Review of Research Methods and Prediction Models for Local Scour of Bridges

Bin Chen[1], Yuxuan Ding[2], Chengquan Wang[1,*], Xiangjun Yan[3], Jianwei Wang[3]
[1]*Department of Civil Engineering, Hangzhou City University, Hangzhou, Zhejiang, China*
[2]*College of Civil Engineering and Architecture, Guilin University of Technology, Guilin, Guangxi, China*
[3]*Hangzhou Municipal Facilities Management Center, Hangzhou, Zhejiang, China*
[*]*Corresponding Author*

Abstract: Bridges, key transportation infrastructure, face severe local scour threats to safe operation; statistics show hydrological factors cause 46.69% of bridge collapses, with scour contributing 31.53%-far more than floods or collisions. This paper systematically sorts out the core research on bridge local scour: it analyzes scour's nature via flow-pier interaction and sediment transport, identifying key drivers like stagnation points and vortices; quantitatively examines four influencing factors-flow, sediment, piers, protective devices-and clarifies parameter regulation on scour depth with experimental data; compares three research methods-in-situ tests, flume tests, numerical simulations-and their applicability in complex scenarios; reviews scour depth prediction models for unprotected piers and compares formula accuracy via engineering cases. Finally, it notes issues-insufficient combined protective device research, inadequate flow field analysis, limited models-and proposes directions-multi-device synergistic optimization, CFD-AI modeling, intelligent monitoring. The paper offers theoretical support and engineering reference for bridge foundation design optimization, scour protection implementation and long-term health maintenance.

Keywords: Local Scour of Bridges; Scour Mechanism; Influencing Factors; Research Methods; Scour Depth Prediction Models; Pier Protective Devices

1. Introduction

Bridges are core infrastructure that underpins regional transportation networks and social-economic development, with their structural safety and operational durability directly linked to people's wellbeing and economic stability. However, amid frequent extreme hydrological events triggered by global warming, flood-induced bridge failures have shown a clear upward trend; among these, local scour has become the primary cause of bridge foundation instability and structural collapse, with its hazards far exceeding traditional risk factors like overloading and collisions [1].

From the perspective of historical accident statistics, the threat of scour to bridge safety is universal and severe. Xiong et al. [2], based on an analysis of data on 1,716 collapsed bridges worldwide from 1807 to 2021, found that collapses caused by hydrological factors accounted for nearly half; as the dominant type of hydrological factor, scour had a contribution rate of 31.53%—more than twice that of floods [3]. Domestic cases are equally alarming: Liu et al. [4] compiled data on 102 collapsed bridges in China from 2007 to 2015, showing hydrological factors accounted for 43.1%; after Typhoon Nepartak in 2016, a survey of damaged bridges by Liu [5] revealed that 81.6% of flood-induced failures were caused by pier foundation scour. A typical case is the Jiangyou Qinglian Panjiang Bridge in 2013—flood scour led to voids in pier foundations, eventually causing the entire bridge to collapse and resulting in severe casualties and economic losses. The 2022 collapse of Baotou Nataigou Medium Bridge further confirmed this risk: local scour-induced voids and damage to the pier spread foundations directly caused the downstream deck to collapse, disrupting regional traffic for several days [6].

The above cases and data indicate that local scour has become a key bottleneck restricting the safe operation of bridges. In-depth analysis of scour mechanisms, development of scientific research methods, and establishment of accurate prediction models are not only core research

 Copyright @ STEMM Institute Press

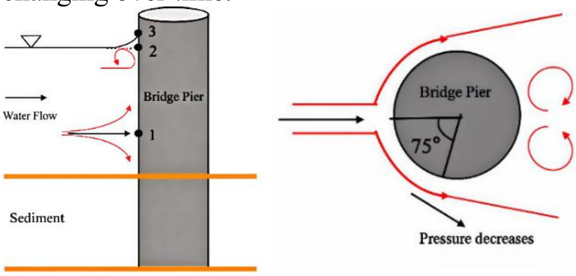
topics in the field of bridge engineering, but also practical needs to ensure the safety of transportation infrastructure and reduce disaster losses, with significant theoretical value and engineering practical significance.

2. Overview of Scour Mechanism

Local scour of bridges is a complex physical process under the coupled interaction of water flow, sediment and bridge piers, and its essence is a phenomenon where hydrodynamic force overcomes the shear strength of sediment, leading to the scouring and hollowing of sediment on the riverbed around bridge piers. This process can be analyzed from two dimensions: the interaction between water flow and bridge piers, and the sediment movement mechanism, both of which jointly determine the intensity, scope and development law of scour.

2.1 Interaction between Water Flow and Bridge Piers

The obstruction and disturbance of water flow by bridge piers form a multi-scale and highly dynamic flow field structure, which serves as the core driving force for scour. Its key processes can be divided into three interrelated stages that synergistically intensify the scour effect: Firstly, the formation of stagnation points and the development of diving flow, as shown in Figure 1 (a). When the upstream approaching flow encounters the obstruction of the pier, a stagnation point with zero velocity is formed in front of the pier. The water flow above the stagnation point deflects upward due to pressure difference, forming a water surface surge in front of the pier, while the water flow below deflects toward the water depth, forming a diving flow. The velocity of this diving flow can reach 1.2 to 1.8 times that of the approaching flow, with an impact angle usually between 15° and 30°, and the bed shear stress in the impact area is 2 to 3 times that of the approaching flow. This can directly exert strong shearing and dragging effects on the riverbed sediment in front of the pier, providing the core driving force for the initial formation of the local scour hole [7]; Subsequently, the acceleration of bypass flow and the sharp increase of bed shear stress. When the obstructed water flow bypasses both sides of the pier body, the bypass flow velocity increases significantly to 1.5 to 2.0 times that of the approaching flow due to the contraction of the flow cross-section (with a contraction coefficient of 0.6 to 0.8). Moreover, the velocity gradient on the riverbed surface is the largest under the influence of the boundary layer effect, leading to a sharp increase in bed shear stress. When the shear stress exceeds the sediment shear strength, the sediment on both sides of the pier is first initiated to form an initial scour zone. With the continuous action of the bypass flow velocity, the scour zone gradually expands outward, providing space for the subsequent development of the vortex system [8]; Finally, the formation and enhancement of the vortex system. The interaction between water flow and the pier generates two types of key vortices: one is the horseshoe vortex formed by the coupling of the diving flow in front of the pier and the bypass flow on both sides, which is distributed annularly along the bottom of the pier and rotates toward the pier body, with a central negative pressure of 5 to 10 Pa. It continuously erodes the riverbed around the pier to expand the scour hole horizontally; the other is the wake vortex formed by the separation of the bypass flow downstream of the pier, as shown in Figure 1 (b), which presents the form of alternately shedding Karman vortex street (with a shedding frequency of 0.1 to 0.5 Hz). It exerts periodic dragging effects on the sediment in the downstream area to extend the scour hole downstream, as shown in Figure 1. The two types of vortices act synergistically, eventually forming a local scour pattern centered on the pier, with depth and scope dynamically changing over time.



