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Application of Construction Technology for Scour Protection of River Bridge Foundation

Wang Qiusheng*, Zhou Tianqi, Qi Yunpeng

Key Laboratory of Urban and Engineering Safety and Disaster Reduction, Ministry of Education,
Beijing University of Technology, Beijing, 100124, China
**Corresponding author*

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Abstract: The cases of bridge damage due to water erosion are common. The traditional riprap protection method is not only limited in effect, but also expensive, which is difficult to meet the needs of modern engineering. In offshore wind power projects, solidified soil technology has been widely used because of its excellent anti-erosion performance, which provides a new way to solve the problem of anti-erosion. In this paper, the 16# main pier of Chongqing Jiangjin Yangtze River Highway Bridge is taken as the research object. Before construction, Fluent is used to simulate the influence of gabion on water flow characteristics to verify the feasibility of gabion protection technology. The simulation results show that gabion structure can not only significantly reduce the flow rate and reduce the impact of water flow on the surrounding environment, but also provide good construction environmental conditions for solidification soil perfusion. The anti-erosion reinforcement of the 16# main pier of Chongqing Jiangjin Yangtze River Highway Bridge has been successfully realized by the process of steel wire gabion combined with solidified soil perfusion. The test after construction shows that the solidified soil is well integrated with the original riverbed, and there is no obvious local erosion pit or hollowing around the pile foundation. The overall profile of the protection system is stable, and the anti-erosion ability is significantly improved. This process provides an important technical reference for the design and construction of anti-erosion of inland river Bridges.

1. Introduction

Bridges, as key nodes in the transportation network, are crucial structures for overcoming natural obstacles and are of strategic importance to modern transportation systems. Their structural safety directly impacts the effective implementation of national transport strategies and the stable operation of the national economy. However, during their operational life, bridge structures are susceptible to various adverse factors, which can lead to degradation or even instability and failure, potentially causing catastrophic consequences. According to relevant research data, between 1989 and 2000,503 bridges in the United States experienced collapse incidents, over half (55%) of which were caused by hydrological disasters[1]. Additionally, the economic losses due to bridge scouring each year amount to as high as $30 million[2]. Therefore, it is particularly important to implement scour protection for bridge foundations.

In recent years, stabilized soil technology has received increasing attention as a new protective measure. Ding Jian et al. [3] studied the effects of different moisture contents and varying amounts of stabilizers on the performance of sludge-stabilized soil and proposed in-situ sludge stabilization methods. Yuan Jianzhong [4] outlined that stabilized soil protection must meet the following requirements: homogeneous and cohesive, good integrity, strong fluidity, easy pumping construction, good water stability, and environmental friendliness. Zhou Maoqiang et al. [5] compared stone dumping protection with stabilized soil protection and found that the performance of stabilized soil protection is superior to that of stone dumping protection, suggesting that stabilized soil protection can replace traditional stone dumping protection. Li Tengfei et al. [6] used ANSYS finite element software to simulate the protective capability of sludge-stabilized soil for offshore wind turbine foundations, concluding that stabilized soil can enhance the horizontal resistance of pile foundations, reduce pile deformation, bending moment, and stress, while also improving the cohesion of soft soil foundations and reducing the sand-carrying capacity of water flow. Ouyang et al. [7] conducted physical scouring tests on pile foundations protected by cement-stabilized soil using a water tank, demonstrating the feasibility of this protection method. Shen Xiaolei et al. [8] obtained through finite element simulation that stabilized soil can significantly increase the horizontal bearing capacity of pile foundations. Roulund et al. [9] combined experimental and three-dimensional numerical simulations to study the flow field and scouring issues around bridge piers, utilizing dynamic mesh technology to update the process of riverbed deformation. In scouring simulations, when the slope of the scour pit exceeds the underwater angle of repose, it may lead to computational distortion or even divergence. Sun Dongpo et al. [10] combined experimental and numerical simulation methods to study the three-dimensional flow field of scour pits near bridge piers, with relatively accurate results. Ling Jianming et al. [11] used a three-dimensional standard $k-\varepsilon$ model combined with VOF modeling to track free surfaces, simulating the flow field around bridge piers, providing theoretical support for further analysis of scour mechanisms and the formulation of protective measures. Currently, scour protection measures mainly include active and passive protection. Passive protection is more commonly used, which involves laying protective materials on the bed around the pile foundation to increase its resistance to shear stress caused by water flow. Passive protection methods primarily include stone throwing protection, partial stone grouting protection, and stabilized soil protection. Stone throwing protection is the most traditional scour protection measure, widely applied in the scour protection of offshore wind turbine foundations [12]. Heibaum et al. [13] believe that partial stone grouting protection offers better stability and integrity compared to stone throwing protection. Partial stone grouting evolved from the overall grouting method, offering some permeability that meets scour protection requirements [14]. Du Shuo [15] found that stabilized soil with different cement contents is harder to activate than ordinary clay, exhibiting better scour resistance.

