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Research on Load Transfer Law of Combined Reinforcement Using Anchor Cable Frames and Anti-slide Piles: Dynamic Analysis Based on Pile-Soil Contact Stress

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Abstract: From the perspective of dynamic analysis of pile-soil contact stress, this paper investigates the load transfer law of combined reinforcement using anchor cable frames and anti-slide piles. It encompasses the load transfer mechanism of the combined reinforcement using anchor cables and anti-slide piles, collaborative design judgment, and long-term performance prediction. The aim is to provide a reference for subsequent collaborative design and its application, thereby ensuring the effectiveness of the combined reinforcement.

Keywords: Pile-soil contact stress; Anchor cable frame; Anti-slide pile; Combined reinforcement; Load transfer

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1. Introduction

The combined reinforcement using anchor cable frames and anti-slide piles offers advantages such as efficiency and adaptability, and has been widely applied in current slope stabilization projects. However, existing engineering practices often fail to clarify the specific load distribution mechanism between the two, neglecting the impact of soil-structure interface interactions on load transfer. This results in insufficient targeted collaborative design and makes the combined reinforcement system prone to fatigue failure under long-term cyclic loading ^[1]. To avoid such issues, researchers need to take the dynamic changes in pile-soil contact stress as the fundamental starting point, focusing on three basic directions: load transfer mechanism, collaborative design judgment, and long-term performance prediction. Scientific research should be conducted on the load transfer law to ensure the stability and durability of the combined reinforcement system.

2. Load transfer mechanism of combined reinforcement using anchor cable frames and anti-slide piles

2.1. Experimental design and data collection

To investigate the dynamic transfer law between anchor cable prestress and pile-soil contact stress of anti-slide piles, this study utilized typical landslide geology as a test sample, characterized by silty clay soil with a natural moisture content of 22%, cohesion of 28 kPa, an internal friction angle of 18° , and a dry density of 1.72 g/cm^3 . Based on these conditions, a 1:10 scale experimental model was constructed and validated through Midas/GTS finite element software simulations. During the experiment, low-relaxation high-strength steel strands with a diameter of 15.2 mm and a tensile strength of 1860 MPa were selected. Anti-slide piles were constructed using C30 reinforced concrete, with specifications of $200 \text{ mm} \times 200 \text{ mm} \times 2.5 \text{ m}$. Strain gauges and pressure sensors were deployed at the pile-soil contact interface to collect real-time data on contact stress, anchor cable prestress, and soil displacement. Loads were applied in stages, with each stage controlled at 50 kN and a holding time of 30 minutes, reaching a final load of 300 kN. Simultaneously, parameter changes were monitored at holding times of 1d, 3d, 7d, 14d, and 28d, with a focus on the impact of shear action between the soil and structural interface. During the experiment, data on anchor cable prestress loss, pile-soil contact stress distribution, and interface shear displacement were synchronously recorded, with environmental interferences such as temperature and humidity excluded to ensure data accuracy ^[2]. Three sets of parallel experiments were conducted, and the average values were used as the basis for subsequent analysis, focusing on the dynamic correlation between anchor cable prestress and pile-soil contact stress, as well as exploring the impact of interface shear action on load distribution. A three-dimensional model diagram is shown in **Figure 1**.

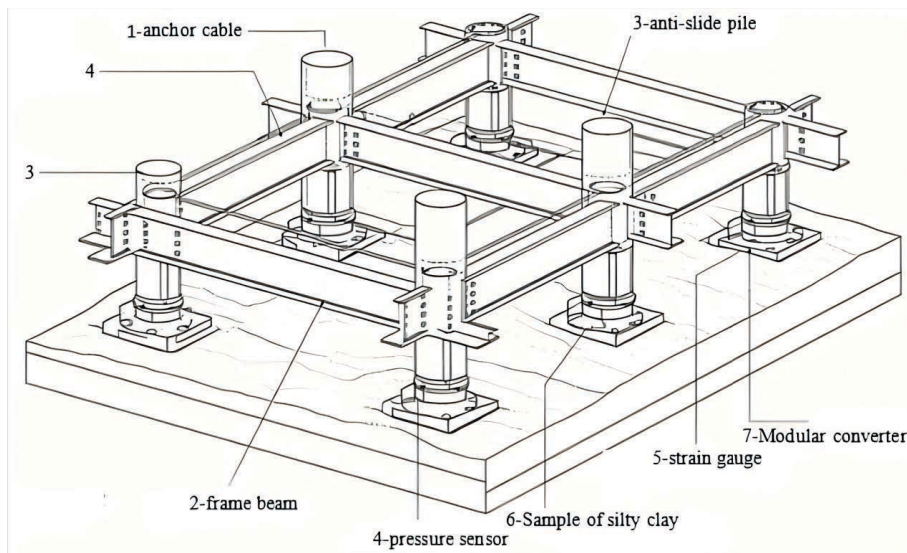


Figure 1. Three-dimensional schematic diagram of the scaled model of the joint reinforcement of the anchor frame and anti-slip pile

2.2. Analysis of dynamic transfer law

The experiment revealed that during the initial loading phase, the prestress in the anchor cables increased rapidly, with the concentrated area of pile-soil contact stress located in the middle to lower part of the pile,

approximately 1.5–2.0 meters from the pile top. At this time, the soil was in the elastic stage, with minor shear displacement at the interface, not exceeding 0.3 mm. The main load was borne by the anchor cables, with the anti-slide piles accounting for only 30%–35% of the load, indicating an unstable load distribution between the two ^[3]. When the load was between 100–200 kN, the growth rate of the anchor cable prestress began to slow down, while the prestress loss gradually increased, reaching a cumulative loss rate of 8%–12%. The pile-soil contact stress began to spread to the upper part of the pile, and the shear displacement at the interface increased significantly, reaching 0.3–0.8 mm. At this point, the soil had entered the plastic stage, with strong shear action at the interface, and a significant portion of the load began to be borne by the anti-slide piles, accounting for 70%–80% of the load, while the load borne by the anchor cables decreased significantly. However, the load distribution was relatively balanced. The basic load distribution proportions are shown in **Figure 2**. When the load exceeded 200 kN, the prestress in the anchor cables reached a stable state, with a prestress loss rate of 12%–15%. The pile-soil contact stress was uniformly distributed along the entire pile, and the shear displacement at the interface remained stable at 0.8–1.0 mm. The soil had entered the plastic yielding stage, with stable shear action at the interface. At this time, the loads borne by the anti-slide piles and anchor cables were of similar magnitude, both ranging from 45%–55%, and remained stable, indicating good collaborative load-bearing performance between the two. Time-effect analysis showed that as the loading time increased, the anchor cables experienced greater prestress loss, while the pile-soil contact stress initially increased and then stabilized. During the first 1–7 days of loading, the anchor cables exhibited the fastest rate of prestress loss, and the pile-soil contact stress also increased rapidly, with a daily growth rate of up to 3%–5%. After 7 days of loading, the rate of prestress loss began to slow down, and the pile-soil contact stress gradually reached a stable state. By 28 days of loading, the prestress loss rate stabilized at 15%–16%, and the fluctuation range of the pile-soil contact stress remained within 2% or less. This phenomenon occurred because the creep effect of the soil continuously reduced the shear strength at the interface, causing the load to gradually transfer from the anchor cables to the anti-slide piles, ultimately achieving a dynamic equilibrium ^[4].

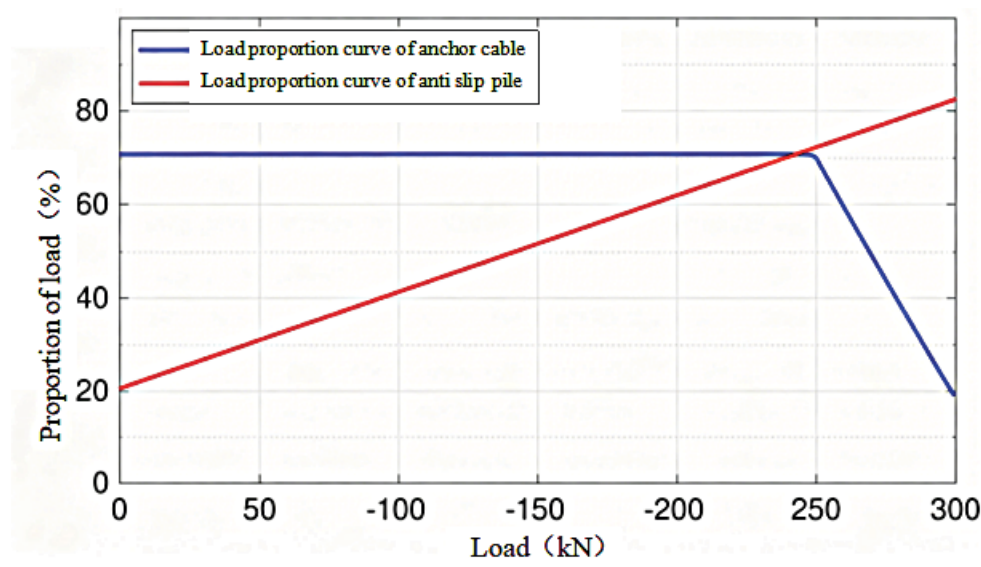


Figure 2. Comparison of load distribution between the anti-sliding pile and the anchor cable

2.3. Establishment of a dynamic load distribution model

Based on experimental data, and through comprehensive consideration of time effects and the shear interaction at the soil-structure interface, a dynamic load distribution model is constructed for the combined reinforcement system of anchor-cable frames and anti-slide piles ^[5]. The core parameters of this model include the loss rate of anchor cable prestress, pile-soil contact stress, interface shear displacement, and load-holding time. The relationship between load distribution ratio and time is fitted using an exponential function, with the basic model presented as follows.

$$\eta_1(t) = 0.68e^{-0.02t} + 0.32 \quad (1)$$

$$\eta_2(t) = 0.32(1 - e^{-0.02t}) + 0.18 \quad (2)$$

In the formula, $\eta_1(t)$ represents the proportion of load borne by the anchor cable; t represents the load holding time; $\eta_2(t)$ represents the proportion of load borne by the anti-slide pile. Through model validation, it is found that the error between the calculated and experimental values does not exceed 5%, and the goodness of fit can reach 0.96 or above, accurately reflecting the load distribution pattern under different load holding times. After incorporating the time effect factor, the prediction accuracy of the model will be further improved, enabling its use in dynamic prediction of engineering load distribution. In terms of load distribution impact, the greater the interface shear strength, the larger the proportion of load borne by the anchor cable. As the interface shear strength gradually decreases, the load will gradually transfer from the anchor cable to the anti-slide pile, thereby increasing the force on the anti-slide pile ^[6]. Therefore, during modeling, the interface shear strength and correction coefficient should also be reasonably introduced to further enhance its applicability.

3. Criteria for collaborative design of combined reinforcement with anchor cable frames and anti-slide piles

3.1. Analysis of the impact of soil heterogeneity

To clarify the impact of soil heterogeneity on the collaborative effect of anchor cables and anti-slide piles, this study selected three typical heterogeneous soil types, namely silty clay, sandy loam, and gravelly soil, and conducted experiments on their collaborative reinforcement effects. During the experiments, the basic parameters of the anchor cables and anti-slide piles were kept constant, while only the soil type was altered ^[7]. Monitoring continued according to the aforementioned plan until the system failed, with a focus on analyzing the impact pattern of soil properties on the collaborative effect. The experiments revealed that the heterogeneous nature of the soil directly affects collaborative failure. Silty clay, with an interface shear strength below 50 kPa, exhibits significant creep effects, causing long-term load deviation towards the anti-slide pile and ultimately leading to its premature failure. Sandy loam, with an interface shear strength between 50–100 kPa, maintains a balanced load distribution between the pile and anchor, allowing the entire system to fail collaboratively. Gravelly soil, with an interface shear strength above 100 kPa, bears most of the load on the anchor cable, which may fail first under long-term effects. Additionally, the stratified nature of the soil exacerbates the imbalance in pile-anchor loading, making local damage more likely.

3.2. Classification of collaborative failure modes

Based on experimental data and the heterogeneous characteristics of the soil, this study primarily classifies

the combined reinforcement system of anchor cable frames and anti-slide piles into three collaborative failure modes. The first mode is the premature failure of the anti-slide pile, triggered primarily by soil with high clay content, poor permeability, and significant creep effects. The main manifestations are overall cracking or breaking, with the anchor cable's bearing capacity not reaching its limit, and the system failure being dominated by the anti-slide pile. The second mode is the premature failure of the anchor cable frame, triggered mainly by coarse soil particles, strong permeability, and high interface shear strength. The main manifestations are anchor cable pullout or breakage, with the anti-slide pile's load-bearing role not being fully utilized, and the system failure being dominated by the anchor cable ^[8]. The third mode is a collaborative failure of both. Triggered by uniform soil properties and moderate interface shear strength, in this mode, the anchor cable and anti-slide pile fail simultaneously under ultimate bearing capacity.