(a)Scour Side View (b)Scour Plan View

Figure 1. Side View of Local Scour Mechanism of Bridge Pier

2.2 Sediment Movement Mechanism

The movement state of riverbed sediment directly determines the scour intensity and final equilibrium morphology, and its core characteristics can be categorized from two dimensions: movement patterns and sediment supply conditions. Different types of sediment movement contribute significantly differently to scour. From the perspective of movement patterns, riverbed sediment is divided into bed load and suspended load: bed load mostly consists of coarse particles (e.g., fine sand, medium sand) with a size of 0.05–2 mm, which roll or jump along the bed surface and are the main cause of sediment loss at the bottom of the scour hole; suspended load refers to fine particles (e.g., clay, silt) smaller than 0.05 mm, which migrate in suspension due to water flow turbulence and cause sediment loss around the scour hole. Under a moderate flow velocity (1–1.5 m/s), the two account for 60%–70% and 30%–40% of the sediment loss respectively, and jointly determine the depth, volume and morphology of the scour hole. From the perspective of sediment supply conditions, local scour is divided into clear-water scour and live-bed scour: in clear-water scour, the flow velocity is ≤ the sediment incipient velocity, there is no sediment supply in the hole, and the scour depth continues to increase until it reaches equilibrium after 24–72 hours (e.g., deep-sea bridge piers); in live-bed scour, the flow velocity exceeds the incipient velocity, there is sediment supply in the hole, and the equilibrium depth is 20%–30% shallower than that of clear-water scour, which mostly occurs in sediment-laden rivers [9–11].

3. Analysis of Influencing Factors

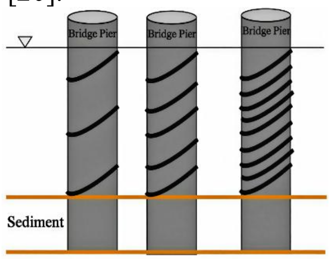
Based on the above-mentioned scour mechanisms, the depth and scope of local scour are jointly regulated by four types of factors: water flow, sediment, bridge piers, and protective devices. Each factor exerts a quantitative impact on the scour process by changing the hydrodynamic conditions or the anti-scour characteristics of sediment. Clarifying the action laws of each factor is the basis for conducting scour research and protective design.

Water flow is the core dynamic source driving scour. Its three key parameters—approaching flow velocity, water depth, and impact angle—directly determine the scour intensity by regulating water flow energy and flow field structure [12]. The approaching flow velocity is the most critical parameter, showing a significant positive correlation with the scour depth. In the clear-water scour stage, when the flow velocity exceeds the sediment incipient velocity, the amount of initiated sediment increases exponentially. When the flow velocity increases from 1 m/s to 2 m/s, the scour depth of fine sand and medium sand riverbeds increases by 3–5 times and 2–3 times respectively. Moreover, for every 10% increase in turbulence intensity, the scour depth can increase by 5%–8% [13]. Water depth has a threshold effect on scour: when the water depth is less than twice the pier diameter, the scour depth increases linearly with water depth; when it exceeds 2.5 times the pier diameter, the influence tends to stabilize. Arneson et al. [14] verified that when the ratio of water depth to pier width reaches 3, the contribution rate of water depth to the maximum scour depth drops to less than 5%. The larger the water flow impact angle, the more severe the scour. Tests by Tian et al. [15] showed that when the angle increases from 0° to 45°, the depth of the scour hole for skewed piers increases by 60% and the volume increases by 80%. When the angle exceeds 15°, conjugate scour holes appear on the upstream side of the pier tail, which intensifies sediment loss and increases the risk of pier instability.

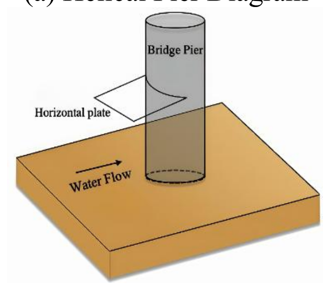
The physical properties of sediment determine its anti-scour capacity, and the scour process is mainly regulated by three parameters: particle size, gradation, and non-uniformity. The larger the sediment particle size, the higher the incipient velocity and the stronger the anti-scour capacity. The scour depth of piers in coarse sand riverbeds is usually 40%–60% shallower than that in fine sand riverbeds. The uniformity of sediment gradation is negatively correlated with the depth of the scour hole. Tests by Wang et al. [16] found that the scour hole of uniform fine sand is 30%–40% deeper than that of wide-graded sediment, because the coarse particles in wide-graded sediment are retained to form a natural skeleton, which prevents the loss of fine particles. Non-uniform sediment has better anti-scour capacity: coarse particles are retained first to form a protective layer, making its scour hole 20%–30% shallower than that of uniform sediment, and the equilibrium time is shortened by 15%–20%.

The geometric characteristics of bridge piers affect the scour distribution by changing the intensity of flow field disturbance, with core parameters including pier shape, pier width, and arrangement. The influence of pier shape on scour is quantified by the pier shape coefficient, and the scour effect of streamlined piers is lower than that of non-streamlined piers: the pier shape coefficient of circular piers is the smallest at approximately 1.0 (due to smooth flow around them); the coefficient of rectangular piers (with the long side perpendicular to water flow) is approximately 1.1; the coefficient of square piers is approximately 1.2 (due to obvious flow separation around them). Under the same water flow conditions, the scour depth of square piers is 20%–25% greater than that of circular piers. The larger the pier width, the more significant the flow cross-section contraction effect. Chen et al. [17] found through fitting measured data from multiple countries that when the pier width increases from 1 m to 3 m, the scour depth can increase by 50%–80%. However, when the pier width exceeds 1.5 times the water depth, the water flow changes from around-flow to weir flow, and the regulatory effect of pier width on scour depth weakens. The arrangement of multiple piers has an interference effect. Yu et al. [18] found through numerical simulation of tandem double cylindrical piers that the around-flow and horseshoe vortices of the upstream pier increase the approaching flow velocity of the downstream pier by 10%–20%. The interference is the strongest when the distance between pier centers is 4 times the pier diameter; when the distance exceeds 8 times, the interference disappears, and the scour of the two piers can be regarded as an independent process.