In summary, although there have been some studies on the use of stabilized soil for scour protection in bridge foundations, there are no similar cases in inland rivers, and numerical simulation studies on the effect of gabions on water flow are relatively scarce. Therefore, this study focuses on Pier 16 of the Chongqing Jiangjin Yangtze River Highway Bridge, addressing the severe scouring issues encountered by the pier foundation under rapid currents. Based on theoretical analysis using numerical simulation, a combined anti-scour solution involving steel wire gabions and stabilized soil was designed and implemented. This solution not only provides a new technical approach for bridge scour protection but also offers valuable experience for the design and construction of similar projects.

2. Project overview

2.1 Project background

The Jiangjin Highway Yangtze River Bridge project is located within the jurisdiction of Jiangjin District, Chongqing Municipality, at the tail end of the Three Gorges Reservoir area in the middle and upper reaches of the Yangtze River. For detailed geographical information, see Figure 1. The bridge axis crosses the main channel of the Yangtze River at the upstream navigation mile post K735+600. The main riverbed cover layer in the engineering area is primarily composed of dense gravel mixed with pebbles, with a thickness 8.0~9.0m. The underlying bedrock is a mudstone layer. The mudstone has a clayey cemented structure, containing sandy bands and clod-like structures, with poor rock mass integrity and susceptibility to weathering. The thickness of the strongly weathered zone is 2.0~5.0m, and the natural uniaxial compressive strength of the rock mass is Ra=16.5MPa.

Figure 1: Location diagram of Jiangjin Yangtze River Highway Bridge

2.2 Bridge pier scouring

After constructing piers in a river, the presence of these piers significantly reduces the cross-sectional area of water flow, altering the original hydrodynamic characteristics and sediment transport patterns. The water velocity near the piers increases due to the reduced cross-section, leading to significant scouring effects on the riverbed. This scouring phenomenon is primarily composed of three parts: first, natural scouring formed over long periods during natural evolution; second, general scouring caused by the reduction in cross-sectional area; and third, local scouring generated by changes in water flow structure around the piers. Among these, local scouring has the most prominent impact. When water encounters the piers, it creates noticeable surface fluctuations and subsurface currents in front of the piers, as well as complex turbulent zones around them. The water flow structure in these turbulent zones is extremely complex, including subsurface currents on the upstream side, horseshoe vortices formed by bypassing flows, wake vortices produced by separation of water on both sides of the pier, and small-scale vortices generated on both sides and behind the pier. These complex water flow structures collectively exacerbate the local scouring around the piers.

During the inspection of the underwater foundation of the bridge pier, it was found that the water flow on the upstream face and both sides was turbulent, while the water flow on the downstream backside was relatively gentle. Taking pile foundation No.16-5 as an example, it is externally wrapped with a steel casing. However, due to the turbulent water flow, it is impossible to directly observe whether the bottom is still being eroded and if the steel casing remains intact. Based on the estimated water depth around the abutment, the exposed height of the 13 piles at the bottom of the abutment is approximately 350-430 cm, and the surrounding riverbed is mainly composed of stones. The current erosion depth may have reached the bottom of the steel casing, while the steel casings of the other piles have penetrated into the bedrock. Therefore, these piles are still protected by the steel casings at the current erosion depth. To further clarify the erosion situation, a sonar sweep survey was conducted on the area around the bridge pier, and the scan cloud map is shown in Figure 2.

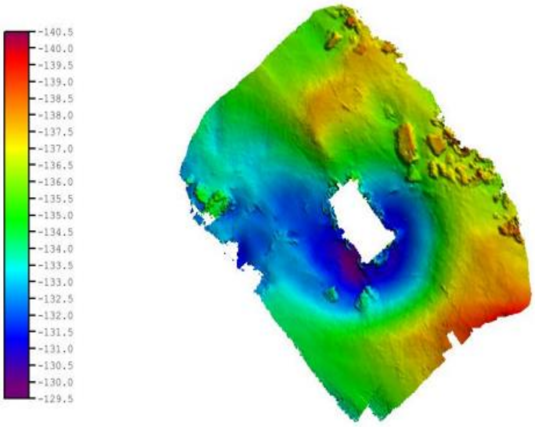


Figure 2: Scanning cloud map of scour range before construction

3. Numerical simulation analysis

3.1 Model establishment

The gabion cage is a structure made of high-strength metal wire mesh and filled with solid stones, widely used in river protection, slope reinforcement, isolation projects, and coastal defense [16]. Its unique design not only effectively resists water erosion but also adapts to ground settlement, offering excellent permeability and ecological friendliness. However, it is less commonly applied in the scour protection of inland river bridges. To verify the feasibility of the gabion process, a three-dimensional model was created using ANSYS Fluent software to simulate the impact of the gabion structure on water flow characteristics. A rectangular pipe was used as the water flow model, with the lower left corner of the rectangle as the origin, where length is the x-axis, width is the y-axis, and height is the z-axis. The geometric dimensions of the pipe are 16m in length, 4m in width, and 4m in height, providing a stable water flow environment for analysis. The gabion structure is located inside the rectangular pipe, set up in a trapezoidal shape as per the design drawing, with dimensions of 14m in length, 4m in width, and 4m in height, aligned with the center of the pipe to ensure that water can fully flow through the gabion area. A schematic diagram of the model plane is shown in Figure 3.