3.3. Proposal of differentiated design criteria

For the three collaborative failure modes mentioned above, during the design process of the combined reinforcement system, designers can propose differentiated design criteria based on key indicators such as actual soil type, interface shear strength, and creep coefficient, combined with specific geological conditions. This will comprehensively clarify the three design directions of strong pile-weak anchor, strong anchor-weak pile, and balanced pile-anchor ^[9]. This approach ensures that different design plans are well-suited to specific geological conditions, thereby reasonably avoiding the risk of collaborative failure in the combined reinforcement system. The basic criteria and design points are shown in **Table 1**.

Table 1. Key points for differentiated design criteria of combined reinforcement plans for anchor cable frames and anti-slide piles based on different geological conditions

No.	Criterion Indicator	Strong Pile – Weak Anchor	Strong Anchor – Weak Pile	Balanced Pile-Anchor
1	Soil Type	Silty clay	Sandy loam	Gravelly soil
2	Interface Shear Strength (kPa)	< 50	50–100	> 100
3	Creep Coefficient	> 0.03	0.01–0.03	< 0.01
4	Collaborative Failure Mode	Pile fails first	Anchor fails first	Simultaneous pileanchor failure
5	Design Key Points	Appropriately increase the length and crossection of the antislides pile, enhance the pile strength, reduce the anchor prestress, and reasonably decrease the load transfer from the pile.	Optimize pileanchor parameters, ensure the ratio of anchor prestress to pile bearing capacity > 1 to achieve uniform load distribution.	Select highstrength anchors, appropriately increase anchor prestress and number, moderately reduce the crossection of the antislides pile, and achieve reasonable cost savings.

4. Long-term prediction of combined reinforcement with anchor cable frames and anti-slide piles

4.1. Fatigue crack propagation test under cyclic loading

To delve into the fatigue crack propagation behavior of anchor cable threads under cyclic loading conditions, this study selected the most representative threaded segment of the anchor cable as the test section. Made of high-strength steel, this segment was 100mm in length and featured a thread specification of M24×3. Fatigue crack propagation tests were conducted using an MTS fatigue testing machine, with a stress ratio set at 0.3,

a frequency controlled at 5Hz, and a maximum stress value of 1200MPa, cycling until fracture occurred in the threaded segment of the anchor cable. During the tests, the fatigue, crack initiation, and propagation processes of the threaded segment were observed in real-time using a microscope. Based on the observations, the relationships between crack length, propagation rate, and the number of cycles were recorded. Additionally, the specific stress distribution within the threaded segment was monitored. To clarify the impact of surface treatments on fatigue performance, this study conducted tests on four groups of threaded segments with different surface treatments: untreated, chrome-plated, zinc-plated, and shot-peened. Three specimens were tested for each group, and the average values were taken as the final test results for subsequent analysis, ensuring more reliable outcomes.

4.2. Analysis of fatigue crack propagation behavior

The tests revealed that, under cyclic loading conditions, the fatigue crack propagation characteristics of the anchor cable threaded segment could be divided into three stages. The first stage is crack initiation, occurring between 0–105 cycles, where cracks begin to appear in the stress concentration area at the root of the thread, with a length of 2mm or less and a relatively slow propagation rate of 1×10^{-7} m/cycle or less. The primary factor influencing crack propagation at this stage is stress concentration. The second stage is stable crack propagation, occurring between 105–109 cycles, where the crack length increases to approximately 2.0mm, and the propagation rate remains stable at 1×10^{-7} – 5×10^{-7} mm/cycle. Both stress concentration and material fatigue wear play dominant roles in this stage. The third stage is unstable crack propagation, occurring after more than 106 cycles, where the crack length exceeds 2.0mm and exhibits a tendency for rapid propagation, with a propagation rate exceeding 5×10^{-7} mm/cycle, ultimately leading to fracture of the thread. Additionally, the surface treatment method significantly affects the fatigue cracks of anchor cable threads. The tests found that, under shot-peening treatment, the crack initiation time can be extended by 30%–40% compared to the untreated condition, and the propagation rate can be reduced by 25%–30%, resulting in the longest fatigue life. Chrome-plating follows, then zinc-plating, with the untreated segment having the shortest fatigue life. Furthermore, time effect analysis revealed that, after 1–5 years of service, the fatigue performance of the anchor cable threaded segment begins to decline, with crack propagation increasing at an annual rate of 5%–8%, primarily due to environmental corrosion.

4.3. Life prediction model and anti-fatigue optimization measures

Based on the above test data, as well as time effects and fatigue crack propagation behavior, this study constructed the following life prediction model for the anchoring system.

$$N(t) = N_0 \cdot k \cdot e^{-0.07t} \quad (3)$$

Among them, $N(t)$ represents the fatigue life of the threaded section after years of service; N_0 represents the initial life; k represents the correction factor for thread surface treatment; and t represents the years of service. Verification shows that the error of this model is below 4%, with a goodness of fit reaching 97% or higher, indicating high prediction accuracy. Based on the prediction results of this model, in the design of combined reinforcement, designers can adopt the measures shown in **Table 2** to optimize the threaded section of anchor cables, thereby further extending their fatigue life and ensuring the long-term durability of the combined reinforcement structure ^[10].

Table 2. Optimization measures for fatigue resistance of anchor cable threads

No.	Optimization Measure	Main Function	Fatigue Life Extension
1	Shot peening of threaded section	Reduce stress concentration	30%–40%
2	Optimization of anti-corrosion coating	Improve anti-corrosion performance	20%–25%
3	Optimization of thread parameters	Reduce stress concentration	15%–20%

5. Conclusion

In summary, this paper takes the dynamic analysis of pile-soil contact stress as its foundation to analyze the load transfer law under the combined reinforcement state of anchor cable frames and anti-slide piles. Through experimental methods, it clarifies the dynamic load transfer law, reveals the main collaborative failure modes and fatigue characteristics of anchor cables, and proposes targeted optimization measures. This effectively addresses the challenges associated with the combined reinforcement of these two elements, providing scientific and technical references for subsequent applications in related engineering projects.

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Disclosure statement

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The Value of Construction Quality Management in Safety Risk Management

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Abstract: The construction industry is a pillar industry of the national economy. Its development quality and safety level are directly related to social public interests, personal life, and property safety, as well as the sustainable development of the industry. Focusing on the internal correlation between construction quality management and safety risk management, this paper analyzes the core value of quality management in safety risk management. Combined with the current development situation and practical pain points of the industry, it explores the specific application paths of integrating quality management into safety risk management. The research shows that systematic quality management is the foundation for building a solid safety risk defense line, which can realize advanced risk prediction, whole-process control, and source governance, and provide theoretical support and practical reference for the safe and high-quality development of the construction industry.

Keywords: Construction engineering; Quality management; Safety risk management; Risk prevention and control; Engineering construction

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1. Introduction

Construction projects are characterized by long construction cycles, multiple participating entities, complex operating environments, and diverse technical processes. Safety risks run through the entire life cycle from project initiation, design, construction, to completion and delivery. In recent years, the types of construction projects and safety accidents in China have continued to increase. New types of engineering, such as super high-rise buildings, deep foundation pits, prefabricated buildings, and large-span steel structures, have emerged continuously, making safety risks increasingly diversified and complex. Although the occurrence rate of safety accidents has decreased, major safety incidents still occur occasionally, causing serious casualties and economic losses.

As a core means to reduce the probability and loss of accidents, the effect of safety risk management is closely related to the level of quality management. Quality management is not only related to the physical

quality and service function of engineering projects, but also plays a key supporting role in the identification, assessment, control, and resolution of safety risks ^[1]. At present, some construction enterprises are faced with the disconnection between quality management and safety risk management. They value progress over quality, emphasize post-event remedy over pre-prevention, and rely on traditional experience rather than technical analysis, resulting in frequent potential safety hazards. Based on this, this paper deeply discusses the value and application paths of construction quality management in safety risk management, aiming to promote the coordinated development of quality and safety in the construction industry and lay a solid foundation for the healthy and stable development of the industry.

2. The value of construction quality management in safety risk management

2.1. Build a basic barrier for the source prevention and control of safety risks

The root causes of construction safety risks are often closely related to potential quality hazards. The core of quality management is to control the quality standards of all links from the source, so as to eliminate safety risks caused by quality problems fundamentally.

In the early stage of a project, quality management ensures that the design scheme complies with safety specifications and actual geological conditions by strictly reviewing the quality of survey and design documents, so as to avoid construction hidden dangers caused by design defects ^[2]. For example, in the design of a large-span steel structure convention center, if the wind load and temporary support stress state during construction are not fully considered in the design stage, local instability of the roof truss may occur during the assembly stage. With the intervention of quality management, the design calculation sheets and wind tunnel test data can be rechecked in a timely manner to find deviations in design load values, adjust the support layout scheme and hoisting sequence, so as to eliminate the collapse risk from the design source. The negligence of design quality will turn into major safety hazards during structural construction, which fully reflects the source control role of quality management.

In the construction stage, quality management requires construction personnel to operate in strict accordance with quality specifications and construction drawings, standardize the application standards of materials and equipment, and put an end to cutting corners and irregular operations ^[3]. Taking the core wall concrete construction of a super high-rise building as an example, due to the absence of material acceptance procedures, a batch of low-grade concrete was mistakenly used for the core wall. Quality management personnel discovered the problem in a timely manner through batch traceability and test block detection before pouring, avoiding potential safety hazards such as cracking and even the collapse of the core wall under wind load caused by insufficient concrete strength.

Quality management standardizes all quality links from the front end, moves the safety risk prevention threshold forward, achieves prevention before occurrence, and serves as the most fundamental and core guarantee for safety risk management.

2.2. Avoid safety risks caused by the schedule through quality inspection

In the process of project construction, quality, progress, and safety restrict and promote each other. At present, rushing the construction schedule has become a common phenomenon in the engineering industry, and the resulting hidden quality and safety hazards cannot be ignored. In this process, the investigation of potential quality hazards can often detect and avoid major hidden dangers in advance.

For instance, during the quality hazard investigation of a large bridge project, cracks were found on the newly cast box girder surface. Further analysis showed that the bridge girder erecting machine advanced too fast, and construction loads were applied before the concrete strength reached the standard, resulting in structural cracking. If allowed to develop further, the consequences would be unimaginable. Through this quality hazard investigation, the project attached importance to the progress control of key nodes, curbed the further development of risks in a timely manner, and avoided major safety accidents and property losses.

2.3. Improve the accuracy of safety risk identification and assessment

The primary step of safety risk management is to accurately identify various risk factors throughout the engineering life cycle and scientifically assess their probability and impact degree. Quality management provides systematic methods and data support for risk identification and assessment.

In construction engineering, quality inspection reports, hidden danger rectification records, construction logs, and other materials formed in the quality control process are direct bases reflecting the risk status of each link. By analyzing and sorting out these quality data, managers can accurately locate high-risk points and weak links ^[4]. For example, during the construction of a sea-crossing bridge, the quality management team can count the detection data of the reinforcement cover thickness of prefabricated box girder segments, find the over-limit deviation rate of the cover thickness of some segments, and evaluate long-term safety risks such as steel corrosion and reduced structural bearing capacity caused by such quality defects in combination with the chloride erosion risk in the marine environment. Thus, the formwork reinforcement process and spacer spacing can be adjusted in a timely manner to effectively control the over-limit rate, forming a closed loop from quality data to accurate safety risk assessment and effective control.

At the same time, tools such as the PDCA cycle and quality risk matrix in the quality management system can be combined with safety risk management methods to build a joint quality and safety risk assessment model and realize quantitative risk analysis ^[5]. Accurate risk identification and assessment are the premise of safety risk management. With rich quality data and professional control methods, quality management significantly improves the comprehensiveness and scientificity of risk identification and assessment, and prevents errors caused by cognitive deviation.

2.4. Strengthen the execution of safety risk whole-process control

The construction process is dynamically changing, and safety risks evolve with the change of working procedures and environmental conditions. Quality management itself is a continuous control activity running through the whole construction process, which can promote the implementation of safety risk control requirements in every procedure and every operation link.

Quality management establishes hierarchical quality inspection, on-site supervision, and procedure handover acceptance systems. The previous procedure can only start the next one after passing quality acceptance. This control mechanism naturally realizes the safety risk investigation of each operation and avoids the accumulation of unqualified procedures into hidden dangers ^[6]. For example, in the construction of a deep foundation pit support, after each layer of soil nailing anchorage operation, quality inspection must be carried out on anchor pulling force, soil nail spacing, and shotcrete thickness. The next layer of earthwork excavation can only be carried out after passing the inspection. This process control not only ensures the construction quality of the support structure, but also investigates the foundation collapse risk caused by

insufficient support strength in a timely manner, promoting the synchronous implementation of safety control with the construction progress ^[7].

At the same time, quality management can further clarify the quality control responsibilities of each post, force operators and managers to strictly abide by safety operation specifications, reduce safety risks caused by irregular operations, avoid the suspension of safety risk control responsibilities and formalistic control, and effectively improve the execution of process risk control.

2.5. Optimize the efficiency of safety risk emergency disposal

Safety risk prevention cannot completely eliminate sudden safety accidents, and efficient emergency disposal is the key to reducing losses. Quality management provides a complete plan, system, and resource guarantee for emergency disposal.