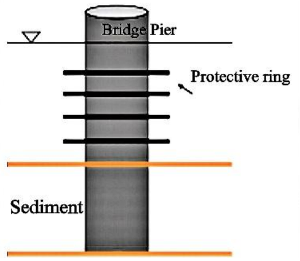
Protective devices such as protective rings, diversion plates, and annular wing anti-scour plates reduce scour by changing the flow field or enhancing sediment resistance, and their size, installation position, and quantity directly affect the protective effect. The larger the diameter of the protective ring and the closer its installation position to the riverbed, the better the effect—as shown in Figure 2; when the diameter is 3 times the pier diameter, the scour depth decreases by 40%; when the center is 5–10 cm below the original riverbed, the protective efficiency increases to 50%. However, when the diameter exceeds 4 times the pier diameter, the efficiency growth tends to slow down and the economy decreases. Cheng et al. [19] found through tests that the annular wing anti-scour plates achieve the best protection when their height is 1/3 of the water depth and the distance from the riverbed is 1/3 of the water depth—under this condition, the maximum near-bed vertical flow velocity decreases by 96% and the scour depth decreases by 57.6%. Excessively high plates tend to intensify flow separation and cause scour behind the plates, while excessively low plates cannot block the diving flow. The parameters of diversion plates need to be optimized synergistically: when the length is 2 times the pier diameter, the distance from the pier is 1.5 times the pier diameter, and the angle with the water flow is 15°, the flow field deflection is optimal, and the flow velocity in front of the pier decreases by 30%–40%. If the angle exceeds 30°, the water flow will impact the plate body and form vortices behind the plate; if the angle is less than 5°, the approaching flow cannot be deflected effectively [20].



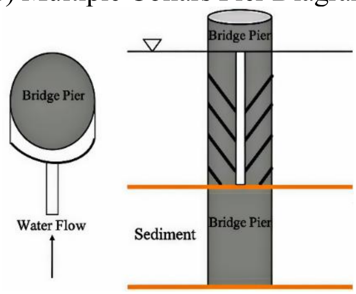
(a) Helical Pier Diagram



(b) Collar Horizontal Plate Diagram



(c) Multiple Collars Pier Diagram



(d) Inclined Baffle Diagram

Figure 2. Diagram of Interaction between Water Flow and Piers

4. Progress in Research Methods

With the development of technology, the research methods for local scour of bridges have been continuously upgraded, forming a three-in-one technical system of "in-situ tests - flume tests -

numerical simulations". These three methods each have their own advantages and applicable scenarios, and they verify and complement each other, jointly promoting the understanding of scour mechanisms and their engineering applications.

In-situ tests monitor the actual scour process using professional instruments at the original bridge site. Their core feature is that they truly reflect the complex on-site conditions, serving as a key link connecting laboratory research and engineering practice. The monitoring equipment is divided into two categories: fixed and portable. Fixed monitoring equipment is permanently installed on bridge foundations or riverbeds: magnetic sliding rings can obtain scour depth in real time, sonar echo sounders can map the 3D morphology of scour holes, and fiber Bragg grating sensors have a resolution of less than 1 cm but suffer from significant signal attenuation in deep water. Ansari et al. [21] once used such sensors for monitoring, but the spatial resolution decreased significantly in deep water environments. Portable equipment such as sounding rods is easy to operate but has an error of ±5 cm, which is only suitable for shallow water; multi-beam sonar on scour monitoring ships improves efficiency but is limited by extreme weather and navigation, making it suitable for periodic inspection of multiple bridges. In typical cases, Li et al. [22] conducted an 8-month monitoring on Piers 3# and 7# of Haiyan Bridge, and found that deep-sea bridge piers, affected by runoff and tides, had an average scour depth of only 8%–10% of the theoretical value, providing a basis for the design of deep-sea bridges; Papanicolaou et al. [23] used magnetic sliding rings to monitor a highway bridge in the United States for 5 years, established a model of scour depth and flood frequency, and proposed a suggestion of special inspection every 3 years. The advantages of this method lie in its ability to capture scour laws under complex hydrological conditions and verify laboratory results; its disadvantages are long monitoring cycle, high cost, difficulty in controlling a single variable, and high susceptibility to interference from the natural environment.

Flume tests simulate the scour process in a controlled environment using scaled models. They are a core method for studying scour mechanisms, optimizing protective devices, and also the basis for verifying numerical models. Tests need to follow the similarity principle: geometric similarity includes a model scale of 1:50~1:100, with the sizes of piers and sediment converted according to the scale; kinematic similarity includes adjusting flow velocity and water depth to ensure consistent Froude numbers (which affect diving flow and vortices); dynamic similarity includes ensuring that the Reynolds number is in the self-modeling region to avoid interference from viscous forces. Data collection relies on the collaboration of multiple devices, such as laser Doppler anemometers, high-speed cameras, and 3D topographic scanners, to ensure high data accuracy. In typical cases, Cheng et al. [24] designed an annular wing pier model and found that the best protection effect was achieved when the baffle was 1/3 of the water depth away from the riverbed, with the maximum near-bed vertical flow velocity reduced by 96%; Mou et al. [25] studied annular wing anti-scour plates and concluded that the medium round-ended piers had the largest reduction rate of scour hole volume (30%); Kai et al. [26] studied skirt-type caissons and found that the scour depth was the smallest when the skirt height was 0.8 times the water depth; Xiang et al. [27] found that the smaller the gap between the square caisson and sediment, the larger the maximum scour depth. The advantages of this method are strong controllability (including the ability to analyze a single factor independently), high data accuracy, and the ability to directly observe the scour process. Liang et al. [28] and Qi et al. [29] studied the laws of riprap protection and group pile scour through tests respectively; its disadvantages are the existence of scale effect, difficulty in simulating complex flow fields such as tides, and the construction cost of large flumes reaching millions of yuan.

