65-1 Amendment	Pier shape coefficient, calculated width of bridge pier, water flow velocity, and sediment initiation velocity	$y_s = k_1 k_{\eta 1} b_e^{0.6}(v - v'_0) \quad v \le v_c$ $y_s = k_1 k_{\eta 1} b_e^{0.6}(v - v'_0)\left(\frac{v - v'_0}{v_c - v'_0}\right)^{n1} \quad v > v_c$	Chinese railway, highway bridge and other engineering scenarios	10%~20%	A highway bridge in the middle reaches of the Yellow River

Chinese Type 65-2	Sediment initiation velocity, pier shape coefficient, pier width, water flow velocity, water depth, and sediment initiation velocity	$y_s = k_1 k_{\eta_2} b_e^{0.6} h_p^{0.15} \left(\frac{v - v_0'}{v_c} \right) \quad v \le v_c$ $y_s = k_1 k_{\eta 2} b_e^{0.6} h_p^{0.15} \left(\frac{v - v_0'}{v_c} \right)^{n2}$ $v > v_c$	Chinese deepwater bridge, suitable for small and medium-sized pier widths, uniform/non-uniform sand conditions	8%~18%	A railway bridge on a tributary of the Yangtze River
Laursen formula	Water depth, riverbed shear stress, and critical shear stress of sediment	$\frac{b}{y_s} = 5.5 \left[\frac{\left(\frac{y_s}{11.5h} + 1 \right)^{\frac{7}{6}}}{\sqrt{\frac{\tau_1}{\tau_c}}} - 1 \right]$	Uniform flow, cylindrical bridge piers, uniform sand bed	12%~25%	A highway bridge in the Huaihe River Plain
HEC-18 formula	Bridge pier form, water flow angle, riverbed condition, Froude number, water depth, bridge pier width	$\frac{y_s}{A} = 2.0 k_1 k_2 k_3 k_4 \left(\frac{y}{A} \right)^{0.35} F_r^{0.43}$	Multiple types of bridge piers, complex riverbeds, as well as uniform/non-uniform sand, small and medium-sized pier width scenes	5%~20%	A cross sea bridge in San Francisco, USA
Oliveto Hager formula	Bridge pier form, sediment non-uniformity coefficient, density particle Froude number, bridge pier width, time	$\frac{y_s}{b} 2.5 f_1 \left(\frac{h}{b} \right) f_2 \left(\frac{v}{v_c} \right) f_3 \left(\frac{b}{D_{50}} \right)$ $\frac{y_s(t)}{b^{2/3} h^{1/3}} = 0.068 k_1 \frac{H^{1.5}}{\sqrt{\sigma}} \ln \frac{t \sqrt{\left(\rho_s / \rho - 1 \right) g D_{50}}}{b^{2/3} h^{1/3}}$	Non uniform sand, dynamic erosion process, cylindrical bridge piers	8%~18%	Bridge in a mountainous area of a tributary of the Yangtze River
Zhou Yuli's formula	Pier shape coefficient, water depth, pier width, sediment particle size, water flow velocity	$h_s = 0.304 k_\xi h^{0.29} B^{0.53} d^{0.13} V^{0.61}$	Multi type bridge piers, medium fine sand beds, and scenarios with medium to low flow velocities	10%~25%	A highway bridge in the Pearl River tributary

There are relatively few existing formulas for predicting local erosion under device protection. Someone proposed a formula for calculating the maximum equilibrium scour depth under the protection of a protective ring, considering parameters such as the diameter of the protective ring and the depth of the protective ring under the free water surface, but did not involve time influencing factors. Another based on Kumar's formula and combined 130 sets of data through nonlinear regression analysis, introduced a dimensionless time factor to establish a relationship between erosion depth and time under protective ring protection. The calculation accuracy is good under non shrinkage effects, but it is only applicable to clear water erosion conditions of rectangular water flow sections and linear water flow. Another developed empirical formulas related to the depth of scour pits and water flow velocity, sediment initiation velocity, bridge pier diameter, and spacing between artificial grasses for the anticorrosion measures of the combination of protective rings and artificial grass through experiments, providing reference for predicting the scour depth of this specific combination device. As shown in Table 3.

Table 3. Prediction Formula for Local Erosion under Device Protection

Formula name	Protection type	Core parameters	Formula form	Applicable Conditions
Kumar formula [65]	Protective ring	Diameter of protective ring, diameter of bridge pier, water depth of protective ring, total water depth	$\left(\frac{ds_p - ds_c}{ds_p} \right) = 0.057 \left(\frac{B}{b} \right)^{1.612} \left(\frac{H}{Y_0} \right)^{0.837}$	Circular protective ring, cylindrical bridge pier, clear water flushing
Pandey formula [66]	Protective ring	Unprotected scour depth, dimensionless time factor, relative density of sediment	$\frac{D_{ct}}{D_t} = 0.23 \left(\frac{B}{b} \right)^{-0.82} \left(\frac{H}{Y_0} \right) \log T_c$	Rectangular cross-section, water flushing (dynamic process)
Yang Shaopeng's formula	Protective rings and artificial grass	Flow velocity difference, bridge pier diameter, artificial grass spacing	$H = 25.7 (v - v_0)^{1.32} + 12.4D - 0.44$	Shallow water sections and fine sand beds (with medium and low flow velocities)

Mou Xianyou combination formula (67)	Ring wing anti-collision plate and bridge pier opening	Flow rate, water depth, seam height, and position of the ring wing plate	$\eta = 45.07\% - 0.8\% \bullet \Delta h$	Medium flow velocity, medium fine sand bed (specific flow rate)

4. Research Prospects

The evolution of local scour protection for bridge piers reflects a clear trajectory from single-method, passive interventions toward integrated, multi-dimensional protection systems. While flow-field alteration techniques demonstrate high efficiency in scour reduction, and riverbed reinforcement offers notable reliability, the integration of combined measures represents the most promising direction for future development. Research methodologies have similarly advanced, progressing from in-situ observations to sophisticated three-dimensional numerical simulations, while predictive models have evolved from purely empirical formulations to multi-parameter coupled approaches.