Quality management requires construction enterprises to formulate targeted emergency plans combined with engineering quality characteristics and risk conditions, and quality emergency plans can be directly transformed into the core content of safety emergency disposal plans ^[8]. For example, in the construction of subway shield tunnels passing through old building clusters, the quality management team can formulate special emergency plans for segment assembly quality, clarifying the emergency disposal process and material reserve for segment damage, dislocation over-limit, and water leakage.

For example, during shield tunneling, in case of sudden geological changes leading to local segment damage and excessive surface settlement, the project shall activate the quality emergency plan in a timely manner, and carry out surface grouting reinforcement and segment support in accordance with the grouting ratio, reinforcement scope, and personnel deployment process specified in the plan, so as to avoid building cracking and collapse accidents. At the same time, the emergency disposal experience accumulated in quality management can provide practical reference for safety accident disposal.

3. Application paths of construction quality management in safety risk management

3.1. Build an integrated control system integrating quality and safety

To realize the in-depth integration of quality management and safety risk management, it is necessary to break the barrier between them and build an integrated control system.

First, construction enterprises shall establish a unified organizational structure, set up a quality and safety management committee, coordinate quality and safety management work, clarify the quality and safety responsibilities of all departments and posts, and form a working pattern of full participation and joint management.

Second, formulate integrated control specifications, integrate safety risk prevention requirements into various quality management standards, and include safety risk prevention indicators in quality acceptance standards, construction specifications, and inspection procedures ^[9]. For example, in the construction of large stadium steel structure roofs, enterprises shall deeply integrate weld quality inspection with structural safety assessment. On the basis of conventional ultrasonic testing for all Class I welds, phased array ultrasonic and magnetic particle double inspection shall be carried out, and weld defect types shall be associated with structural stress analysis results, so as to establish a weld defect and structural safety risk grading evaluation system, making quality acceptance results directly serve structural safety risk assessment and control ^[10].

Finally, establish a collaborative assessment mechanism for quality and safety, incorporate the effect of safety risk management into the quality management assessment system, and include the rectification of quality hidden dangers into safety risk assessment, forcing all construction parties to implement quality safety responsibilities through assessment.

3.2. Empower quality and risk control with digital technology

With the accelerated digital transformation of the construction industry, digital means such as big data, Internet of Things, and BIM can realize the intelligent upgrading of engineering quality and safety management, and improve management efficiency and accuracy.

On the one hand, BIM is adopted to establish a 3D building information model, integrating information of design, construction, materials, and equipment, so as to realize visual control of engineering quality ^[11]. For example, in a super high-rise building, the construction party uses BIM to simulate the collision between steel bars and section steel in complex nodes. It is found that there are many position conflicts between steel bars and steel connection plates in the core area. If constructed according to the original plan, the steel bars cannot be fixed as required, affecting the seismic performance and overall safety of the building. After BIM collision detection and design optimization, the node form and steel layout are adjusted to avoid rework and eliminate potential safety hazards.

On the other hand, develop a digital quality and safety management system integrating quality inspection, hidden danger handling, risk early warning, and data analysis, realizing real-time information sharing and dynamic tracking ^[12]. During the catwalk erection of a river-crossing suspension bridge, Internet of Things sensors can be used to obtain the stress of load-bearing cables, anchorage displacement, and ambient wind speed. By comparing and analyzing the initial tension and cable bolt torque recorded during quality acceptance, the risk of cable force decline can be judged. Once a problem is found, an alarm will be issued immediately with corresponding tension suggestions to prevent catwalk collapse accidents ^[13].

3.3. Strengthen whole-life collaborative control of quality and risk

The whole life cycle of construction engineering includes preliminary decision-making, design, construction, acceptance and delivery, as well as operation and maintenance. Quality management and safety management interact and restrict each other throughout the whole process, requiring integrated whole-process management.

In the preliminary decision-making and design stage, quality management focuses on the quality of survey and design documents, organizing experts to evaluate the safety risks of the design scheme ^[14]. For example, in the design of high-pier and long-span continuous rigid frame bridges in mountainous expressways, quality management institutions shall first carefully review geological survey data. If problems are found in the bridge location, additional surveys and special seismic demonstrations shall be added to optimize the pier position and structural form, deepen pile foundation length, and install energy dissipation bearings to reduce safety risks.

During the construction period, focus on the quality and safety control of key parts and high-risk links, implement on-site supervision and special inspection systems, and strengthen the safety management of deep foundation pits, high formwork supports, large-area steel structure hoisting, high-pier pouring, and other high-risk projects ^[15]. For example, during the cable hoisting construction of large-span concrete-filled steel

tube arch bridges, the quality management team tracks the wear detection of steel cables, rebound detection of anchorage concrete, and flaw detection of buckle tower welds throughout the process, dynamically evaluates the safety state of the hoisting system through quality data, and ensures that the safety redundancy of the cable system meets the maximum lifting working condition.

In the stage of completion, delivery, operation, and maintenance, establish a regular quality and safety inspection system, regularly check the quality status of engineering facilities, timely discover and handle quality and hidden safety hazards in the operation process, and extend the service life of the project to reduce safety risks in the operation and maintenance stage.

4. Conclusion

Construction quality management and safety risk management are complementary and inseparable. Quality management is the foundation and core of safety risk management, while safety risk management is the goal and extension of quality management.

From the construction instability caused by deviation of design load value of large-span steel structures, to structural hidden dangers caused by insufficient concrete strength of super high-rise core walls, to collapse risks caused by defective high formwork erection, and seismic design changes caused by negligence in geological survey, every engineering case reveals the internal causal relationship between quality defects and safety accidents.

Further exploring the core value of quality management in source prevention, accurate assessment, whole-process control and emergency disposal, and adopting application paths such as building integrated control system, empowering with digital technology and implementing whole-life collaborative control can effectively solve the disconnection between quality and safety management, improve the overall efficiency of safety risk management, and promote the coordinated high-quality development of the construction industry, providing solid support for national economic development and social public safety.

Disclosure statement

The author declares no conflict of interest.

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Research on Systematic Investigation and Multi-dimensional Treatment of Tunnel Diseases in the Sichuan-Xizang Highway Tunnel

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Abstract: In this paper, the typical diseases of 17 tunnels in the Zhubalong to Dongjiu section of the Sichuan-Xizang Highway on the National Highway 318 were systematically investigated and analyzed in depth. The investigation results show that the tunnel diseases mainly include the hollowing out of the foundation of the riverside side of the open-cut tunnel, the leakage of the lining (point, line, surface, and construction joint seepage), the lining cracks, the pavement cracks and seepage, and the blockage of the drainage system. Based on the causes of the disease, this paper proposes a multi-dimensional treatment design scheme covering the hole, lining, pavement, and drainage system. It is verified by field implementation that the proposed treatment measures effectively control the development of the disease, significantly improve the operation status of the tunnel, and achieve good engineering results. This study provides valuable engineering practice experience and reference for the accurate diagnosis and efficient treatment of tunnel diseases under similar complex geological conditions of the Sichuan-Xizang Highway.

Keywords: National highway 318 line; Sichuan-Xizang Highway; Tunnel disease; Multi-dimensional treatment; Engineering practice

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1. Introduction

As a key node of highway traffic, the operation safety and durability of tunnels are very important. However, under complex geological and climatic conditions, tunnel diseases occur frequently, which seriously affect traffic safety and structural stability. The geological and hydrological conditions of the Zhubalong to Dongjiu section of the Sichuan-Xizang Highway on the National Highway 318 are complex, which makes the tunnel disease problem in this area particularly prominent. Therefore, it is urgent to carry out systematic investigations, in-depth analyses, and put forward effective treatment schemes for tunnel diseases in this area to ensure the smooth and safe operation of highways.

According to the inspection results, the current tunnel diseases are mainly reflected in the damage of the portal, the damage of the lining structure, the leakage of the lining, the leakage of the pavement, and so on. In view of the hollowing out of the bottom of the foundation of the open-cut tunnel, Zhu Chang'an et al. proposed the use of an anti-erosion pile foundation, and reserved the channel for debris flow, which can avoid the tunnel foundation being hollowed out and lead to overall instability ^[1]. In view of the lining structure disease, Wang Yunshan put forward different treatment methods, such as crack repair glue, riding crack grouting, chiseling, and filling slurry for cracks of different widths ^[2]. According to the degree of tunnel crack damage, Yang Chaoshuai et al. proposed measures such as steel fiber reinforced concrete reinforcement, steel strip reinforcement, and crack grouting reinforcement ^[3]. Song et al. studied the repair materials of concrete structures ^[4]. The study found that cement-based materials have good mechanical properties and good compatibility with the concrete matrix, and polymer-modified materials show lower shrinkage and higher flexural strength, which provides a basis for the selection of crack treatment materials.

For tunnel leakage, He proposed the combination of water plugging and drainage in the tunnel, using polyurethane water plugging and an open stainless steel drainage box to connect water ^[5]. Yan et al. reviewed the new achievements of polymer grouting materials in the treatment of tunnel leakage, introduced the properties and applications of various modified polyurethane and epoxy resin grouting materials, and Kong evaluated the application effect of cement-based anti-seepage coatings in highway tunnels ^[6-7].

Pavement seepage is usually caused by the blockage of tunnel drainage facilities. Zhu et al. proposed to avoid the accumulation of water in the lower part of the road to the central ditch by setting up vertical collecting wells and horizontal drainage blind ditches ^[8]. Through field investigation and sampling analysis, Ma et al. revealed the mechanism of crystallization blockage in the tunnel drainage system, and put forward treatment measures such as increasing side wall drainage holes and well point dewatering holes, and changing drainage ditches to open ditches according to the characteristics of diseases ^[9]. These studies provide important theoretical and technical support for tunnel disease treatment.

However, the existing research mostly focuses on the treatment technology of a single disease, and lacks the “whole chain” research and practical verification of the systematic and comprehensive investigation, cause analysis, and treatment scheme of tunnel diseases under the extremely complex geological and climatic conditions of the Sichuan-Xizang Highway. The purpose of this paper is to form a closed loop of demonstration through the following aspects based on the disease treatment project of Zhubalong to Dongjiu section of Sichuan-Xizang Highway on National Highway 318: Firstly, the disease types and distribution of 17 tunnels in this section are systematically investigated. Secondly, the formation mechanism of various diseases is deeply analyzed, and a set of targeted and operable treatment design schemes is proposed based on the causes of diseases. Finally, the effectiveness of the proposed scheme is verified by the preliminary feedback of field implementation. The results of this study not only provide technical support for the project, but also hope to provide valuable reference experience for the accurate diagnosis and efficient treatment of tunnel diseases in similar complex environments.

2. Project profile

The tunnel site area belongs to the plateau monsoon climate, which has the climatic characteristics of high cold, rainy, and snowy, and is an important cause of tunnel diseases. There are 17 tunnels in the range of

Zhubalong to Dongjiu section of Sichuan-Xizang Highway on National Highway 318, which need to be treated (including 5 dark hole structures, 11 open hole structures, and 1 shed hole structure). Through field investigation, it is found that the main diseases of the tunnel are hollowing out at the bottom of the foundation of the open hole, lining leakage, lining cracks, pavement cracks, pavement seepage, drainage ditch blockage, and water accumulation. The tunnel site disease is shown in **Figure 1**.



(a) The bottom of the foundation of the portal is hollowed out



(b) Water seepage marks on the lining surface



(c) Inspection of well water accumulation



(d) Pavement seepage

Figure 1. Tunnel disease scene photos

3. Disease analysis

3.1. Cause analysis of hole disease

The main disease at the entrance of the tunnel is the hollowing out of the bottom of the foundation on the riverside side of the open-cut tunnel. The causes are complex, mainly including: (1) Hydraulic erosion: the large amount of sediment carried by the river in the flood season and the continuous erosion of the foundation lead to the gradual hollowing out of the bottom of the foundation. (2) Construction quality defects: the base cleaning is not complete, and the degree of compaction is insufficient. (3) Insufficient design consideration: The design specification of the highway tunnel clearly stipulates the structural design of the tunnel portal^[10]. In the design stage of foundation structure, if the local complex hydrogeological conditions, extreme water flow scouring force, or insufficient foundation depth are not fully considered, the foundation itself will not have enough ability to resist scouring, which will induce the phenomenon of bottom hollowing. In summary, the treatment scheme of the hole disease should be based on the enhancement of the anti-scouring ability and structural stability of the foundation, which provides a theoretical basis for the subsequent design of the anti-scouring wall and the stone lead cage.

3.2. Cause analysis of lining disease

Lining diseases mainly include water leakage and cracks. The causes of lining leakage are as follows: (1) Abundant groundwater and permeability of surrounding rock: the development of joints and fissures in the surrounding rock of the tunnel site, the large amount of ice and snow melt water and atmospheric precipitation recharge, resulting in increased leakage; (2) Failure of waterproof system: the tunnel waterproof layer is damaged or aged, so that the groundwater bypasses the waterproof layer and directly enters the back of the secondary lining; (3) Blockage of drainage system: if the drainage system inside the tunnel accumulates water behind the lining due to sediment deposition or freezing, forming water pressure, forcing groundwater to seep from the weak parts of the lining or construction joints, and may cause water accumulation in the inspection wells. Therefore, the treatment strategy of lining leakage water needs to comprehensively consider blocking the water source, repairing the waterproof layer, and ensuring smooth drainage, which provides a design basis for subsequent measures such as grouting, painting waterproof coating, and drilling and drainage for different leakage types.