Numerical simulations are based on fluid mechanics and sediment movement theory, and simulate the scour process by solving control equations with computers. They have developed from one-dimensional to three-dimensional refined models and become an important tool for studying complex flow fields. The development of models is divided into three stages: one-dimensional models focus on the overall evolution of river channels, with core equations including the Saint-Venant equations and sediment continuity equations. Yang et al. [30] summarized the live-bed algorithm, Han et al. [31] established a reservoir sedimentation model, and Zhang et al. [32] used the finite difference method to simulate scouring at drop sills. Although these models are efficient, they cannot simulate local scour. Two-dimensional models consider lateral flow velocity: Zhang et al. [33] used the finite volume method and dynamic mesh to simulate bed surface changes, and Wang et al. [34] used the RNG k-ε model to simulate jet scouring. These models can predict the scope of scour holes but have a depth error of >15% due to the neglect of vertical flow fields. Three-dimensional models consider vertical flow velocity and pressure, and use the Reynolds-averaged Navier-Stokes equations combined with turbulence models. Ma et al. [35] and Zhang et al. [36] used the RNG k-ε model to simulate pier scour; Ling et al. [37] confirmed that the shear stress in front of the pier was 3–4 times that of the approaching flow; Wei et al. [38] used dynamic mesh to handle bed surface changes. In addition, dynamic mesh technology updates the morphology of scour holes, and the Euler-Lagrange method is used to simulate sediment transport. In typical cases, Ataie et al. [39] explained the "synergistic scour" mechanism of side-by-side piers; Wu et al. [40] established a model under ice cover conditions; Chen et al. [41] studied the scour law of double-layer sediment. The advantages of this method are low cost, high efficiency, and the ability to simulate complex scenarios; its disadvantages are the need for test verification of parameters, high computational resource consumption for three-dimensional simulations, and difficulty in reproducing the movement of non-uniform sediment, as shown in Table 1.

Table 1. Comparison of Research Methods for Local Scour of Bridges

Research Method	Core Principle	Key Technical Parameters	Advantages	Disadvantages	Typical Application Scenarios
In-situ Test, Li [42], Papanicolaou [43]	Install instruments on-site to monitor the actual scour process and flow field parameters	Monitoring period: several months to several years; High precision; Applicable water depth: < 50 m	Can reflect complex conditions, data is reliable and can verify laboratory results	Long period, high cost; Difficult to control a single variable;	Long-term bridge operation and maintenance, scour risk assessment
Flume Test, Mou [44], Tian [45]	Simulate scour with scaled models, control variables, observe scour hole morphology and flow field	Model scale: 1:50~1:100; Froude number similarity; Measurement precision: < 5%	Strong controllability, can analyze single factors, high data precision, and intuitively observe the scour process	Scale effect exists; Difficult to simulate complex flow fields;	Scour mechanism research, optimization of protection devices
Numerical Simulation, Zhu [46], Zhang [47]	Based on fluid mechanics equations, solve flow field and sediment transport	Model dimension: 1D/2D/3D; Turbulence model: Calculation error: < 15%	Low cost, can simulate complex flow fields, and output detailed flow field parameters	Models need experimental verification; Difficult to reproduce non-uniform sediment movement	Complex flow field analysis, multi-factor coupling research

5. Scour Depth Prediction Model

5.1 Summary of Scour Depth Prediction Formulas for Unprotected Bridge Piers

After decades of development, various classic models have been formed for the scour depth prediction formulas of unprotected bridge piers, with core differences lying in the factors considered and applicable scenarios. The commonly used Modified Formula 65-1 and Formula 65-2 in China are derived from the *Code for Hydrological Survey and Design of Railway Engineering* [48]; established based on a large number of domestic flume tests and on-site data from the 1960s to the 1980s, the former calculates the scour depth in two segments according to flow velocity and sediment incipient velocity, while the latter supplements the influence of water depth—they are the mainstream formulas for the design of railway and highway bridges in China, but have limitations such as inconsistent dimensions, pier shape coefficients covering only a few types (e.g., circular and square piers), and large prediction errors for non-uniform sediment. The Laursen formula [49, 50] is an early representative model, which was the first to clarify the influence of water depth on scour and establish a relationship based on the principle of shear stress balance; it is suitable for uniform flow, cylindrical piers, and uniform sand riverbeds, but fails to consider pier shape, flow angle, and sediment non-uniformity, resulting in an error of over 25% for non-cylindrical piers. The HEC-18 formula [51], recommended by the U.S. Federal Highway Administration, considers multiple factors such as pier shape, flow angle, and riverbed state and has been applied to over 10,000 bridges worldwide; it has high prediction accuracy for cylindrical piers under clear-water conditions, but tends to overestimate the scour depth for wide piers (diameter > 5 m), and the physical meaning of the Froude number in the formula is controversial [52]. The Oliveto-Hager formula [53, 54] was the first to introduce the sediment non-uniformity coefficient and time factor, enabling it to describe the dynamic change of scour depth, and it is suitable for non-uniform sand scenarios, but most of its test data come from laboratory flumes, so its on-site applicability needs to be verified. Zhou Yuli's formula is based on measured data from multiple countries including China, the United States, and Japan, comprehensively considers factors such as pier shape, water depth, and pier width, and has a wide application range, but it does not involve the time factor and can only predict the equilibrium scour depth. In addition, the clear-water scour formulas integrated by Ettema et al. [55] and Melville et al. [56] introduce correction coefficients for interactions such as water flow-pier and water flow-sediment, but only focus on the median particle size (D50) of sediment and cannot reflect the anti-scour characteristics of non-uniform sediment. Each of these formulas has its own focus, as shown in Table 2, and in practical applications, the selection should be based on the hydrological conditions, sediment characteristics, and pier features of the project site.