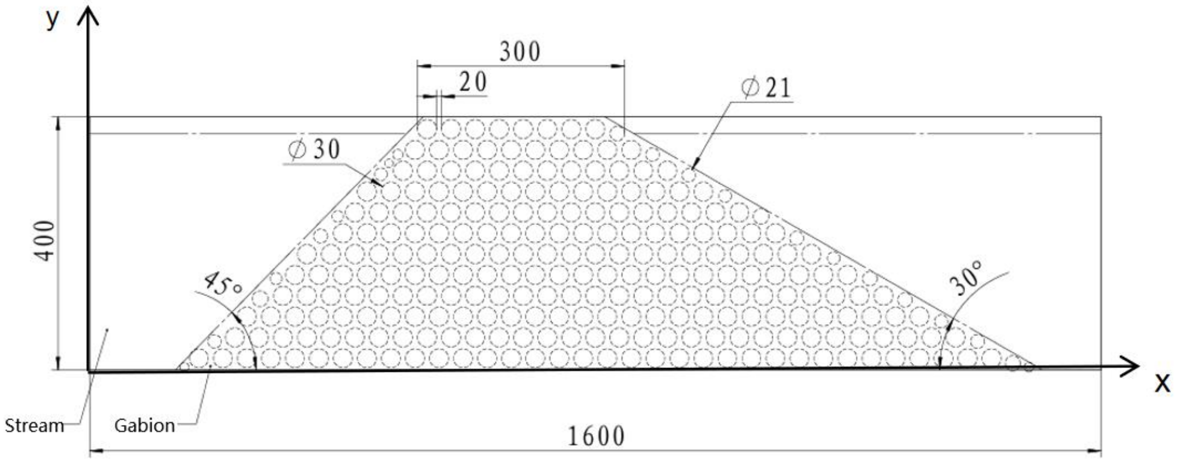


Figure 3: Plan view.

The inlet boundary is set as a velocity boundary condition, with the flow rate selected based on historical hydrological conditions at 5 m/s (using the most unfavorable flow rate). The outlet boundary is set as a free outflow condition, maintaining a fluid depth of 4 m. The top boundary is set as a pressure boundary condition, and the walls in contact with the solid material are treated as non-slip boundaries. By setting these boundary conditions, it is possible to accurately capture the velocity distribution, pressure changes, and turbulence characteristics of the water passing through the gabion. See Figure 4 for the boundary diagram.

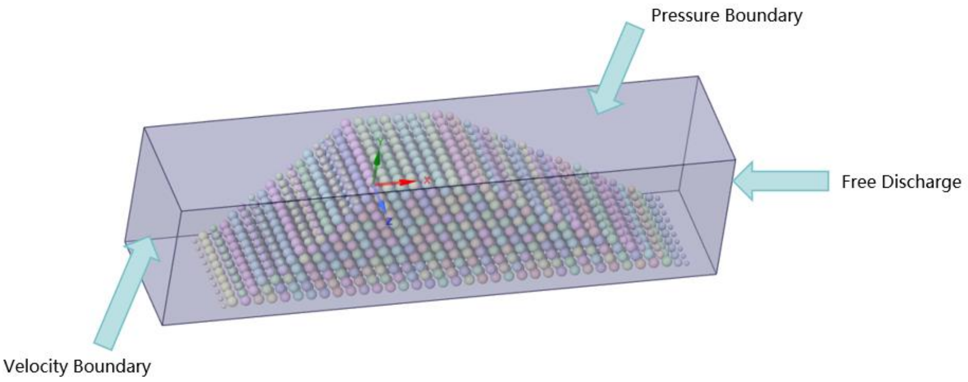
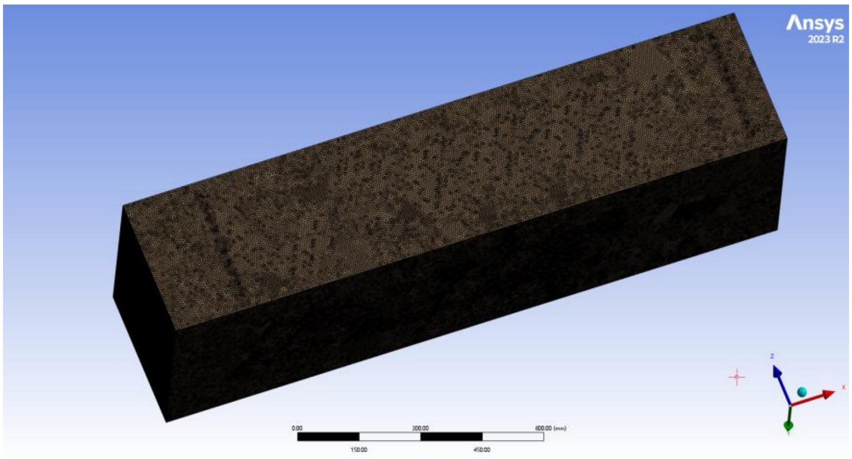