Causes of lining cracks: (1) Complex geological conditions and foundation deformation: uneven soft and hard surrounding rock, faults, or weak interlayers lead to uneven settlement. This foundation deformation will generate additional stress in the lining structure. When the stress exceeds the tensile strength of the concrete, cracks will be formed. (2) The effect of mountain bias: an asymmetric mountain leads to an asymmetric distribution of surrounding rock pressure, and the formation of mountain bias leads to uneven stress of the lining structure, resulting in eccentric load, which in turn leads to local stress concentration, resulting in lining cracking and even structural damage. (3) Construction quality defects: the backfill behind the lining is not dense, or the pouring thickness is insufficient. Under the action of external load, these weak areas are prone to stress concentration, resulting in cracking. In view of the complexity and diversity of the causes of lining cracks, the treatment scheme should take targeted measures according to the type, width, depth, and specific causes of cracks, so as to effectively restore the integrity and durability of the lining structure.

3.3. Cause analysis of pavement disease

Pavement diseases mainly include pavement cracks and pavement seepage. The causes of pavement cracks are as follows: repeated traffic loads lead to fatigue failure of pavement structure, and internal damage accumulation of materials forms through cracks; temperature shrinkage stress aggravates crack development. The treatment needs to close the cracks and prevent water vapor intrusion.

The causes of pavement seepage are as follows: (1) Groundwater upwelling: groundwater upwelling seeps through construction joints or weak parts of cracks; (2) Pavement structure defects: pavement concrete segregation, insufficient vibration to form honeycomb holes, providing a channel for groundwater or surface water to penetrate the pavement; (3) Drainage system failure: improper design or failure of drainage facilities, resulting in the accumulation of water under the road cannot be discharged in time. Therefore, the treatment scheme should comprehensively consider cutting off the water source, repairing the pavement structure defects, and ensuring the smooth drainage system, so as to achieve a complete solution to the problem of pavement seepage.

3.4. Analysis of the causes of drainage system diseases

The main diseases of the tunnel drainage system are drainage ditch blockage and water accumulation. The

main causes include: (1) Design and construction defects, the slope of the drainage pipe is not consistent with the longitudinal slope of the tunnel, which leads to siltation; (2) Sediment and mineral deposition: long-term deposition of sediment minerals narrows the pipeline section; (3) Waterproof system failure and flow around: The failure of the waterproof system leads to the flow of groundwater carrying sediment into the pipeline. Therefore, the treatment plan should focus on regular dredging, optimizing the drainage slope, and checking and repairing the waterproof system to ensure the normal operation of the drainage function.

4. Treatment design for disease

4.1. Treatment of hole disease

In view of the hollowing out of the bottom of the foundation at the riverside side of the open-cut tunnel, the treatment is carried out by adding an anti-scour wall and a block stone lead wire cage.

The specific construction process is as follows: (1) Cofferdam: construction in dry season, 7 m extension along the direction of the river as the cofferdam, using sandbags to fill, height of 1.5 m, select the site sand as filling material; (2) Excavation foundation: after the cofferdam, clean up the bottom of the mud, along the foundation around the deepening of the excavation, the foundation width of 50cm, the depth of the original foundation according to the above 1m, 3m below or into the riverbed at the bottom of the bedrock is not less than 0.5m control. (3) Wall pouring: then use C25 concrete to pour the wall, and backfill the cavity area at the bottom of the foundation of the open-cut tunnel; (4) Lead wire cage enclosure: Finally, a ring of stone lead wire cage enclosure is placed along the outer side of the scouring wall. The size of the lead wire cage is $1 \times 1 \times 1.5$ m (length $\times$ width $\times$ height), the diameter of the wire cage is 6cm, and the diameter of the wire is 2.5 mm, so as to reduce the scouring effect of the river water on the bottom of the scouring wall.

At present, there is an obvious suspension in the section of the open-cut tunnel. It is suggested that the settlement monitoring of the end wall of the open-cut tunnel should be carried out before construction. If there are abnormal conditions, traffic control should be carried out in time to ensure the safety of driving. The design of the hollowing treatment at the bottom of the foundation of the open-cut tunnel is shown in **Figure 2**.

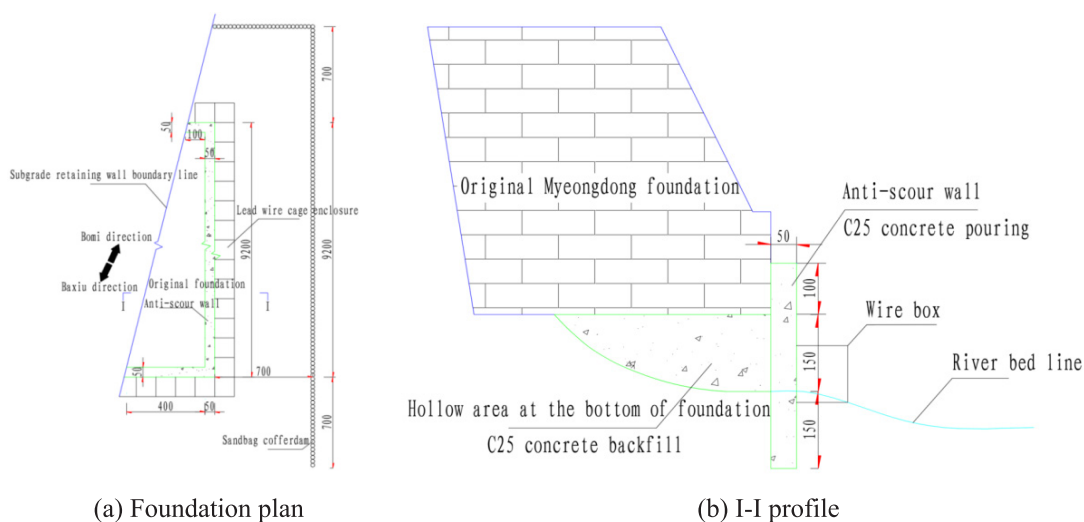


Figure 2. Design drawing of hollowing treatment at the bottom of the open-cut tunnel foundation

4.2.1. Lining leakage water treatment

(1) Point seepage treatment: Drilling (14 mm, 20cm deep), pressure injection, polyurethane grouting material. The treatment construction sequence is to find the water leakage point → drilling → high-pressure air cleaning hole → use the sealing glue to install the grouting nozzle → pressure grouting material → remove the grouting nozzle. The design of point seepage treatment is shown in **Figure 3**.

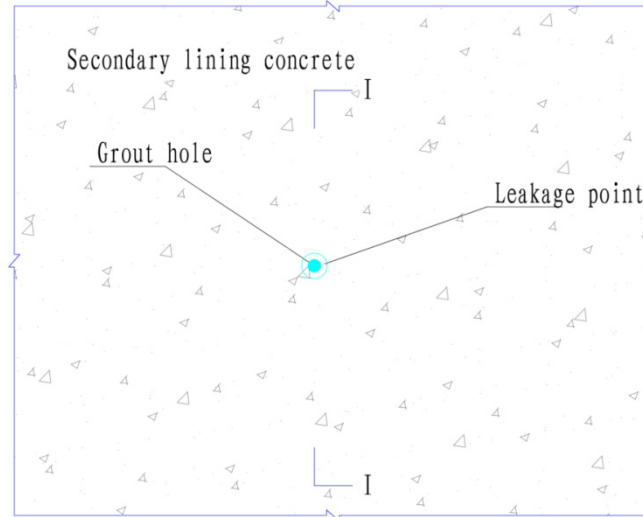


Figure 3. Design of point seepage treatment

(2) Seam seepage treatment: Drilling (14 mm, 20 cm deep, spacing 30 cm), pressure injection of polyurethane grouting material, and then brushing sealing glue, brushing cement-based permeable crystalline waterproof coating.

The construction sequence of the treatment is to find leakage water cracks → drilling → high-pressure air cleaning → grouting → removing the glue nozzle → cleaning the surface → painting waterproof coating. The design of the seam seepage treatment is shown in **Figure 4**.

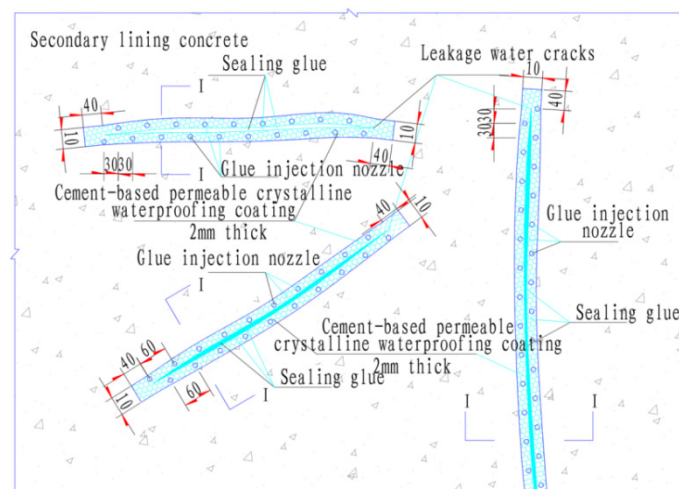


Figure 4. Design of slit seepage treatment

- (3) Surface seepage treatment: Drilling (plum-shaped arrangement, spacing of 50 cm, 14 mm, depth of 20 cm), pressure injection of polyurethane grouting material, coated with cement-based permeable crystalline waterproof coating (coating area expanded by 20 cm). The construction sequence of the treatment is the same as above. The surface seepage treatment design is shown in **Figure 5**.

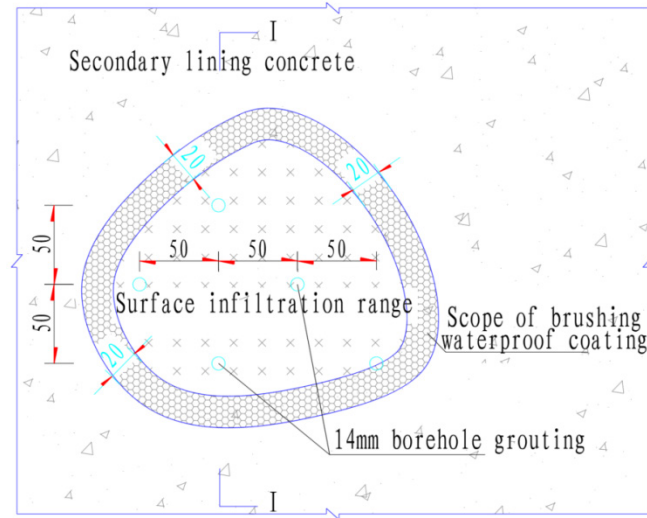


Figure 5. Plane seepage treatment design

- (4) Side wall drilling drainage treatment of the serious seepage section: For the serious water seepage section, after drilling holes into the lining at the foot of the lining side wall, the groove is drilled, and the buried pipe is used for drainage. The main construction steps are as follows: determining the section → drilling the side wall foot ($\phi 60$ mm, 1.5 m long, 1 m deep into the surrounding rock) → drilling the inner side wall of the cable trench, burying the $\phi 50$ mm drainage steel wire hose → connecting with the pre-buried drainage pipe or the side trench. The design of the side wall foot drilling drainage treatment is shown in **Figure 6**.

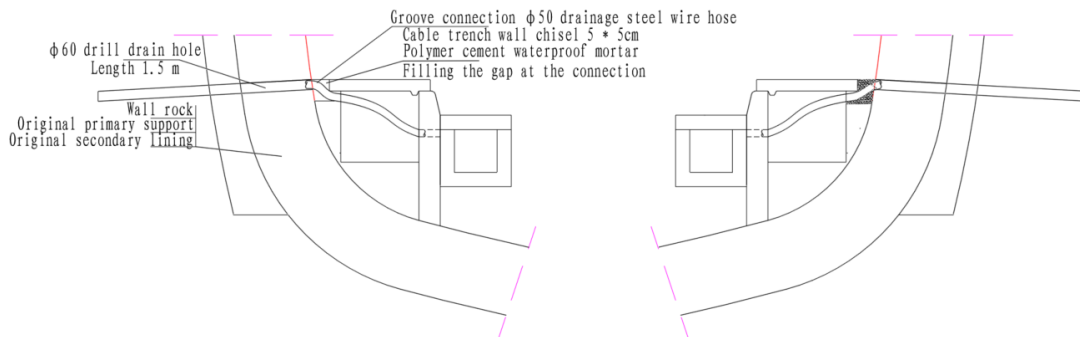


Figure 6. Design drawing of the side wall foot drilling drainage treatment

4.2.2. Treatment of lining cracks

Using surface sealing method: (1) Observe the crack state; (2) Base treatment-clearing dust and oil, steel wire brush cleaning debris, acetone cleaning; (3) Brush crack sealant, width 5 cm, thickness not less than 2 mm.

