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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the current pile foundation construction, such as poor geological adaptability, lax control of process parameters, and outdated detection methods, resulting in insufficient bearing capacity and frequent quality hazards.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 a 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 ≤ 10cm, and that of end bearing piles should be ≤ 5cm. 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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