Table 2. Comparison of Scour Depth Models for Unprotected Piers Formula Name

	Core Parameters	Formula Form	Applicable Conditions	Prediction Accuracy	Engineering Application Cases
Chinese 65-1 Modified Formula	Pier shape coefficient, pier width, flow velocity, sediment incipient velocity	Piecewise function (linear/power function)	Chinese railway/highway bridges, medium-small pier widths, uniform/non-uniform sediment	10%~20%	A highway bridge in the middle reaches of the Yellow River [48]
Chinese 65-2 Formula	Pier shape coefficient, pier width, flow velocity, water depth, sediment incipient velocity	Piecewise function with water depth correction	Chinese deep-water bridges, medium-small pier widths, uniform/non-uniform sediment	8%~18%	A railway bridge in a tributary of the Yangtze River [48]
Laursen Formula	Water depth, bed shear stress, sediment critical shear stress	$y_s=\frac{7}{6}h\,(\frac{T_1}{T_2}-1)$	Uniform sediment, cylindrical piers, uniform sediment bed	12%~25%	A highway bridge in the Huaihe Plain [57,58]
HEC-18 Formula	Pier shape, flow angle, bed condition, Froude number, water depth, pier width	$y_s=2.2K_4Fr^{0.43}a^{0.65}y$	Multi-type piers, complex beds, uniform/non-uniform sediment, medium-small pier widths	5%~20%	A sea-crossing bridge in San Francisco, USA [59]
Oliveto-Hager Formula	Pier shape, sediment non-uniformity coefficient, density, particle Froude number, pier width, time	$y_s=K_1\sigma^{-0.2}H^{-0.5}b^{0.6}t$	Non-uniform sediment, dynamic scour process, cylindrical piers	8%~18%	A mountain bridge in a tributary of the Yangtze River [60]
Zhou Yuli	Pier shape coefficient,	$h_s=0.304K_\varepsilon h^{0.29}\cdot$	Multi-type piers,	10%~25%	A highway

 Copyright @ STEMM Institute Press

Formula	water depth, pier width, sediment particle size, flow velocity	$B^{0.53}d^{-0.13}V^{0.61}$	medium-fine sediment beds, medium-small flow velocities		bridge in a tributary of the Pearl River [17]

5.2 Summary of Scour Depth Prediction Formulas for Bridge Piers with Protective Devices

The number of scour depth prediction formulas for bridge piers with protective devices is relatively small, and most of them target single devices or simple combined devices, with relatively limited application conditions. Peng's formula [61], designed for protective ring protection, is based on 86 sets of flume test data and calculates the reduction ratio of scour depth using the size ratio of protective rings to piers and the ratio of protective ring water depth to total water depth; it is suitable for circular protective rings, cylindrical piers, and clear-water scour conditions, and is widely used in bridges of small and medium-sized rivers in plain areas, but it does not consider the time factor and can only predict the equilibrium scour depth—additionally, the error increases significantly when the diameter of the protective ring exceeds 4 times that of the pier. Pandey's formula [62], which introduces a dimensionless time factor based on Kumar's formula and integrates parameters such as relative sediment density and particle size, can describe the dynamic scour process under protective ring protection; it is suitable for clear-water scour scenarios with rectangular cross-sections (e.g., bridges in urban inland rivers), with a prediction error of approximately 10% for the 72-hour equilibrium scour depth, but its applicability to complex flow fields such as tides and skewed water flow is limited, and it does not consider the influence of protective ring thickness. Yang Shaopeng's formula [63], targeting the combined protection of "protective rings + artificial grass", correlates the scour depth with the flow velocity difference and pier diameter to indirectly reflect the blocking effect of artificial grass; it is suitable for shallow water sections (water depth < 5 m) and fine sand riverbeds, and the scour reduction efficiency can reach 52% in the application of bridges in southern farmland irrigation rivers, but it does not quantify the influence of artificial grass spacing, nor does it consider water depth and flow angle, and is only applicable to specific flow velocity (1–2 m/s) and sediment particle size (0.1–0.2 mm) conditions. Mou et al. [20], focusing on the combined device of "annular wing anti-scour plates + pier slits", proposed a correlation between the scour depth reduction rate and slit height deviation based on test data under specific discharge (100 m³/s) and water depth (18 cm); the scour reduction efficiency reaches 45% in the application of bridges with medium flow velocity and medium-fine sand riverbeds, but it relies on specific test conditions—calibration is required when discharge and water depth change, and it cannot reflect the influence of time on scour. In addition, Izadinia [64], aiming at the combined protection of "cables + protective rings", fitted a scour depth prediction relationship through tests, as shown in Table 3, with a maximum scour reduction efficiency of approximately 40%, but it is only applicable to cylindrical piers and clear-water scour scenarios. Overall, existing formulas for piers with protective devices are mostly based on specific test conditions, and prediction models for combined devices are particularly scarce, making it difficult to meet the design needs of complex engineering scenarios.

Table 3. Comparison of Prediction Formulas for Pier Scour Depth with Protection Devices

Formula Name	Protection Type	Core Parameters	Formula Form	Applicable Conditions
Kumar Formula [65]	Collar	Collar diameter, pier diameter, collar water depth, total water depth	$\frac{d_{sc}}{d_{sp}}=0.837(\frac{B}{b})^{-0.25}(\frac{H}{Y_0})^{-0.15}$	Circular collar, cylindrical pier, clear water scour
Pandey Formula [66]	Collar	Unprotected scour depth, dimensionless time factor, relative density of sediment	$D_{ct}=0.2D_tT_C^{0.5}$	Rectangular section, clear water scour, dynamic process
Yang Formula [63]	Artificial Grass +Collar	Velocity difference, pier diameter, artificial grass spacing (empirical)	$H=25.7(v-v_0)^{1.32}+12.4D-0.4$	Shallow river reach, fine sediment bed, medium-small flow velocity

Mou Combined Formula [67]	Annular Wing Anti-scour Plate + Pier Slit	Discharge, water depth, slit height, annular wing plate position	$\mu=45.07\%-0.8\%\Delta h$	Medium flow velocity, medium-fine sediment bed, specific discharge

6. Existing Problems and Research Prospects

6.1 Existing Problems

Despite significant progress in the research on local scour of bridges, there are still the following key issues to be addressed urgently in terms of theoretical understanding, technical methods, and engineering applications:

6.1.1 Lack of research on combined protective devices

Most existing studies focus on single devices, with insufficient research on the combination of multiple devices: first, there is a lack of quantitative analysis on the synergistic mechanism between devices, such as how protective rings and diversion plates jointly suppress horseshoe vortices, and the parameter matching relationship between the two is unclear; second, the scour risk of the devices themselves is not fully considered—for example, a local low-pressure area is likely to form downstream of protective rings, which may lead to the scouring and hollowing of the protective ring foundation and affect the overall stability of the protective system; third, there is no systematic method for the optimal design of combined devices, which mostly relies on empirical trial calculations and has not formed a standardized design process, making it difficult to promote and apply in engineering. Parker et al. [68] emphasized the potential aesthetic drawbacks of using sacrificial piles, which may also affect waterways; Tafarojnoruz et al. [69] reviewed scour prevention measures that change the flow field and pointed out that most studies are relatively single, focusing only on one type of scour prevention measure.