4.3. Pavement disease treatment

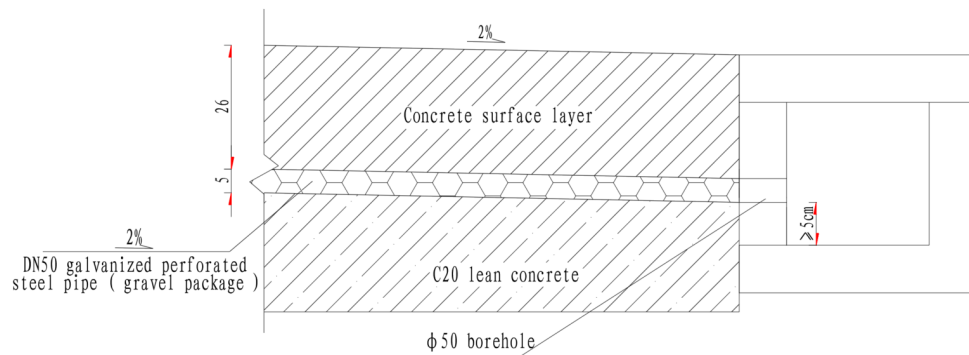
4.3.1. Pavement crack treatment

For the slightly cracked sections of the pavement, the cracks are treated by filling and closing. The surface sealing construction technology of pavement cracks is as follows: (1) Remove the loose crack edge; (2) remove debris and dust in the seam; (3) fill the seam with epoxy resin and tamping; (4) flatten the repaired surface.

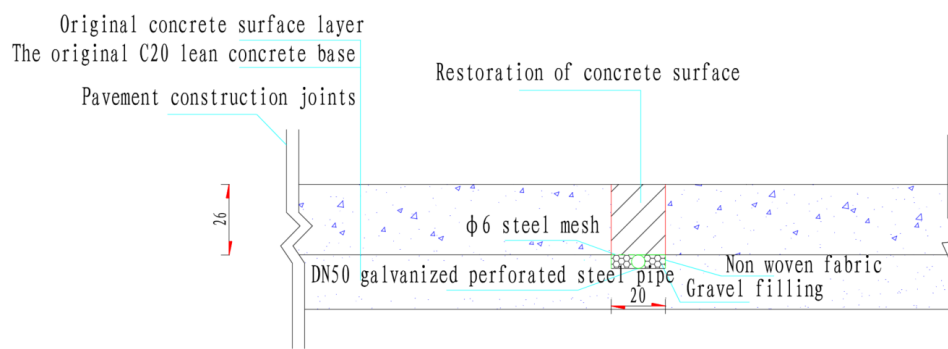
4.3.2. Pavement seepage treatment

In view of the seepage situation of the tunnel pavement, the method of chiseling the buried pipe to introduce seepage into the side ditch is adopted for treatment.

The specific measures are as follows: (1) grooving 20 cm × 31 cm (to the pavement base); (2) DN50 mm drainage pipe is laid at the bottom of the groove, the slope is 2%, and the distance between the bottom of the pipe and the bottom of the side ditch is not less than 5 cm; (3) gravel cover, wrapped seepage geotextile anti-blocking, above the $\Phi 6$ mm steel mesh (spacing 5 cm×5 cm, width 20 cm); (4) Drilling $\phi 50$ mm connected side ditch at the side ditch; (5) C35 concrete to restore the road. The design of pavement seepage treatment is shown in **Figure 7**.



(a) Large sample drawing of drainage pipe leading into side ditch



(b) Drainage pipe into the side ditch section diagram

Figure 7. Design drawing of pavement seepage treatment

4.4. Treatment of drainage system diseases

(1) Treatment of road drainage ditch blockage: The treatment is carried out by manual cleaning and

dredging.

- (2) Treatment of blockage of the central drainage ditch and transverse drainage blind pipe: The combined pipeline is used to dredge the high-pressure flushing of the sewage suction vehicle, and the electric dredger is rotated and inserted into the open pipeline; the cable wearer pulls the sediment back and forth, and dredges it repeatedly until it is completely unblocked.
- (3) Vertical drainage pipe inspection and well drilling water diversion treatment: First, try to dredge the transverse diversion pipe; if it cannot be dredged, a hole is drilled between the inspection well and the cable trench, and the side trench is connected with a hose (if there is a pre-buried drain pipe, it is connected, otherwise the hole is led to the side trench). The design of vertical drainage pipe inspection and well water treatment is shown in **Figure 8**.

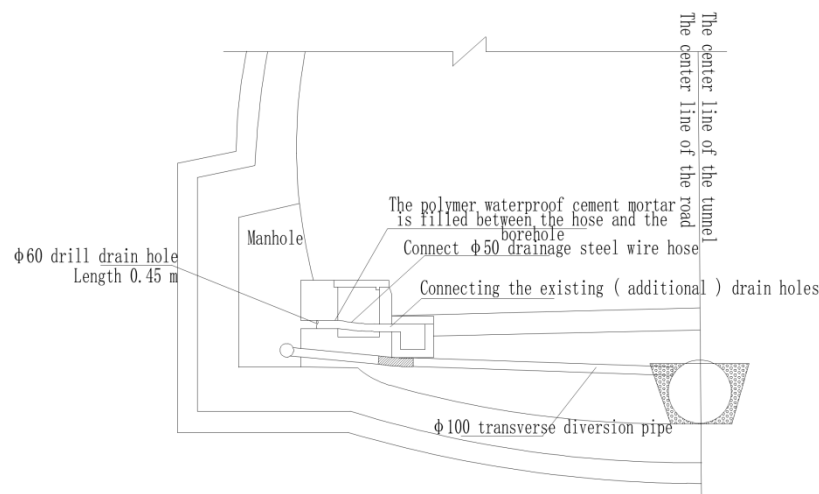


Figure 8. Design drawing of vertical drainage pipe inspection and well water treatment

5. Discussion and outlook

In this paper, the systematic investigation, cause analysis, and treatment design of the tunnel diseases from Zhubalong to Dongjiu section of Sichuan-Xizang Highway 318 are carried out. The field implementation shows that the treatment measures have achieved good engineering results and effectively controlled the development of the disease.

At present, the evaluation of treatment effect is mainly based on on-site qualitative observation and short-term feedback. There is a lack of long-term quantitative monitoring data (water seepage, crack width change, structural settlement, etc.), and quantitative demonstration has limitations. This is also the direction that future research needs to focus on. In order to further improve this study, future work will focus on the following aspects:

- (1) Establish a long-term monitoring system: sensors are arranged in the treatment area to monitor the key indicators such as water seepage, lining deformation, and pavement condition for a long time and continuously, and obtain quantitative data;
- (2) Quantitative evaluation of treatment effects: Based on long-term monitoring data, statistical methods and engineering evaluation models were used to scientifically evaluate the long-term effectiveness and

durability of different treatment measures.

- (3) Promotion, application, and experience summary: The experience of this study is extended to tunnel projects in Sichuan-Xizang Highway and other similar areas to form a more universal disease treatment guide. Through the above efforts, it is expected to form a complete closed loop from disease diagnosis, treatment design, implementation, to effect evaluation and feedback, and provide a more solid scientific basis for the long-term safe operation of tunnel engineering.

6. Conclusion

In this paper, a complete demonstration chain of disease investigation-cause analysis-treatment design-preliminary effect verification is constructed for 17 tunnels in the Zhubalong to Dongjiu section of the Sichuan-Xizang Highway on Line 318. The main conclusions are as follows:

- (1) Systematic investigation identified the types of diseases: open-cut tunnel foundation hollowing, lining leakage (point, linear, planar, and construction joint leakage), lining cracks, pavement cracks and leakage, drainage ditch blockage, etc.
- (2) Disease mechanism: the hollowing out of the open cut tunnel foundation is related to river erosion, improper construction, and insufficient design; the leakage of lining is related to the joint of surrounding rock, waterproof damage, and drainage blockage. Lining cracks are related to geological conditions, mountain bias, and construction defects.
- (3) A multi-dimensional treatment design scheme covering the hole, lining, pavement, and drainage system is proposed. The effectiveness is verified by field implementation, which significantly improves the disease condition and shows a good engineering effect. It provides practical experience and technical reference for the treatment of tunnel diseases in the Sichuan-Xizang highway and similar complex geological environments, and initially forms a closed loop from problem discovery to disposal scheme implementation.

Disclosure statement

The authors declare no conflict of interest.

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Research on Comprehensive Treatment Technology of High Fill and Deep Excavation Special Subgrade of Mountain Highway

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Abstract: The terrain of mountainous areas is high and undulating. This leads to high filling and deep excavation in the construction of mountain roads. The quality and safety risk of high fill and deep excavation construction is greater. If the construction treatment or subsequent treatment is improper, it is very easy to cause engineering diseases. Based on this, this paper takes the characteristics of high fill and deep excavation special subgrade projects in mountainous areas as the breakthrough point to explore the particularity of the project. Then, from the perspective of the disease mechanism of high fill and deep excavation subgrade, this paper analyzes the internal logic of common diseases such as subgrade settlement deformation, slope instability, damage, and destruction. Finally, the paper summarizes the key technologies for the treatment of high fill and deep excavation special subgrade in mountainous areas, and the disease problems and mechanism of anchored high fill and deep excavation subgrade. And it explores the effective disease treatment technology to ensure the high-quality development of Highway Engineering in mountainous areas.

Keywords: Mountain highway; Special subgrade with high filling and deep excavation; Compaction reinforcement technology; Slope reinforcement treatment

Online publication: July 10, 2026

1. Introduction

Against the background of the continuous expansion of China's highway network, the construction projects of mountain roads are increasing. However, due to the undulating terrain, complex terrain structure, and serious and deep weathering of the rock and soil layer in the mountain area, the construction of highway subgrade is more difficult. In order to ensure the safety of highway construction, the subgrade construction needs to adopt the special construction technology of high filling and deep excavation^[1]. But the scope of earth excavation and filling construction in this construction process is too large. So the disturbance to the soil is serious, and it will inevitably have a huge and far-reaching impact on the stress of the soil, and

then lead to the subgrade disease in the operation of subsequent projects. Moreover, through the statistics of subgrade diseases of highways in mountainous areas, it can be found that the proportion of high fill and deep excavation subgrade diseases is significantly higher (accounting for 78.2%), and the treatment is more difficult. This makes the traditional plain highway subgrade treatment technology unable to meet its treatment needs. Therefore, construction enterprises should explore accurate and efficient treatment technologies in combination with the characteristics of high fill and deep excavation subgrade engineering of mountain highway, so as to improve the stability of high fill and deep excavation subgrade.

2. Characteristics of high filling and deep excavation subgrade engineering in mountainous areas

Due to the influence of geographical location, the terrain difference of high filling and deep excavation subgrade in a mountainous area is large. Moreover, the geotechnical types are complex (refer to **Table 1** for details), which leads to uneven distribution of subgrade stress. Therefore, in order to ensure the quality of highway construction, it is necessary to adopt the method of high filling and deep excavation to ensure the stability of the highway structure. This leads to excessive subgrade filling height (>20m) and excessive excavation depth (more than 15 m). This construction mode will inevitably increase the self-weight of the filled soil, and then increase the stress of the subgrade ^[2]. At the same time, slope excavation will affect the soil structure, causing soil structure deformation and increasing the risk of slope instability. The soil structure in mountainous areas is also complex, and most of the filling soil is mainly a soil-rock mixture. The uneven size and structure of soil and rock particles not only easily cause the problem of large soil porosity, but also increase the risk of rainwater infiltration, thus increasing the probability of consolidation settlement. In addition, the rainfall in mountainous areas is relatively large, and the long-term scouring and soaking of the basement by rainwater can easily lead to soil softening, further increasing the risk of slope instability. Due to the limited space of highway construction sites in mountainous areas, it is also difficult to carry out some construction technologies. Furthermore, the operation of some large machinery is limited, which leads to the inadequate implementation of subgrade compaction and slope trimming technology. The occurrence of these problems will affect the quality of subgrade construction, so it will increase the incidence of subgrade diseases ^[3].

Table 1. Characteristics of high filling and deep excavation subgrade in mountainous areas

Type of subgrade	Geotechnical structure	Moisture content (%)
High fill subgrade	Earth-rock mixed soil	18.622.3
Deep excavation subgrade	Weathered mudstone soil	23.527.8
Special subgrade	Expansive soil, soft soil	26.431.2

3. Analysis of the disease mechanism of high fill and deep excavation subgrade

3.1. Disease mechanism of settlement deformation of high fill subgrade

High fill subgrade is prone to settlement and deformation diseases. According to its settlement deformation characteristics, it can be divided into three types: one is instantaneous settlement. It is generally caused by a sudden increase in load, which leads to rapid deformation of the soil, but the deformation elasticity of

the instantaneous settlement is large, and there is the possibility of subsequent recovery ^[4]. The second is a consolidation settlement, which is also the most common settlement disease. It is not elastic and will continue to accumulate. This settlement type is mainly due to the high porosity and self-weight of the high fill subgrade. Combined with external loads, it leads to the continuous and significant reduction of the porosity of the soil. And the amount of settlement formed by different soil layer structures is different. The calculation method of consolidation settlement of high fill subgrade can refer to Formula 1:

$$S = \sum_{i=1}^n \frac{\sigma_{zi}}{E_{si}} h_i \quad (1)$$

In the formula: S is the final consolidation settlement of subgrade (mm); σ_{zi} is the average additional stress of soil layer the i -th soil layer (kPa); h_i is the thickness of the i -th layer of fill (m); E_{si} is the compression modulus of the i -th soil layer (MPa); n is the number of filling layers.