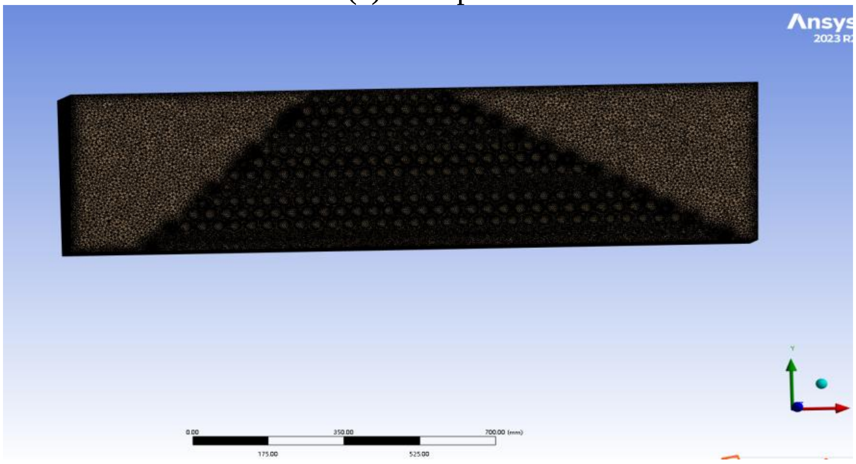
Figure 4: Boundary Settings diagram

3.2 Grid division

Using the orthogonality quality method, this is an indicator for evaluating the quality of mesh elements, especially in finite element analysis (FEA) or computational fluid dynamics (CFD). Orthogonality quality measures the orthogonality between the surface or edge of a mesh element and its normal vector. The value range of orthogonality quality typically ranges from 0 to 1, where 1 indicates perfect orthogonality, and 0 represents the poorest orthogonality. The higher the orthogonality quality, the better the quality of the mesh element. See Figure 5 for meshing details.



(a) Grid plan



(b) Grid facade view

Figure 5: Grid division diagram

3.3 Result analysis

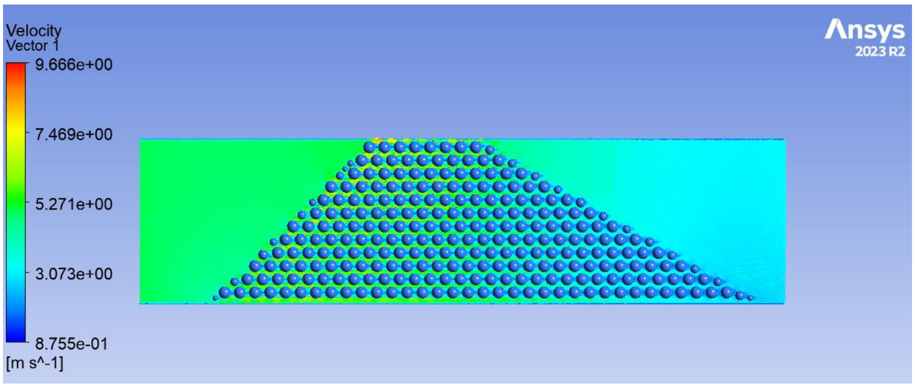


Figure 6: Cloud map of simulation results

As shown in Figure 6, when the inlet velocity is set to 5m/s (the most adverse condition), the flow velocity significantly decreases after passing through the gabion structure. This phenomenon fully demonstrates the crucial role of the gabion structure in water flow regulation. In the upper region of the gabion, the flow velocity first increases and then decreases from the inlet, stabilizing between 2-3m/s inside the gabion; in the lower region of the gabion, the flow velocity further decreases to about 1m/s, with some areas experiencing a minimum flow velocity as low as 0.9m/s, representing an average reduction of 70% and a maximum reduction of 80%. This stepwise decrease in flow velocity indicates that the physical properties of the porous structure of the gabion can effectively disperse the kinetic energy of the water flow, reduce its impact force, and thus achieve control over the water flow velocity.

The flow velocity changes with vertical height as shown in Figure 7. At the top of the gabion at 0m, the highest velocity is 5.2 m/sm/s, and the lowest is 4.6 m/sm/s, a decrease of 12%, with minimal overall variation along the height. Inside the gabion at 16m, influenced by the structure, the highest velocity drops to 3 m/sm/s, and the lowest to 0.9 m/sm/s, a reduction of 70%, showing significant variation along the height. This is due to the trapezoidal structure of the gabion, where the lower part is wider, providing better obstruction to the water flow, resulting in a significant difference between the upper and lower sections.