Despite these advances, several critical challenges remain. Existing predictive formulas for scour depth under protective devices—particularly for combined configurations—suffer from limited applicability. The intrinsic response mechanisms of these systems under complex water–sediment dynamics and varying boundary conditions are still not fully elucidated. Moreover, research on the synergistic scour-reduction effects and long-term durability of composite protective devices remains inadequate.

Looking ahead, future efforts should prioritize the development of intelligent scour prediction models that seamlessly integrate hydraulic, sedimentological, structural, and device-related parameters. The incorporation of machine learning with multi-source monitoring data could substantially enhance predictive accuracy under challenging conditions such as non-uniform sediment beds, oblique flows, and ice-covered scenarios. Further investigation is also needed into the fluid–structure interaction mechanisms of combined protection systems—such as those incorporating wing plates, collars, and artificial grasses—to optimize parameter matching and improve the durability of adaptive device designs. Finally, through the integration of IoT sensing, remote monitoring, and numerical simulation, a lifecycle-oriented risk assessment and intelligent scour management framework can be established. Such integration will facilitate the effective translation of research insights into practical applications, especially in demanding environments like cross-sea bridges and cold regions, thereby providing more robust theoretical and technical support for the safety and resilience of bridge foundations.

Acknowledgement

The authors would like to thank Tutor Yifang Huang at the Training Platform of Construction Engineering at the Polytechnic Institute of Zhejiang University for their help.

This research was supported by Hangzhou Agricultural and Social Development Key Project under Grant No. 20231203A16, the Zhejiang Provincial Natural Science Foundation of China under Grant No. LTGG23E080001.

Reference

[1] Melville B W, Raudkivi A J. Flow characteristics in local scour at bridge piers. Journal of Hydraulic Research, 2010, 15(4): 373-380.

[2] Lim S, Chiew Y. Protection of bridge piers using a sacrificial sill. Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering, 2003, 156(1): 51-62.

[3] Abd El-Razek M, Abd El-Motaleb M, Bayoumy M. Scour reduction around bridge piers using internal openings through the pier. Alexandria Engineering Journal, 2003, 42(2): 241-248.

[4] Vittal N, Kothyari U C, Haghighat M. Clear water scour around bridge pier group. Journal of Hydraulic Engineering, 1994, 120(11).

[5] Moncada-m A T, Aguirre-Pe J, Bolí var J C, et al. Scour protection of circular bridge piers with collars and slots. Journal of Hydraulic Research, 2009, 47(1): 119-126.

[6] Qi Meilan, Zhou Mashang, Tang Gaichun The influence of pile erosion and stone throwing gradation and thickness on protective effect. Journal of Water Resources, 2021, 52 (06): 723-730

[7] Li Weipeng, Zhou Chenying, Deng Jianhua Research on Anticorrosion Technology and Analysis of Pier Columns of Haiyan Bridge

under Deep Sea Conditions. Highway Engineering, 2017, 42 (01).
[8] Ansari S A, Qadar A. Ultimate depth of scour around bridge piers. Proceedings of the Hydraulic Engineering, 1994.
[9] Papanicolaou T, Moustakidis I V, Tsakiris A G, et al. An adaptive field detection method for bridge scour monitoring using motion-sensing radio transponders (RFIDs). Iowa: Dept. of Transportation, 2014.
[10]Mou Xianyou, Wang Dan, Ji Honglan, etc Local scour test and hydraulic characteristics of circular end bridge piers using wing shaped anti scouring plates. South to North Water Diversion and Water Resources Technology, 2017, 15 (05): 146-155
[11]Cheng Lanyan, Mou Xianyou, Wen Heng, etc Partial scour protection test of ring wing bridge pier. Progress in Water Resources and Hydropower Technology, 2012, 32 (03):
[12]Tian Yong, Hou Zhijun, Hou Jiaojian Experimental study on the morphology of local scour pits in inclined bridge piers . People's Yellow River, 2018, 40 (12): 39-45
[13]Hou Zhijun, Hou Jiaojian, Yi Xiaoyan Experimental study on local scour of parallel bridge piers. Sedimentation Research, 2021, 46 (01): 74-80
[14]Mou Xianyou, Qiao Chunlin, Ji Honglan, etc Experimental study on a new type of protection combination of annular wing shaped anti-collision plate and slotted joint on bridge piers. Journal of Hydroelectric Power, 2017, 36 (04): 26-37
[15]Mohsen R Z, Alireza K, Hadi K, et al. Optimizing flow diversion structure as an effective pier-scour countermeasure. Journal of Hydraulic Research, 2021, 59(6): 963-976.
[16]Xiang Q, Wei K, Li Y, et al. Experimental and Numerical Investigation of Local Scour for Suspended Square Caisson under Steady Flow. KSCE Journal of Civil Engineering, 2020: 1-12.