It can be seen that the consolidation settlement is directly related to the fill thickness, and the fill thickness of high fill subgrade is larger, so the problem of consolidation compression settlement will be more obvious. The third is secondary consolidation settlement. The settlement occurs after the consolidation settlement is basically stable, which is manifested as a relatively subtle settlement problem.

3.2. Mechanism of instability disease of the deep excavation subgrade slope

The most common disease of deep excavation subgrade in mountainous areas is the instability of the subgrade slope. This is because the deep excavation of the subgrade will cause disturbance to the mountain structure, which will lead to serious and irreversible structural deformation, resulting in cracks in the slope and other problems ^[5]. At the same time, under the action of external load, it is very easy to cause slope collapse or a landslide. The core cause of slope instability is the loose soil structure, which seriously affects its shear strength, and then leads to the reduction of the safety factor of soil stability. The calculation formula of the stability safety factor can refer to Formula 2:

$$K_s = \frac{\sum (l_i \cos \alpha_i - u_i l_i) \tan \varphi_i}{\sum G_i \sin \alpha_i} \quad (2)$$

In the formula: K_s is the safety factor of slope stability; c_i is the cohesion of the soil (kPa); l_i is the length of the slip arc (m); G_i is the weight of the soil (kN); α_i is the dip angle of the slip arc ($^\circ$); u_i is pore water pressure (kPa); φ_i is the internal friction angle of soil ($^\circ$).

The safety factor of the deep excavation slope stability of the mountainous highway needs to reach more than 1.25. Therefore, once the excavation causes disturbance to the soil, resulting in the safety factor lower than 1.25, it is very easy to cause the imbalance of the slope structure. This will lead to a landslide and other risks.

3.3. Damage and development mechanism of water-sensitive subgrade

The water sensitivity of soil in mountainous areas is relatively strong, so the soil in mountainous areas is prone to deformation in the rainy season. This led to cracks in the highway subgrade and slope. At the same time, after rainwater enters the subgrade along the cracks, it will further soften the soil structure and weaken the bearing capacity of the subgrade. The strength calculation of water-sensitive soil can refer to Formula 3:

$$T_f(\omega) = T_{f0} \cdot e^{-k(\omega - \omega_0)} \quad (3)$$

In the formula: $T_f(\omega)$ is the shear strength of the soil corresponding to the water content ω (kPa); T_{f0} is the initial shear strength corresponding to the natural moisture content ω_0 (kPa); k is the water-sensitive attenuation coefficient.

Through the determination of a large number of water-sensitive attenuation coefficients in mountainous areas, it is generally between 0.08 and 0.12, and will increase with the increase of rainfall [6]. Therefore, in the case of high precipitation in the rainy season, the stability of the subgrade soil will continue to decrease significantly, which will lead to damage and other diseases of the subgrade under the impact of rainwater.

3.4. Failure mechanism of subgrade under load

In the operation of the mountain highway, it needs to bear the self-weight and vehicle load, which leads to the continuous increase of subgrade stress. At the same time, the load stress has the characteristics of randomness and repeatability, which affect the recovery ability of the subgrade soil structure. Therefore, when the load is superimposed to a certain extent, it will cause soil deformation. The proportion of high fill and deep excavation subgrade replacement fill is large. Although the construction will carry out strong and repeated compaction on the soil, the control ability of external pressure on the porosity of subgrade soil is limited. Therefore, under the influence of equivalent additional stress of vehicle load, the risk of instability of subgrade is extremely easy to occur [7]. The calculation of the equivalent additional stress of the vehicle load can refer to Formula 4:

$$\sigma_d = 0.75 \frac{P}{A} (1 + 0.12v) \quad (4)$$

In the formula, σ_d is the equivalent additional stress of dynamic load (kPa); P is the vehicle axle load (kN); A is the tire grounding area (m²); v is the driving speed (km/h).

It can be seen that with the increase in the running time of the highway and the increase in the number of vehicles, the deformation of the subgrade will continue to accumulate. After accumulating to a certain extent, it is likely to cause subgrade damage.

4. Key technology for the treatment of special subgrade with high fill and deep excavation

4.1. Compaction reinforcement treatment technology of high fill subgrade

The probability of settlement deformation of high fill subgrade in mountainous areas is large, and the consequences are serious. In order to effectively prevent subgrade settlement and deformation, comprehensive compaction reinforcement technology should be adopted according to the characteristics of high fill subgrade (Table 2). This technology combines compaction, dynamic compaction, and grid reinforcement technology in the construction of ordinary subgrade, and then realizes the reinforcement of subgrade through the complementary technology [8]. First, fine compaction technology is adopted. Before the application of this technology, it is necessary to measure the moisture content of the subgrade (preferably 19%–23%), and personnel can use different compaction standards at different locations. The compaction strength standard of subgrade and upper roadbed is the same, which should reach more than 96%; The compaction strength

of the lower roadbed can be properly reduced to more than 94%; The tamping strength of the lower layer of fill shall be controlled above 93%. Secondly, when the filling height of high fill subgrade exceeds 20 m, it is only necessary to strengthen the subgrade structure by dynamic compaction technology. The energy level of compaction shall reach 1200 kN·m. Personnel shall control the distance between adjacent points of compaction at about 4 m, and the number of compaction not less than 8 times. Finally, personnel need to use reinforcement technology. This technology needs to add a geogrid in the subgrade construction, generally adding a layer of grid at an interval of 2 m, and the tensile force of each layer of grid should reach 80 kN/m. Through the setting of a grid, the quality of filling body is improved, and then the settlement of soil body is effectively reduced.

Table 2. Comprehensive compaction reinforcement technology

Disposal plan	Filling height (m)	Average degree of compaction (%)
Fine compaction	22.5	92.3
Fine compaction and dynamic compaction	22.8	95.8
Fine compaction, dynamic compaction, and geogrid reinforcement	23.1	96.2

4.2. Reinforcement and treatment technology of deep excavation subgrade slope

The slope of the deep excavated subgrade in a mountainous area is prone to instability under the scouring of rainwater. In view of this disease, the method of graded excavation can be adopted, supplemented by anchor frame reinforcement and ecological protection technology. This can not only strengthen the slope structure but also optimize the ecological environment. In the graded excavation of the deep excavation slope, the excavation depth of each layer is basically the same (8~10 m). At the same time, the slope shall be determined in combination with the soil structure of the subgrade. Anchor frame reinforcement technology is mainly used in the reinforcement of slopes after excavation, and the full-length bonding anchor reinforcement technology is widely used. In this technology, the drilling depth (4~6 m) and diameter (Φ : 25 mm) of the anchor rod shall meet the construction requirements. In addition, slope protection should be strengthened^[9]. The three-dimensional geonet mat can be used as the base of ecological planting protection. This construction method can not only maintain the vegetation, but also buffer the erosion of rainwater on the soil.

4.3. Improvement and treatment technology of special rock and soil subgrade

The area of expansive soil and weathered rock and soil in the mountainous rock and soil layer is large. The high water sensitivity of these soil layers determines that they are prone to landslides and other diseases in the rainy season. Therefore, for special rock and soil subgrade, it is necessary to improve the compactness of soil structure by subgrade improvement to ensure the stability of the soil structure. Firstly, before the construction of special geotechnical subgrade, the indoor proportioning test of construction materials is carried out, and the soil strength and structural stability are taken as the test evaluation criteria. For example, the test comparison results show that the compressive effect of soil in the test group with 5% cement content is the best, so this proportion can be used as the construction standard. Secondly, the improved construction technology is adopted to reduce the water sensitivity of soil structure. For example, the water content of soil can be reduced by crushing and screening of rock and soil, and cement mixing. Then the stability of the soil is improved through the compaction process (compactness $\geq 96\%$). Finally, the water sensitive attenuation coefficient of soil is controlled within a reasonable range (≤ 0.03), so as to ensure the stability of soil

structure^[10].

4.4. Supporting technology of the subgrade waterproof and drainage system

The diseases of high fill and deep excavation Subgrade in mountainous areas are directly related to the moisture content of the subgrade. Therefore, reducing soil water content is the key to subgrade prevention and control. To solve this problem, the combined drainage mode of ground interception and drainage, underground drainage, and slope drainage can be adopted to reduce the impact of water on the subgrade. First, surface drainage technology. The core application of this technology is to set intercepting ditches at the top of the slope to intercept the runoff on the ground, so as to effectively prevent the soaking of rainwater on the subgrade. At the same time, concrete pouring drainage ditch and side ditch shall be set to ensure the continuous and stable drainage of water. Secondly, groundwater drainage technology. This technology requires setting a blind ditch (0.8 m wide and 1.0 m deep) underground, and laying gravel and permeable geotextile in the ditch, so as to effectively and quickly dredge groundwater. In addition, the blind pipe is used to connect the filling and excavation junction, so as to improve the drainage capacity of groundwater. Finally, slope drainage technology. Slope drainage is mainly through the design of the horizontal and vertical pipe network at the side of the anchor rod to divert rainwater, and then effectively control the infiltration of rainwater into the base.

5. Conclusion

To sum up, the particularity of the geographical environment of mountainous expressways determines that the subgrade construction method of high fill and deep excavation is required in highway construction. However, the technological limitations of high fill and deep excavation construction lead to the inevitable occurrence of subgrade diseases, and the role of traditional disease management technology in the treatment of high fill and deep excavation subgrade is limited. Therefore, the construction unit needs to try to solve the problem of subgrade disease treatment through the comprehensive application of reinforcement technology, improvement technology, and drainage technology. Integrating the advantages of multiple technologies can improve the compactness of soil structure, reduce soil moisture content, and ensure the stability of subgrade structure. In the future, in the construction of high fill and deep excavation Subgrade of mountain highway, it is also necessary to try to use digital technology to strengthen the optimization of various parameters in the engineering construction and form a targeted treatment scheme.

Disclosure statement

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Research on the Construction of Urban Luggage Transportation and Storage Service System Based on User Demand

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Abstract: Centering upon the prevailing practical predicaments, including cumbersome luggage carriage, interim baggage depositing, and short-distance cross-site transshipment emerging amid urban outbound journeys, the present research has gathered a total of 58 valid research questionnaires. Statistical outcomes manifest that over 85 percent of sampled respondents have once been plagued by various luggage-related troubles during trips, whereas up to 89.29% of surveyed individuals acknowledge the indispensable value of point-to-point dedicated luggage conveyance service. Rooted in diversified urban travel scenarios, this paper systematically sorts out a full set of operational links covering luggage collection, transit distribution, temporary warehousing, pickup confirmation, as well as emergency exception disposal, so as to formulate an integrated systematic framework for urban luggage transportation and custodial services. The research achievement possesses profound theoretical instructional implications as well as feasible popularization value, which can deliver referential practical suggestions for advancing the convenience coefficient of urban resident travel activities.

Keywords: Urban logistics; Luggage custody; Point-to-point transit; User-oriented demand; Service system construction

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1. Introduction

In recent years, domestic sightseeing tourism and intercity commuting demands have maintained a sustained upward momentum on a nationwide scale. According to authoritative statistical records released by competent departments, the aggregate number of domestic tourist arrivals hit 5.615 billion person-times in 2024, rising by 724 million person-times against the previous year with a year-on-year growth rate of 14.8% ^[1]. Such passenger flow further climbed to 6.522 billion person-times in 2025, registering a 16.2% year-on-year

incremental margin ^[2]. Against such a booming market scale, diversified luggage-related dilemmas inevitably impair the holistic travel experience of tourists throughout the whole itinerary. Relevant field surveys indicate that nearly seventy percent of sightseers are compelled to shuttle among traffic hubs, accommodation hotels, and scenic spots with personal luggage on hand, while roughly ninety percent of the traveling population put forward explicit practical demands for professional luggage consignment services. Although conventional luggage deposit services have achieved partial coverage over commercial blocks and transportation terminals, prominent drawbacks still linger in cross-node cargo transfer flexibility, pickup-and-return operability, and standardized pricing benchmark formulation ^[3].