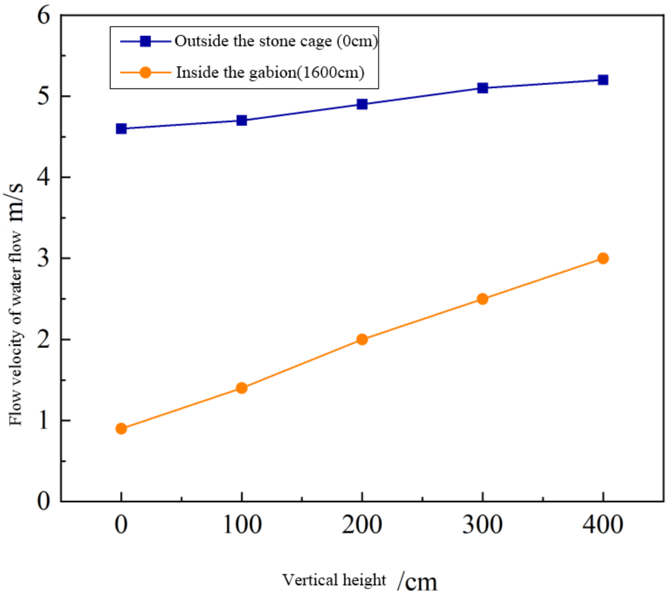


Figure 7: Variation of flow rate with vertical height

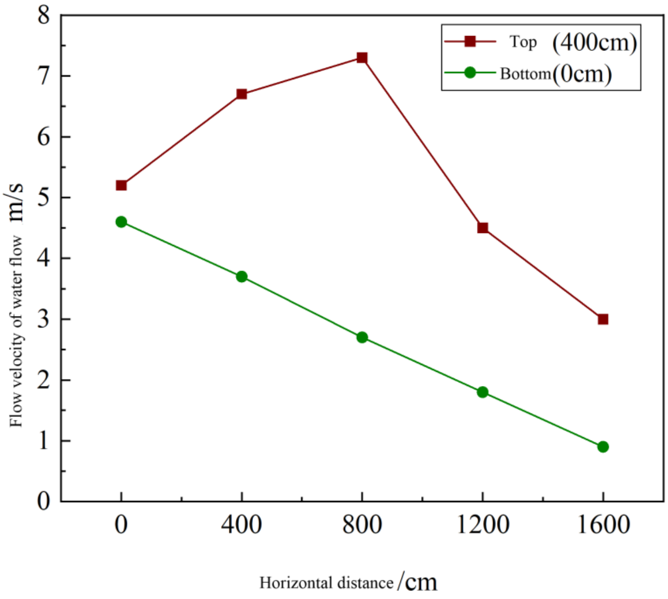


Figure 8: Variation of flow rate with horizontal distance

The flow velocity of the water changes with horizontal distance as shown in Figure 8. At the top of the gabion (at a height of 4 meters), the flow velocity first increases and then decreases with increasing horizontal distance. This is because when the water approaches the gabion, its presence reduces the cross-sectional area of the flow. According to the continuity equation, the flow velocity increases due to the reduced cross-sectional area. However, the high resistance characteristic of the gabion causes energy dissipation in the water, leading to a gradual decrease in flow velocity. At the bottom of the gabion (at a height of 0 meters), the flow velocity decreases from 4.6 m/sm/s to 0.9 m/sm/s, showing a significant linear decrease as can be seen from the figure. Therefore, the gabion structure not only significantly reduces flow velocity and minimizes the impact of water on the surrounding environment but also provides an excellent construction environment for the injection of stabilized soil.

4. On-site construction cases

4.1 Scheme design

The project employs a combination of gabion placement and pre-mixed fluidized soil backfilling techniques, as shown in Figure 9: First, the gabions are positioned and placed. Then, a ring-shaped geotextile isolation layer is laid on the inner side and bottom of the gabion to create a relatively enclosed still water working environment. Finally, specialized ship-mounted solidified soil mixing equipment prepares the mixture, which is pumped into the gabion interior through pressure conveying pipes. The construction diagram is shown in Figure 10, and the main engineering quantities are detailed in Table 1.

Table 1: Summary of the number of anti-erosion projects for pile foundation

Name of material	unit	P16 pier
Cemented soil	m^3	4296
geotechnical cloth	m^3	1620
gabion	m^3	3214