6.1.2 Insufficient CFD analysis of flow fields

There is little research on the variation law of flow fields under protective devices, especially after the installation of combined devices, the quantitative variation characteristics of the flow field around piers are unclear: first, there is a lack of comparative analysis of hydraulic characteristics before and after device installation, making it impossible to clarify the scour reduction mechanism of combined devices from the flow field perspective; second, most existing numerical simulations adopt the standard k-ε turbulence model, which has insufficient simulation accuracy for strong swirling flows and inaccurate description of flow field details; third, most sediment transport models use empirical formulas and do not fully consider the impact of protective devices on sediment initiation and transport, resulting in deviations between the predicted scour depth and the actual situation.

6.1.3 Significant limitations of prediction models

Scour prediction formulas under protective conditions are scarce, and existing formulas have obvious limitations: first, most formulas are based on specific test conditions, with a narrow scope of application, and it is difficult to take into account complex hydrological conditions such as tides and skewed water flow, as well as complex riverbed conditions such as double-layer sediment and non-uniform sediment; second, most formulas are empirical fits, lacking support from physical models and having poor extrapolation—when extended from the laboratory scale to the on-site prototype, the error can exceed 30%; third, prediction models for combined devices are almost non-existent, failing to provide a theoretical basis for the design and effect evaluation of combined protective engineering.(4) Bottlenecks in in-situ monitoring technology

Existing in-situ monitoring equipment cannot meet the needs of high-precision, real-time, and large-scale monitoring: first, the contradiction between resolution and measurement range is prominent—sonar sounders have a large measurement range but low resolution, while optical fiber sensors have high resolution but a small measurement range, making it impossible to meet the needs of deep-water and high-precision monitoring at the same time; second, most monitoring data are single-point or local information, making it difficult to achieve real-time and continuous monitoring of the 3D morphology of scour holes, which restricts the understanding of the dynamic laws of on-site scour; third, the intelligence level of data transmission and analysis is low, and there is a lack of real-time early warning functions, making it impossible to respond to scour risks in a timely manner.

 Copyright @ STEMM Institute Press

6.2 Research Prospects

In response to the above problems, combined with the technical development trends in fields such as fluid mechanics, materials science, and artificial intelligence, future research can advance in the following directions to improve the theoretical understanding and engineering application level of local scour of bridges:

6.2.1 Research on collaborative optimization and mechanism of multiple devices

Carry out systematic research on combined devices such as "protective ring + diversion plate + artificial grass" and "skirt-type caisson + sacrificial pile": first, reduce the scale effect through large-scale flume tests, and quantitatively analyze the synergistic effect between devices by combining PIV (Particle Image Velocimetry) technology; second, establish an evaluation index system for the scour reduction efficiency of combined devices, comprehensively consider factors such as scour depth reduction rate, device cost, and construction difficulty, and propose a multi-objective optimization design method; third, clarify the applicability of combined devices in complex scenarios through numerical simulation and on-site test verification, and form a standardized design guide.

6.2.2 High-precision prediction model integrating CFD and AI

Promote the in-depth integration of computational fluid dynamics (CFD) and artificial intelligence (AI) technologies: first, use CFD technology to generate massive flow field and scour data, and construct a multi-factor coupled dataset; second, train machine learning models based on the dataset, with input parameters including water flow, sediment, bridge piers, and protective devices, and output parameters including scour depth, scour rate, and scour hole morphology; third, introduce physical constraints to avoid the "black box" problem of AI models, improve the extrapolation and interpretability of the model, and control the prediction error within 10% to meet the accuracy requirements of engineering design.

6.2.3 Development of intelligent monitoring and early warning system

Integrate multi-sensor technology and the Internet of Things to build an intelligent monitoring and early warning system for bridge scour: first, develop a multi-sensor fusion monitoring device combining "LiDAR + optical fiber + sonar"—use LiDAR to obtain the 3D morphology of scour holes, optical fiber sensors to monitor local scour depth, and sonar for auxiliary verification, so as to achieve high-precision and large-scale monitoring; second, build a real-time data transmission network based on 5G/Beidou technology to ensure the timely acquisition of monitoring data; third, combine prediction models and monitoring data to establish a scour risk level evaluation system, which automatically alarms when the scour depth is close to the safety threshold, providing decision support for bridge operation and maintenance and realizing the transformation from regular inspection to real-time early warning.

6.2.4 Cross-scale research and engineering transformation

Carry out cross-scale research between the laboratory and the field to solve the problem of achievement transformation: first, establish a scale correction model for scour depth through the comparison of large-scale flume test data and on-site monitoring data, quantify the impact of scale effect, and improve the on-site applicability of laboratory achievements; second, carry out special research on special scenarios such as deep sea, cold regions, and sediment-laden rivers—for example, Liang [70] studied the scour protection measures and early warning models for structural foundations in marine environments, and Bai [71] studied the large eddy simulation of suspended sediment transport—to improve the scour mechanism and prediction models under different scenarios; third, carry out demonstration applications of protective technologies in combination with typical engineering cases, form promotable engineering technical solutions, and promote the transformation of research achievements from theory to practice.

Acknowledgments

This research received no specific grant from any funding agency. The authors would like to express their sincere gratitude to Tutor Chengquan Wang from the College of Engineering, Zhejiang University City College for their professional guidance in this research work.

References

[1] Lan L. Analysis on the Construction of Cross-Sea Bridges in China. Traffic World (Construction & Maintenance Machinery), 2012, (10): 24-30.

[2] Xiong W, Cai C S, Zhang R Z. Review on Research of Bridge Scour Damage. China Journal of Highway and Transport, 2021, 34(11): 10-28.