Existing academic literature corroborates that supporting elements such as transit infrastructure and livelihood-oriented convenient amenities within the tourist public service system exert tangible influences on the tourist satisfaction index and immersive destination experience ^[4]. From such an analytical perspective, luggage storage and cargo transportation are far beyond trivial segmented logistics details, and would further exert restrictive effects over itinerary transfer planning, accommodation docking arrangement, and sightseeing efficiency optimization. Current domestic research focusing on urban logistics distribution predominantly evaluates operational efficiency from delivery lead time, comprehensive operating cost, standardized service quality, and ecological environmental influence dimensions, whereas in-depth academic discussions targeting short-distance customized point-to-point passenger luggage conveyance remain relatively insufficient ^[5]. Under such a research backdrop, this thesis elaborates on the detailed construction blueprint of the urban luggage transportation and storage service system from the perspective of real user requirements.

2. Demand analysis of urban luggage transportation and custody service

To profoundly excavate authentic user requirements for luggage carriage, temporary deposit, and transshipment amid urban traveling scenarios, the research team has launched a targeted questionnaire investigation and harvested 58 valid response samples. Statistical analysis reveals that more than 85% of interviewees have encountered troubles stemming from inconvenient luggage transportation, which demonstrates the widespread universality of such a practical social issue. Furthermore, respondents' feedback concerning luggage obstacles is not merely confined to overweight or cumbersome physical attributes of baggage; most complaints originate from schedule-related conflicts, such as unavailable luggage storage space after hotel check-out and extra detour costs to finish luggage custody prior to scenic touring activities.

A total proportion of 89.29% of surveyed users approve the necessity of a point-to-point luggage delivery service, which reflects widespread public recognition of the customized transit mode delivering luggage from the designated origin to the predetermined terminal destination. Empirical data also manifests that consumers prioritize service quotation, standardized service quality, scheduled transit duration, and cargo safety guarantee when selecting relevant luggage service products. Previous academic studies verify that timeliness, security, delivery accuracy, and information transparency constitute core influential determinants of end-user satisfaction in the logistics industry ^[6].

With regard to safety perception and extra payment willingness, a portion of surveyed consumers are inclined to pay premium charges in exchange for upgraded secure luggage transit solutions. It illustrates that end users attach equal importance to service accessibility as well as whole-process safety supervision and post-accident liability identification throughout luggage custody and transportation links. Consumers' acceptance level of relevant services is jointly conditioned by pricing strategy and their subjective judgment

on comprehensive service quality and operational reliability ^[7].

3. Systematic scheme design for urban luggage transportation and storage service

On the basis of the collected questionnaire statistical data, the proposed urban luggage service system is positioned as an all-dimensional comprehensive service solution tailored for diversified urban travel contexts. Centered around a point-to-point customized luggage delivery business and supplemented by an interim baggage storage module, this system effectively interconnects core urban functional nodes such as air terminals, railway passenger stations, hospitality hotels, and tourist attraction zones. The *Easy Tour* luggage service reform project implemented in Hangzhou has pioneered multiple innovative service forms, including onsite luggage deposit, terminal-oriented consignment delivery, and railway-tourism industrial linkage, facilitating multi-scenario consignment cooperation among scenic resorts, hotel clusters, commercial districts, and passenger transport hubs ^[8]. Distinct from such existing projects, which simply pursue quantity expansion of fixed storage outlets, the design emphasis of this research's system lies in seamless connection covering tourists' cross-city mobile itineraries. Supported by standardized procedural design, service subscribers are capable of submitting personalized requirement information, including departure location, receiving address, luggage specification classification, and expected service timeline, which sequentially triggers systematic order auditing, task dispatching, and real-time operational status refreshment.

The established system synchronously satisfies dual service demands covering direct cargo transit and temporary baggage warehousing. For passengers requiring one-stop direct delivery to target destinations, core service links consist of luggage pickup inspection, optimal route formulation, cargo distribution, and final delivery confirmation; for travelers who demand deferred pickup or short-term luggage safekeeping, pivotal procedures involve interim storage management, real-name identity authentication, and authorized pickup verification. The two service modules can realize organic seamless connection during actual implementation, enabling users to flexibly adjust luggage disposal schemes in accordance with transit shift schedule, hotel check-in timeline, and sightseeing arrangement.

During practical system operation, synchronized order status visibility among service users, administrative supervisors, and field delivery couriers serves as an indispensable precondition; inconsistent pickup appointments and ambiguous liability demarcation would readily emerge. Relevant logistics literature substantiates that information sharing mechanisms, real-time order tracking, and visualized whole-process monitoring can remarkably improve collaborative operational efficiency of supply chains ^[9]. Specifically, the user terminal undertakes functions of requirement submission, information confirmation, and post-service pickup feedback; the administrative terminal is responsible for order reception, information authenticity audit, service task allocation, dynamic status management, and abnormal event coordination; the delivery terminal fulfills duties of onsite luggage collection, cargo outbound distribution, progress updating, and unexpected condition feedback. Tripartite collaborative operation contributes to enhancing whole-process traceability and clarifying respective liability boundaries of all participants.

The systematically optimized framework effectively alleviates users' physical burden caused by repeated luggage relocation, and eliminates consumers' potential worries by implementing standardized handover documentation, strict identity verification, and standardized exception handling clauses.

4. Construction of service flow chart and functional modules

Relevant academic viewpoints indicate that sorting out standardized service workflows centering on customer

contact points and backstage collaborative links is conducive to upgrading integral organizational efficiency of service operation ^[10]. Combined with the above system design, the holistic service procedure can be split into six sequential phases: requirement submission, systematic order auditing, physical luggage collection, outbound transportation distribution, temporary storage or terminal delivery, and authorized customer pickup. Starting from end-user practical needs, key controlling nodes are set along the whole luggage circulation path from departure site to destination, ensuring complete written records for every cargo handover, transit delivery, and pickup operation.

4.1. Detailed design of standardized service procedures

At the requirement submission stage, service subscribers fill in detailed information, including departure coordinates, target addresses, luggage classification, reserved service period, and other auxiliary essential data via an online user terminal. Within the order processing phase, the managerial backend receives submitted orders and inspects information integrity, then rationally distributes delivery tasks according to geographical distance, luggage property, and service time slot. During the luggage acceptance session, field couriers conduct onsite cargo handover, compile exclusive serial numbers, inspect outer package integrity, and retain photographic archives, followed by formal confirmation signed by service requesters. Subsequent transportation and distribution are carried out along pre-planned routes with dynamic order status updated synchronously, allowing both users and administrative personnel to monitor real-time service advancement. After cargo arrives at the designated destination, luggage will either be put into temporary storage or delivered straight to end users, subject to personalized demands, and the entire service process terminates after formal identity verification and pickup confirmation.

4.2. Partition of system functional modules

Based on procedural design, functional modules of the user terminal, management terminal, and delivery terminal are categorized elaborately as shown in **Table 1**, which mainly serve for procedural specification and follow-up digital system development planning. Through rational division of labor among three terminals, end-user demand collection, order centralized management, field task execution, and abnormal problem feedback are integrated into an organic unified operational framework.

Table 1. Functional module design of urban luggage transportation and storage service system

Terminal Category	Core Functional Content	Detailed Function Interpretation
User Terminal	Online order placement, address filling, luggage type selection, real-time order query, pickup confirmation	Facilitate service applicants to finish demand submission, whole-process order tracking, and post-service confirmation
Management Terminal	Order centralized processing, task rational allocation, dynamic status supervision, abnormal incident disposal, operational data sorting	Enable service organizers to complete order auditing, resource collaborative scheduling, and whole-process operational documentation
Delivery Terminal	Task reception, onsite pickup confirmation, service status update, delivery completion submission, abnormal condition feedback	Support frontline practitioners to conduct luggage receiving, cargo distribution, and timely reporting of unexpected malfunctions

The above three modular components jointly constitute the fundamental operating skeleton of the whole service system. User terminal prioritizes operating convenience and data transparency; management terminal focuses on overall coordination and controllability; delivery terminal highlights execution efficiency and timeliness of abnormal feedback. Research on logistics informatization confirms that synchronous

information sharing, real-time data refresh, and visualized management effectively promote service transparency and inter-departmental synergy ^[9]. Organic coordination among three terminals helps form a steady, normative, and traceable service circulation mechanism.

5. Safety guarantee framework and exception disposal mechanism

Service safety and credible operation constitute the core concern of luggage custody and transportation subscribers. Different from conventional commodity distribution, tourist luggage carries distinctive personal attributes, which usually contain identity certificates, daily garments, portable electronic devices, and other private belongings. Delivery delay would disrupt subsequent passenger boarding or hotel check-in arrangements; cargo damage will trigger intricate liability judgment and compensation negotiation; wrongful pickup or illegal claim directly damages users' trust toward relevant service providers. Previous research on logistics service quality proves that timeliness, cargo safety, and delivery precision serve as foundational prerequisites determining customer satisfaction, while logistics risk management literature points out multiple potential risks, including substandard service quality, irregular staff administration, cargo physical damage, and information system malfunction, that exist in the distribution industry, requiring targeted precautionary measures ^[6, 11]. Accordingly, this research takes exclusive luggage coding, pre- and post-transit photographic filing, formal handover certification, identity authentication, pickup endorsement, liability ascertainment, and graded compensation mechanism as core design contents, as displayed in **Table 2**.

Specifically, unique luggage serial coding marks every single baggage with distinguishable identification tag so as to avoid cross-confusion among multiple parcels or diversified customer orders; photographic filing preserves original outer appearance before and after handover, providing objective evidence for liability confirmation once package damage disputes emerge afterward; handover and pickup certification fix each circulation node of luggage to eliminate ambiguous disputes over receiving party, delivery timeline and actual pickup status; identity verification effectively guards against wrongful collection and fraudulent claiming risks. Under an intelligent logistics application background, Internet of Things technology realizes real-time positioning, remote monitoring, and pre-warning against potential hazards to elevate the cargo transportation safety coefficient ^[12].

When a service breakdown occurs, end users care most about the liable subject, the judgment basis, and the feasible compensation standard. From the perspective of legal risk prevention for logistics service contracts, relevant rights, obligations, and compensation liabilities ought to be explicitly stipulated in contractual clauses; disputes would easily emerge during damage settlement, delivery delay treatment, and indemnity negotiation ^[13]. Therefore, differentiated disposal schemes are formulated targeting delivery postponement, exterior package damage, and cargo missing risks respectively, while a practical compensation benchmark shall be further defined combining luggage value certification materials, handover photographic evidence, bilateral confirmation records, service classification, and attached insurance clauses. Especially for important items such as identity credentials and precision electronic equipment, uniform lump-sum compensation cannot be mechanically applied, which demands further consultation with cooperative operators and insurance institutions to clarify detailed liability boundaries in follow-up implementation.

Exception disposal design shall be formulated by combining practical traveling scenarios. Relevant studies indicate that standardized abnormal disposal of logistics service relies on real-time tracking monitoring, effect evaluation, problem feedback, and flexible scheme adjustment ^[14]. Meanwhile, timely

communication, reasonable indemnity, and follow-up problem settlement after service fault contribute to restoring customer satisfaction and optimizing subsequent service evaluation ^[15]. Within the research's applicable scenarios, delivery delay may result in tourists missing accommodation check-in, transit shift or prearranged sightseeing schedule, hence disposal measures shall not be confined to simple prompt handling, but include notifying revised estimated arrival time and optional pickup location adjustment for affected users; luggage damage identification depends on photographic archives and handover records to define liability instead of merely oral statement; address alternation would influence transit route, delivery cycle and service charge, which demands reconfirmation of relevant parameters; order cancellation standards vary according to different service implementation phases; service delivery shall be suspended under abnormal identity verification pending administrative staff's further confirmation.

Table 2. Major abnormal scenarios and corresponding disposal strategies

Abnormal Circumstance	Detailed Handling Measures
Delivery Postponement	Refresh order status instantly, inform affected users of delay inducement and updated expected delivery time; coordinate schedule revision via the administrative department if necessary
Luggage Physical Damage	Complete onsite photographic evidence collection and handover inspection, implement follow-up settlement in line with liability identification result and graded compensation regulations
Delivery Address Modification	Reconfirm updated receiving location, revised transit route and service schedule, synchronize possible variations of service cost and delivery efficiency
Unilateral Order Cancellation	Adopt differentiated disposal standards subject to ongoing service progress, archive cancellation reasons, and bilateral communication records
Irregular Identity Verification	Suspend cargo handover temporarily, verify the user's authentic identity information, and complete the pickup operation after administrative confirmation

6. Conclusion

Focusing on the realistic predicaments of luggage carriage and interim deposit arising during urban outbound trips, this paper finishes the overall architectural design of urban luggage transportation and storage service system together with detailed service procedures and modular functional partition on the premise of authentic user demand investigation. The standardized service workflow is mainly divided into three core phases, including centralized order auditing, onsite luggage acceptance, and outbound cargo distribution, while functional modules are split into three categories: user terminal, management terminal, and delivery terminal. On such a foundational framework, the paper further establishes a complete safety precaution system and multi-type abnormal disposal specification.

Nevertheless, the current research still contains inherent limitations: systematic prototype development and detailed functional refinement remain at the theoretical design stage, whereas compensation stipulation drafting, personal privacy protection norms, legal liability delimitation, and field staff scheduling optimization require successive in-depth discussion. Follow-up empirical research can verify route planning rationality, delivery timeliness matching degree, and operability of abnormal disposal clauses, so as to polish the whole scheme and boost its practical implementability in real industrial scenarios.