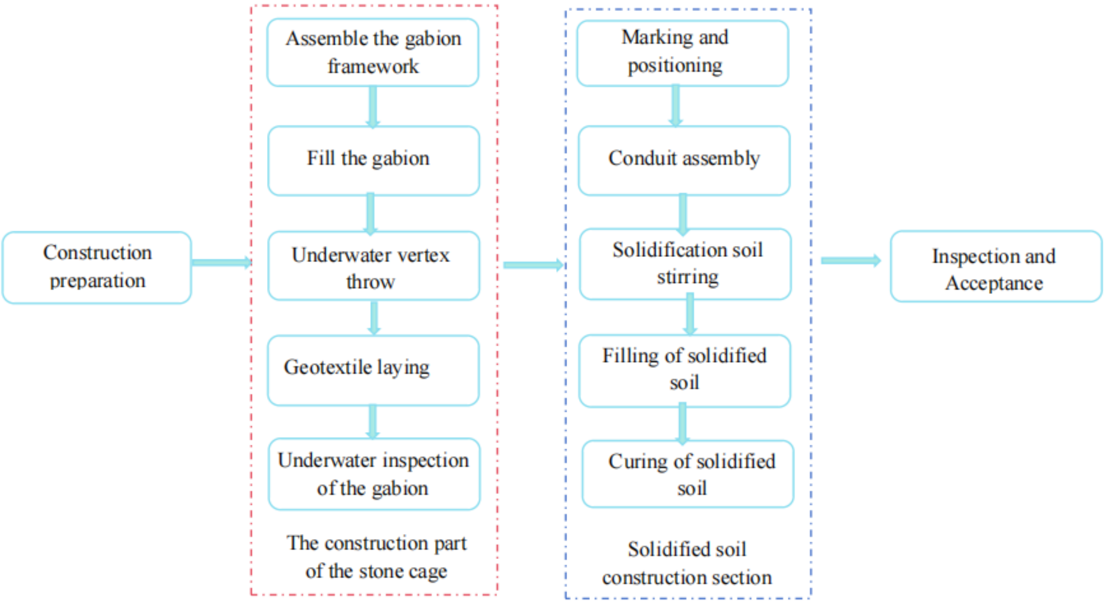


Figure 9: Construction flow chart of solidified soil

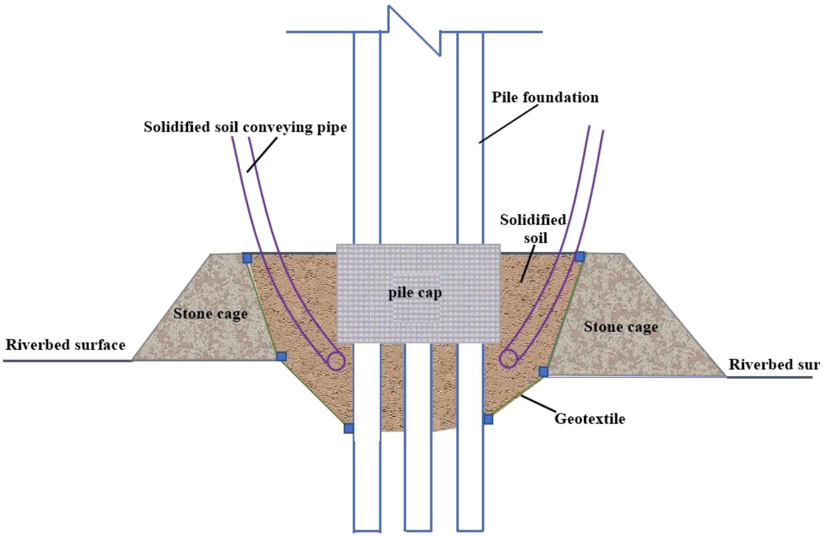


Figure 10: Schematic diagram of soil scour protection

4.2 Gabion

This project uses galvanized gabion nets with a diameter of 2 meters and a height of 1 meter to ensure their durability and corrosion resistance. The vertical design of the gabion is shown in Figure 11. By adopting this highly durable and stable gabion net, it not only effectively addresses complex water flow erosion conditions but also maintains structural reliability and ecological benefits over long-term use.

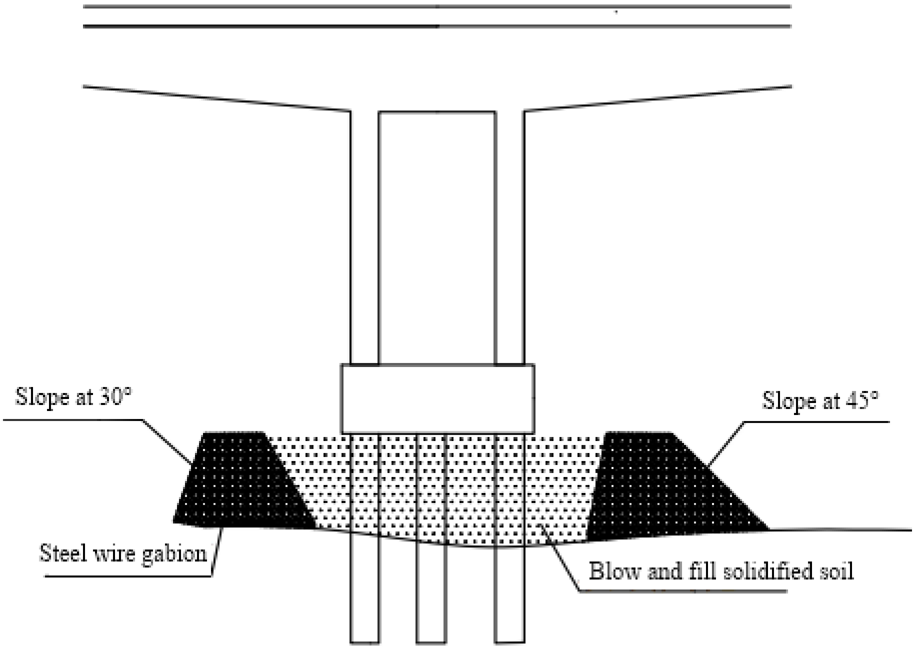


Figure 11: Stone cage layout facade

4.2.1 Gabion filling

The filling of gabion is a key step to ensure the stability and functionality of the gabion structure. The filling process should be carried out in strict accordance with the design requirements to ensure the density and integrity of the gabion.

(1) Construct the gabion frame: First, according to the design requirements, we use steel pipe couplers to build a gabion frame measuring 2 meters by 2 meters by 1.5 meters. The construction of the frame must ensure its stability and reliability, with a certain degree of verticality. The stability of the frame directly affects the subsequent fixation and filling of the gabion nets, so measurements are taken during the construction process to ensure that the verticality and levelness of the frame meet the standards.

(2) We can secure the gabion cage: Fix the gabion cage to the frame and secure it firmly with connecting clips. When filling with stones, begin by placing 50cm to 70cm large-sized stones to ensure sufficient weight and stability at the bottom of the cage. Then, we fill in with approximately 30cm small-sized stones to fill the gaps between the larger stones, reducing porosity and ensuring the cage is fully packed and compact. During the filling process, we need to pay attention to the even distribution of stones to avoid local voids or excessive accumulation.