[3] Guo J, Jiang B. Research Progress and Key Issues of Bridge Foundation Scour in the Past 30 Years. China Journal of Highway and Transport, 2020, 33(07): 1-16.

[4] Liu K, Liu J L, Yu W C. Statistical Analysis of Bridge Collapses Caused by Floods from 2007 to 2015. Urban Roads, Bridges & Flood Control, 2017, (01): 90-2+12-3.

[5] Liu B R. Investigation and Calculation Analysis of Bridge and Culvert Scour Damage Caused by Typhoon Nepartak. Fujian Traffic Science & Technology, 2017, (01): 70-73.

[6] Liang F Y, Wang C. Comparative Analysis of Local Scour Protection Technologies for Bridge Pier Foundations. Structural Engineers, 2014, 30(05): 130-138.

[7] Wang X, Li W, Peng Z, et al. Optimization of Combined Scour Protection for Bridge Piers Using Computational Fluid Dynamics. Water, 2025, 17(18): 2742-2742.DOI:10.3390/W17182742.

[8] Niknam A, Heidarnejad M, Masjedi A, et al. Data-based models to investigate protective piles effects on the scour depth about oblong-shaped bridge pier. Results in Engineering, 2024,23102759-102759.2024.102759.

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

[10]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.

[11]Humairi A J A B, Tayeb A F, Mahdi S N. Effect of different discharges and type of soils on scour under bridge piers by using statistical analysis. International Journal of Hydrology Science and Technology,2025,19(4):460-471. DOI: 10.1504/IJHST.2025.146514.

[12]Jia X, Mou X, Ji H. Experimental study on local scour protection and contact pressure of the facing water surface at the pier based on the guide pillar. Ocean Engineering, 2024, 302117670-. DOI: 10.1016/J.OCEANENG.2024.117670.

[13]Grimaldi C, Gaudio R, Calomino F, et al. Countermeasures against local scouring at bridge piers: slot and combined system of slot and bed sill. Journal of Hydraulic Engineering, 2009, 135(5): 425-431.

[14]Arneson L, Zevenbergen L, Lagasse P, et al. Evaluating scour at bridges. National Highway Institute (US), 2012, Report No. NHI-12-029: 1-286.

[15]Tian Y, Hou Z J, Hou J J. Experimental Study on the Morphology of Local Scour Holes around Skewed Bridge Piers. Yellow River, 2018, 40(12): 39-45.

[16]Wang S Y, Duan W G, Li L. Study on Movement Characteristics of Wide-Graded Non-Uniform Sediment. Yangtze River, 2011, 42(13): 72-5+105.

[17]Chen J G, Weng B W, Wu J Y, et al. Study on safety protection methods for local scour of cylindrical bridge piers. Journal of Zhejiang University of Technology, 2022, 50(03): 299-308.

[18]Yu P, Zhu Z W. Refined Simulation of Local Scour around Tandem Double Cylindrical Bridge Piers. China Journal of Highway and Transport, 2019, 32(01): 107-116.

[19]Cheng L Y, Mou X Y, Wen H, et al. Experiment on Local Scour Protection for Bridge Piers with Annular Wings. Advances in Science and Technology of Water Resources, 2012, 32(03): 14-8+61.

[20]Mou X Y, Wang D, Ji H L, et al. Experiment and Hydraulic Characteristics of Local Scour around Round-End Piers with Annular Wing Anti-Scour Plates. South-to-North Water Transfers and Water Science & Technology, 2017, 15(05): 146-155.

[21]Ansari S A, Qadar A. Ultimate depth of scour around bridge piers. Proceedings of the Hydraulic Engineering, F, 1994: 456-462.

[22]Li W P, Zhou C Y, Deng J H. Study on Scour Prevention Technology and Analysis of Haiyan Bridge Piers under Deep Sea Conditions. Highway Engineering, 2017, 42(01): 60-5+70.

[23]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, Report No. IA-2014-05: 1-78.

[24]Cheng L Y, Mou X Y, Wen H, et al. Experiment on Local Scour Protection for Bridge Piers with Annular Wings. Advances in Science and Technology of Water

Resources, 2012, 32(03): 14-8+61.
[25]Mou X Y, Wang D, Ji H L, et al. Experiment and Hydraulic Characteristics of Local Scour around Round-End Piers with Annular Wing Anti-Scour Plates. South-to-North Water Transfers and Water Science & Technology, 2017, 15(05): 146-155.
[26]Kai W, Fang Q, Shun Q Q. Experimental and numerical investigation into effect of skirted caisson on local scour around the large-scale bridge foundation. Ocean Engineering, 2022, 250.
[27]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.
[28]Liang F Y, Wang C. Comparative Analysis of Local Scour Protection Technologies for Bridge Pier Foundations. Structural Engineers, 2014, 30(05): 130-138.
[29]Qi M L, Zhou M S, Tang G C. Group Pile Scour and the Influence of Riprap Gradation and Thickness on Protection Effect. Journal of Hydraulic Engineering, 2021, 52(06): 723-730.
[30]Yang G L, Wu W M. Overview of One-Dimensional River Numerical Simulation Algorithms. Journal of Sediment Research, 1995, (04): 34-41.
[31]Han Q W, He M M. (One-Dimensional) Mathematical Model for Reservoir Sedimentation and Riverbed Evolution. Journal of Sediment Research, 1987, (03): 14-29.
[32]Zhang X, Wang X H, Dong L, et al. One-Dimensional Numerical Simulation of Scour at Drop Sill Based on Finite Difference Method. Journal of Water Resources and Water Engineering, 2021, 32(01): 172-8+86.
[33]Zhang Z Y, Shi B, Fan F F, et al. Two-Dimensional Numerical Simulation of Local Scour around Horizontal Cylinders near the Bed Surface. Chinese Journal of Computational Mechanics, 2012, 29(05): 759-764.
[34]Wang J J, Ni F S. Numerical Simulation of Two-Dimensional Vertical Submerged Jet Scour on Coarse Sand Bed. Science Technology and Engineering, 2014, 14(03): 108-111.
[35]Ma H G. Study on the random incipient motion law of bed load sediment. Northwest A&F University, 2022.
[36]Zhang Q, Zhou X L, Wang J H. Numerical investigation of local scour around three adjacent piles with different arrangements under current. Ocean Engineering, 2017, 142: 625-638.
[37]Ling J M, Lin X P, Zhao H D. Analysis of Three-Dimensional Flow Field and Local Riverbed Scour near Cylindrical Bridge Piers. Journal of Tongji University (Natural Science Edition), 2007, (05): 582-586.
[38]Wei Y J, Ye Y C. Three-Dimensional Numerical Simulation of Local Scour around Short Cylinders on the Bed Surface. Journal of Hydrodynamics, Ser. A, 2008, (06): 655-661.
[39]Ataie-Ashtiani B, Aslani-Kordkandi A. Flow field around side-by-side piers with and without a scour hole. European Journal of Mechanics / B Fluids, 2012, 36: 152-166.
[40]Wu P, Balachandar. Local scour around bridge piers under ice-covered conditions. Journal of Hydraulic Engineering, 2016, 142(1): 04015069.
[41]Chen W, Ye Y, Fayun L, et al. Experimental investigation of local scour around cylindrical pile foundations in a double-layered sediment under current flow. Ocean Engineering, 2022, 251: 111152.
[42]Li W P, Zhou C Y, Deng J H. Study on Scour Prevention Technology and Analysis of Haiyan Bridge Piers under Deep Sea Conditions. Highway Engineering, 2017, 42(01): 60-5+70.
[43]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, Report No. IA-2014-05: 1-78.
[44]Mou X Y, Wang D, Ji H L, et al. Experiment and Hydraulic Characteristics of Local Scour around Round-End Piers with Annular Wing Anti-Scour Plates. South-to-North Water Transfers and Water Science & Technology, 2017, 15(05): 146-155.
[45]Tian Y, Hou Z J, Hou J J. Experimental Study on the Morphology of Local Scour Holes around Skewed Bridge Piers. Yellow River, 2018, 40(12): 39-45.
[46]Zhu Z W, Liu Z Q. Three-Dimensional Numerical Simulation of Local Scour around Cylindrical Bridge Piers. China Journal of Highway and Transport, 2011, 24(02): 42-48.
[47]Zhang Q, Zhou X L, Wang J H. Numerical