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Research on Bearing Characteristics and Construction Quality Control of Highway Bridge Pile Foundation

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Abstract: As a concealed project, the bearing characteristics and construction quality of highway bridge pile foundations directly determine the safety and durability of bridge structures. However, there are still problems in the current pile foundation construction, such as poor geological adaptability, lax control of process parameters, and outdated detection methods, resulting in insufficient bearing capacity and frequent quality hazards. This article refers to the standardized academic paper architecture, systematically analyzes the load transfer mechanism and bearing characteristics evolution law of pile foundations, constructs a quality control system guided by bearing mechanisms, with process control as the core and dynamic detection as the guarantee, proposes the implementation path from “experience construction” to “data-driven construction”, studies the control methods of key links such as geological exploration, pore forming technology, concrete pouring, integrity testing, etc., aiming to provide theoretical and practical support for improving the construction quality and optimizing the bearing performance of highway bridge pile foundations.

Keywords: Highway bridges; Pile foundation; Bearing characteristics; Construction quality; Process control; Data-driven

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1. Research background and significance

With the continuous expansion of the construction scale of highway bridges in China, pile foundations, as the core components for transferring bridge loads to deep foundations, have a direct impact on the safety and stability of the upper structure in terms of their bearing capacity. Pile foundation is a typical concealed project, and the construction process is irreversible. Quality hazards are difficult to visually detect. Once quality problems such as insufficient bearing capacity, broken piles, reduced diameter, and segregation occur, the cost of reinforcement and repair in the later stage is high, and it may even affect the service life and operational safety of the bridge ^[1].

Currently, some engineering projects still use traditional empirical methods in pile foundation construction, with insufficient matching between geological conditions and process parameters. Process control relies on manual inspections, and result testing mainly relies on post-inspection. There are prominent problems such as large quality fluctuations, lagging risk identification, and incomplete data recording. Promoting the transformation of pile foundation construction from “passive detection” to “active control”, with bearing characteristics as constraints, process data as the basis, and dynamic monitoring as the means, has become an inevitable choice to improve the quality level of bridge engineering. This article systematically studies the bearing mechanism and quality control methods of pile foundations, and constructs a full-process active control system, which has important engineering value for ensuring the safety of bridge structures and reducing the total life cycle cost ^[2].

2. Analysis of pile foundation bearing characteristics and construction quality status

2.1. Load transmission mechanism and bearing characteristics of pile foundation

The bearing capacity of a pile foundation is jointly provided by the pile side friction resistance and the pile end resistance, and the load transmission follows the law of “load first transmitted to the pile side and gradually transferred to the pile end with the increase of settlement.” The manifestation of pile side frictional resistance depends on the relative displacement between the pile and soil, the properties of the soil around the pile, the pile forming process, and the roughness of the pile body; The pile end resistance is influenced by factors such as the strength of the bearing layer, sediment thickness, and the depth of pile end embedment. The bearing characteristics have significant spatiotemporal evolution characteristics: during the construction phase, they are affected by the quality of mud wall protection and concrete pouring; During the usage phase, the bearing capacity may experience attenuation due to long-term loads and environmental erosion ^[3].

Understanding the above bearing mechanism is a prerequisite for quality control. Only by clarifying the dominant factors of bearing capacity under different geological conditions and construction techniques can process control parameters be set in a targeted manner, avoiding a one-size-fits-all management approach ^[4].

2.2. Common problems and cause analysis of construction quality

The prominent problems in the construction quality of highway bridge pile foundations include: exceeding the limit of sediment at the bottom of the hole, significantly reducing the pile end resistance; Thick mud skin weakens the lateral friction resistance of the pile; Concrete segregation, pile breakage, shrinkage, steel cage floating and other grouting defects; The integrity of the pile body is poor, and the local bearing capacity is seriously insufficient. The causes of the above problems can be attributed to four categories: firstly, insufficient accuracy in geological exploration, mismatch between process selection and geological conditions; Secondly, the control of key process parameters such as pore formation, cleaning, and injection is not strict; Thirdly, the process detection methods are outdated, and problems cannot be remedied by the time they are discovered; The fourth issue is incomplete construction records and incomplete data connectivity, making it difficult to achieve quality traceability and continuous improvement ^[5].

2.3. Limitations and transformation direction of traditional quality control

The traditional quality control of pile foundation is based on the core mode of “final inspection+sampling

inspection”, which means that after construction is completed, quality judgment is carried out through methods such as low strain, ultrasonic, and static load testing. If unqualified piles are found, they can be supplemented or reinforced. This model has obvious shortcomings: lagging discovery of quality issues and high disposal costs; The sampling ratio is limited, making it difficult to cover all pile foundations; The process data is not effectively utilized, making it impossible to achieve real-time warning and dynamic correction. The transformation direction is from “result detection” to “process control”, from “experience construction” to “data-driven construction”, guided by the carrying characteristics, to build an active quality control system covering the entire chain of “geology design construction testing feedback.”

3. Active quality control system based on bearing mechanism

3.1. Core logic and operating mechanism of active control

Active quality control takes the bearing characteristics of pile foundations as the core constraint and follows a closed-loop process of “geological modeling process matching process monitoring dynamic correction integrity verification bearing capacity evaluation.” By standardizing the collection of multi-dimensional data such as formation parameters, pore parameters, concrete parameters, and grouting parameters, a data platform for pile foundation construction is established. Numerical simulation and statistical analysis methods are used to determine in real time whether the current construction status deviates from the optimal range of bearing characteristics, output correction instructions, and continuously record construction data to optimize the control threshold in reverse, achieving a transformation of quality control from “post inspection” to “process feedforward+real-time feedback.”

3.2. Quality control data system and standards

The active quality control data system includes geological data (geological distribution, soil parameters, groundwater level), design data (pile diameter, pile length, reinforcement, bearing capacity requirements), construction process data (drilling speed, mud indicators, sediment thickness, concrete slump, pouring speed, temperature), and testing data (drilling quality, integrity, bearing capacity). It is necessary to unify the frequency, accuracy, storage format, and interface standards of data collection, establish rules for data verification and anomaly labeling, and form a quality data asset that is interconnected, traceable, and analyzable, providing reliable input for active control.

3.3. Four layer integrated architecture design

The active quality control system adopts a four layer integrated architecture: the perception layer collects data throughout the construction process through drilling detection, mud monitoring instruments, concrete flow meters, and borehole cameras; Building a construction quality data platform on the data layer, completing multi-source data aggregation, cleaning, alignment, and storage; Analyze the integrated carrying capacity prediction model, process deviation identification model, and quality risk warning model; The application layer is developed for on-site management, including hole quality evaluation, grouting process monitoring, initial integrity assessment, rapid evaluation of bearing capacity, and automatic generation of quality reports. The four layer architecture is vertically interconnected and horizontally coordinated to achieve active prediction and dynamic closed-loop control of pile foundation construction quality.

4. Key link quality control methods

4.1. Geological exploration and process adaptability selection

Geological exploration is the first hurdle of quality control. Comprehensive methods such as drilling, in-situ testing, and geophysical exploration should be used to accurately obtain key parameters such as formation interfaces, weak interlayers, bearing layer strength, and groundwater corrosiveness. On this basis, the drilling process is optimized according to the geological conditions: rotary excavation or normal circulation can be used for cohesive soil layers; It is advisable to use reverse circulation or impact drilling and strengthen mud wall protection for sand and gravel layers; Rock formations require the use of rock socketed drilling machines. The process selection should be dynamically matched with the geological model to avoid collapse, expansion, or contraction of the borehole wall due to incorrect equipment selection.

4.2. Quality control and monitoring of pore forming process

During the drilling stage, the focus is on controlling pile position deviation, verticality, hole diameter, hole depth, and sediment at the bottom of the hole. Real time monitoring of verticality using an inclinometer while drilling, with automatic alarm when deviation exceeds 1%; Real time monitoring of mud indicators through mud density meter and viscosity meter to maintain wall protection performance; After pore formation, the ultrasonic pore forming detector or mechanical aperture meter is used to scan the aperture curve of the entire cross-section to determine the position of diameter reduction or expansion; The sediment thickness should be accurately measured using a sediment meter or hammer method. The sediment thickness of friction piles should be $\leq 10\text{cm}$, and that of end bearing piles should be $\leq 5\text{cm}$. All drilling parameters should be entered into the data platform to form a single pile drilling quality file.

4.3. Dynamic control of concrete pouring process

Concrete pouring is the process with the highest quality risk. The slump of concrete should be controlled between 180–220 mm, with good workability, and the initial setting time should meet the requirements of the pouring time. The burial depth of the conduit should be controlled within 2–6 m, and it is strictly prohibited to pull out the conduit to cause pile breakage. Real-time collection of pouring speed, cumulative volume, and pipe burial depth using concrete flow meters and pouring recorders, generating pouring curves and automatically identifying abnormal segments (such as sudden speed drops and shallow burial depths). Collect concrete temperature or resistivity data every 2–3 m during the pouring process to assist in determining the uniformity and compactness of the concrete. Once abnormalities such as pipe blockage, water ingress into the conduit, and concrete segregation occur, the system should issue an alarm and prompt a disposal plan.

4.4. Pile integrity testing and bearing capacity evaluation

After the completion of grouting, integrity testing should be carried out in a timely manner: the low strain method is suitable for preliminary screening of pile defects, determining the location of shrinkage, segregation, and pile breakage; Ultrasonic transmission method or borehole camera are used for large-diameter or important bridge pile foundations, with higher accuracy; The high strain testing method can quickly estimate the ultimate bearing capacity of a single pile on site. For important bridges or geologically complex road sections, static load tests should be conducted at a certain proportion to obtain the most reliable bearing capacity data. All test results should be fed back to the data platform for correlation analysis with construction process parameters, identifying the root cause of quality issues, and used to optimize the control

threshold for subsequent pile foundation construction.

5. Transformation implementation path and guarantee measures

5.1. Phased implementation path

The implementation of transformation is divided into three stages: the first stage is the infrastructure construction period, which completes the digitization of geological data, deployment of key process sensors, and formulation of construction data collection standards; The second stage is the capability enhancement period, during which an active quality control platform will be launched and validated in 3–5 typical bridge engineering pilot projects to establish a bearing capacity prediction and quality warning model; The third stage is the comprehensive promotion period, where data standards and management processes are improved to achieve active quality control in the construction of pile foundations for all new and expanded bridges. Staged promotion can reduce implementation risks and ensure synchronous maturity of technology and management.

5.2. Technical equipment and information platform support

Key configurations for technical equipment support: inclinometer while drilling, mud automatic monitoring instrument, ultrasonic hole forming detector, concrete flowmeter, low strain and ultrasonic detector, etc. The construction of the information platform focuses on the active control of construction quality, integrating geological modeling, process recommendation, pore evaluation, grouting monitoring, integrity analysis, and bearing capacity evaluation functions. It supports on-site reporting on mobile devices and data analysis on PC devices, achieving automatic generation of quality reports, real-time warning of deviations, and rapid traceability of problem piles.

5.3. Management system and personnel capability guarantee

At the management system level, it is necessary to revise the construction quality acceptance standards, incorporate process monitoring data into the quality assessment basis, and establish a data-driven process acceptance and risk grading control mechanism. In terms of personnel capability guarantee, special training on quality control of pile foundation construction will be carried out, focusing on enhancing the geological mapping, data collection equipment operation, abnormal parameter identification, and emergency response capabilities of on-site technicians, cultivating composite talents with knowledge of geotechnical engineering and information management, and providing manpower support for the continuous operation of the active quality control system.

6. Conclusion

This article systematically studies the bearing characteristics and construction quality control methods of highway bridge pile foundations, clarifies the mechanism of pile side friction resistance and pile end resistance, points out the limitations of the traditional “final inspection+sampling inspection” mode, proposes an active quality control system guided by bearing characteristics, with process data as the core and dynamic monitoring as the means, constructs a four layer integrated architecture, forms a full chain closed-loop method of geological exploration hole control grouting monitoring integrity detection bearing capacity

evaluation, and provides a phased implementation path and technical management guarantee measures. Research has shown that active quality control based on bearing mechanisms can significantly improve the consistency of pile foundation construction, reduce quality risks, and extend the service life of bridges. The constructed system is scientifically feasible and can directly guide engineering practice.

Disclosure statement

The author declares no conflict of interest.

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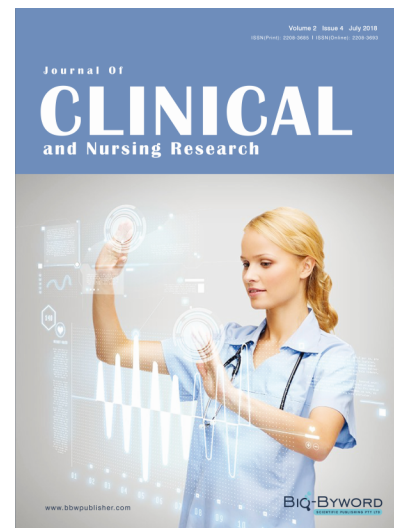
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