(3) Sealing treatment: After filling, the gabion is sealed with steel wire rope and iron wire to ensure the integrity and stability of the gabion net. Special attention should be paid to the tightening degree of the steel wire rope when sealing, so as to avoid the scattering of stones or deformation of the gabion due to loose sealing.

4.2.2 Gabion throwing

Gravel cage throwing is an important part of gravel cage construction, especially in underwater construction, the accuracy and stability of throwing directly affect the protective effect of gravel cage.

(1) Determination of the throwing position: Based on the scope of the scour pit, measure the horizontal placement position of the gabions using the design distance between the outer side of the foundation slab and the stone cage cofferdam. Divers must mark the throwing area underwater with buoys to ensure that the gabions are accurately placed at the designated location. The determination of the throwing position should take into account the water flow velocity, direction, and riverbed topography to ensure that the gabions can effectively resist erosion by the water.

(2) Drop Construction: During the drop process, a floating crane is used for operations. The floating crane is equipped with an automatic uncoupling device that can automatically disengage when the gabions approach the riverbed bottom, reducing damage to the gabions and ensuring their precise positioning. When dropping, it is important to control the descent speed of the gabions to prevent damage or misalignment due to excessive speed. After the drop is complete, divers must inspect the position of the gabions to ensure they meet design requirements.

(3) Adjustment after throwing: After the stone cage is thrown, it needs to be adjusted according to the actual situation. If the position of the stone cage is found to be inaccurate or there is a tilt phenomenon, it should be adjusted in time to ensure the stability and protection effect of the stone cage.

4.3 Geotextile

The geotextile used in this project is a needle-punched/woven composite permeable geosynthetic material, primarily made from high-strength polyester or polypropylene fibers through a three-dimensional needle-punching and weaving process to form [17]. The technical specifications of this material meet the requirements of the "Technical Specifications for Application of Geosynthetic Materials" (GB/T 50290-2014). Specific parameters include: unit area mass ≥ 260g/m², nominal tensile strength ≥25kN/m, CBR puncture strength ≥ 5.5kN, and vertical permeability coefficient ≥ 1×10^{-2}cm/s. After the gabion throwing process is completed, the construction technique involves layered laying and anchoring treatment, with full-section laying along the inner side of the gabion structure and around the pile foundation area, forming a continuous closed impermeable structural layer.

During construction, the laying sequence of "first vertical then horizontal" is adopted to ensure a 100% material coverage rate. The overlap width of adjacent sheets is strictly controlled within a range of 30cm ± 2cm. For complex nodes, additional stainless steel U-shaped anchors are used for mechanical fixation, with an anchoring spacing not exceeding 50cm. By laying geotextiles, seepage isolation and filtration protection functions can be achieved, forming a relatively closed hydraulic boundary condition. This further reduces the water flow velocity inside the gabion, effectively preventing the loss of stabilized soil slurry.

4.4 Solidified soil

4.4.1 Properties of solidified soil

The technology of stabilized soil must meet the conditions for pumping construction in scour protection projects, which imposes high demands on the fluidity of materials. At the same time, the strength characteristics of stabilized soil are one of the most critical mechanical properties in engineering, directly affecting the project's resistance to scour and durability. The raw materials used for preparing stabilized soil mainly include local red clay, cement, stabilizer, and water. Through a combination of laboratory tests and field trials, the optimal ratio of red clay: cement: stabilizer: water was determined to be 100:10:0.3:55, which meets the following performance indicators for stabilized soil (Table 2).

Table 2: Performance indexes of stabilized soil

order number	performance index	Criteria requirements
1	density	1.50~1.80g/cm3
2	Unconfined compressive strength (28d)	≥800kPa
3	Cohesion (28d)	≥40kPa
4	Internal friction Angle (28d)	≥15°
5	slumps	≥180mm
6	Corrosion resistance flow rate (5h)	≥2.0m/s
7	Loss after construction (7d)	≤10%
8	Water stability	It is not dispersed at room temperature for 60d after saturation

4.4.2 Mixing and pouring

(1) Floating crane positioning and equipment layout. Based on the specific needs of pier protection, the coordinates of the piers to be protected are first determined, and then the floating crane is used for precise anchoring. The floating crane is equipped with specialized flow-curing soil mixers, pump trucks, and excavators, ensuring the efficiency and accuracy of the construction process. The layout of these equipment is carefully designed to meet the requirements for subsequent material transportation, mixing, and pouring.

(2) Material transportation and preparation. Raw materials required for construction, including red clay, cement and curing agent, are transported from the wharf to the floating crane ship by flat-bottomed barges. During transportation, ensure that the quality and quantity of materials meet the design requirements to avoid construction interruption or material waste.

(3) Curing Soil Mixing. Red clay, cement, and curing agent are added to the mixer according to the design ratio. The mixer is equipped with an electronic scale, which can precisely control the amount of each material, ensuring the accuracy of the mix. The mixing time is set at 5 minutes to ensure all materials are thoroughly mixed, forming a uniform pre-mixed flowable cured soil. After mixing, the well-blended flowable cured soil is pumped to the construction site using a pump truck, ensuring continuous and efficient construction.