investigation of local scour around three adjacent piles with different arrangements under current. Ocean Engineering, 2017, 142: 625-638.
[48]Code for Hydrological Survey and Design of Highway Engineering (with Explanations of Provisions). Traffic Industry Standard, 2002:1-118.
[49]Laursen E M. Scour at bridge crossings. Journal of the Hydraulics Division, 1960, 86(2): 39-54.
[50]Laursen E M. An analysis of relief bridge scour. Journal of the Hydraulics Division, 1963, 89(3):1-20.
[51]Calappi T, Miller C J, Carpenter D. Revisiting the HEC-18 scour equation. Scour and Erosion, 2010: 1102-9.
[52]Olsen N R B, Kjellesvig H M. Three-dimensional numerical flow modeling for estimation of maximum local scour depth. Journal of Hydraulic Research, 1998, 36(4): 579-590.
[53]Hager W H, Oliveto G. Shields entrainment criterion in bridge hydraulics. Journal of Hydraulic Engineering, 2002, 128(5): 481-488.
[54]Kothyari U C, Hager W H, Oliveto G. Generalized approach for clear-water scour at bridge foundation elements. Journal of Hydraulic Engineering, 2007, 133(11): 1229-1240.
[55]Ettema R, Melville B W, Constantinescu G. Evaluation of bridge scour research: pier scour processes and predictions. Citeseer, 2011, Report No. UMN-CEE-11-01: 1-156.
[56]Melville B W, Coleman S E. Bridge Scour. Water Resources Publication, 2000: 1-320.
[57]Laursen E M. Scour at bridge crossings. Journal of the Hydraulics Division, 1960, 86(2): 39-54.
[58]Laursen E M. An analysis of relief bridge scour. Journal of the Hydraulics Division, 1963, 89(3): 1-20.
[59]Calappi T, Miller C J, Carpenter D. Revisiting the HEC-18 scour equation. Scour and Erosion, 2010: 1102-9.
[60]Hager W H, Oliveto G. Shields entrainment criterion in bridge hydraulics. Journal of Hydraulic Engineering, 2002, 128(5): 481-488.
[61]Peng Y J. Analysis on the application of geotextile bag concrete construction technology: taking the Zhaoqing section of the Xijiang Main Stream Regulation Project in Guangdong Province as an example. Haihe Water Resources, 2022, (S1): 51-54.
[62]Pandey M, Azamathulla H M, Chaudhuri S, et al. Reduction of time-dependent scour around piers using collars. Ocean Engineering, 2020, 213: 107732.
[63]Yang S P, Shi B. Experimental Study on Artificial Grass for Bridge Pier Scour Protection. Transactions of Oceanology and Limnology, 2017, (05): 43-47.
[64]Izadinia E, Heidarpour M. Simultaneous use of cable and collar to prevent local scouring around bridge pier. International Journal of Sediment Research, 2012, 27(3): 394-401.
[65]Kumar V, Raju K G R, Vittal N. Reduction of local scour around bridge piers using slots and collars. Journal of Hydraulic Engineering, 1999, 125(12): 1298-1305.
[66]Pandey M, Azamathulla H M, Chaudhuri S, et al. Reduction of time-dependent scour around piers using collars. Ocean Engineering, 2020, 213: 107732.
[67]Mou X Y, Wang D, Ji H L, et al. Experiment and Hydraulic Characteristics of Local Scour around Round-End Piers with Annular Wing Anti-Scour Plates. South-to-North Water Transfers and Water Science & Technology, 2017, 15(05): 146-155.
[68]Parker G, Toro-Escobar C, Voigt J R R L. Countermeasures to protect bridge piers from scour, 1998, Report No. FHWA-RD-98-073: 1-89.
[69]Tafarojnoruz A, Gaudio R, Dey S. Flow-altering countermeasures against scour at bridge piers: a review. Journal of Hydraulic Research, 2010, 48(4): 441-452.
[70]Liang S D. Study on Scour Protection Measures and Early Warning Model for Structural Foundations in Marine Environment. Tsinghua University, 2014: 1-120.
[71]Bai J. Study on Large Eddy Simulation of Suspended Sediment Transport. Tsinghua University, 2013.1-105.
 Copyright @ STEMM Institute Press