(4) Segmental and layered pouring and grouting process. A segmented and layered pouring method is adopted, with strict control over the height of each pour to ensure the uniformity and stability of the cured soil. To minimize the impact of water flow during the grouting process, a special grouting technique is used: extending the end of the conduit 30cm above the bottom of the existing scour pit, and first pouring the cured soil slurry to the bottom of the scour pit. Utilizing the high flow characteristics of the cured soil slurry, it gradually fills the bottom of the scour pit, then slowly rises upward until the entire scour pit is filled. During the grouting process, as the level of the cured soil rises, a crane synchronously lifts the conduit while keeping its end below the surface of the cured soil slurry. This design significantly reduces the impact of water flow on the grouting construction, ensuring both quality and efficiency.

4.5 Quality inspection and acceptance

After the completion of the solidified soil grouting construction, systematic inspection and acceptance work must be carried out on the underwater scour protection system and riverbed topography. A high-precision 3D sonar scanning measurement system was used to conduct underwater topographic surveys in the construction area. The survey results show: (1) The solidified soil has good adhesion with the original riverbed surface, forming a continuous and stable overall structure; (2) The scour around the pile foundation is well developed, with no localized scour pits or voids; (3) Based on the overall contour changes of the protection system, its stability is judged to be good.

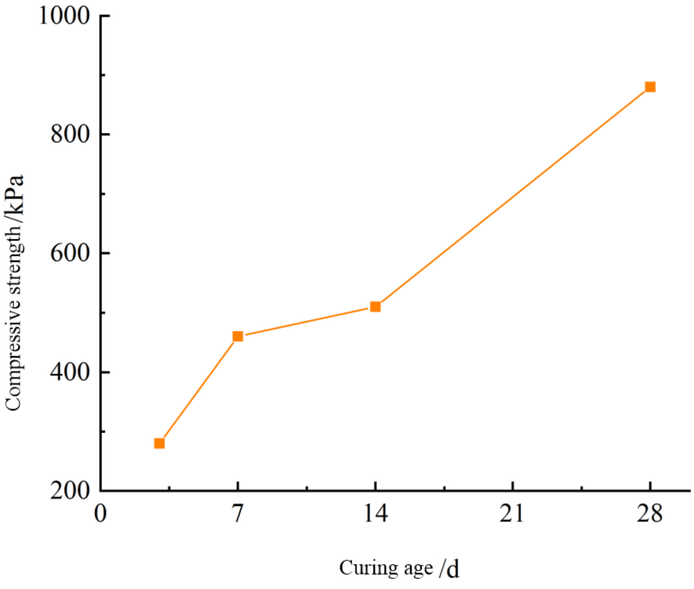


Figure 12: Variation law of solidified soil strength

At the same time, to accurately assess the changes in the strength of stabilized soil over time, random sampling was conducted at the construction mixing site. The specimen size is a cube of 100mm × 100mm × 100mm, with no fewer than three samples per group. After the specimens were prepared, they were immediately subjected to standard curing (temperature 20±2°C, relative humidity ≥95%). At curing ages of 3d,7d,14d, and 28d, unconfined compressive strength tests were performed according to the methods specified in the "Code for Design of Cement Soil Mix Proportions" (JGJ/T 233-2011). As shown in Figure 12, the strength of the stabilized soil gradually increases over time, with a compressive strength of 880kPa at 28d, meeting the design requirement of greater than 800kPa. This indicates that the stabilized soil has sufficient resistance to water erosion and can provide excellent protection. Additionally, it is recommended to regularly conduct durability tests on the stabilized soil, including indicators such as impermeability and frost resistance, to comprehensively evaluate the long-term performance of the protective system.

5. Conclusions

This paper takes the 16# main pier of the Yangtze River Highway Bridge in Jiangjin District, Chongqing as the research object. By combining numerical simulation with field construction, the effectiveness of steel wire gabion and pre-mixed fluid solidified soil composite injection technology in bridge foundation scour protection is successfully verified. The following conclusions can be obtained:

1) Under the most unfavorable flow velocity conditions, the flow velocity in the upper region of the gabion cage increases first and then decreases from the inlet, and the flow velocity in the internal part of the gabion cage is stable between 2-3m/s; the flow velocity in the bottom region of the gabion cage further decreases to about 1m/s, and the lowest flow velocity in some local areas even reaches 0.9m/s, with an average reduction of 70% and a maximum reduction of 80%.

2) Through numerical simulation analysis, the effectiveness of gabion structure in water flow regulation and its practicability in engineering are verified. Gabion structure can not only significantly reduce the flow velocity and reduce the impact of water flow on the surrounding environment, but also provide good construction environmental conditions for solidified soil injection.

3) By employing the composite grouting technique of steel wire gabions and pre-mixed fluid-cured soil, successful erosion-resistant reinforcement was achieved for the No.16 main pier of the Chongqing Jiangjin Yangtze River Highway Bridge. Post-construction inspections revealed that the cured soil had good integration with the original riverbed, and no significant localized scouring pits or voids appeared around the pile foundation. The overall contour of the protection system remained stable, and its erosion resistance was significantly enhanced.

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