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Design of Drilling Path and Structural Protection for Micro-pile Implantation Machinery for Ancient Building Reinforcement

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Abstract: Taking the ancient building complex of Zhangguying Village in Yueyang County, Hunan Province as the research object, this paper elaborates the optimization of micro-pile drilling paths, adaptive improvement of light drilling rigs, structural protection design, and construction coordination. Construction schemes including angled drilling layout, modular design, and vibration suppression of micro-drilling rigs, foundation underpinning, external wall support, and waterproofing & anti-seepage are proposed to improve the bearing capacity of ancient building foundations and control settlement. The research conclusions show that settlement can be controlled within 5%–8%, vibration amplitude ≤ 0.5 mm, and crack expansion ≤ 1 mm during reinforcement. The results prove that the proposed scheme can realize efficient and safe micro-pile reinforcement in narrow courtyards and dense wall environments while guaranteeing construction efficiency and structural stability, and effectively reducing disturbance to ancient building foundations.

Keywords: Ancient building protection; Micro-pile reinforcement; Drilling path optimization; Structural protection

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1. Introduction

Threatened by material aging, structural defects, earthquakes and other disasters, ancient buildings, important carriers of Chinese civilization, have long suffered potential safety hazards. Their protection and reinforcement have become a research hotspot in academic and engineering circles ^[1]. Domestic and foreign scholars have carried out extensive research on improving seismic performance, structural safety evaluation, and protection methods of ancient buildings and achieved abundant results. Xue Jianyang summarized common collapse risks of ancient building structures and put forward corresponding seismic reinforcement strategies ^[2]. Wang Long et al. held that a multi-line seismic defense system should be established based on seismic damage characteristics of joints, components, and overall structures ^[3]. Zhou Haibin et al. studied the cracking mechanism of wooden components and explored repair methods using glass fiber reinforced

plastic and resin materials ^[4]. An Jindong et al. verified the value of digital BIM technology in improving the precision and efficiency of ancient building restoration via its application in European historic buildings ^[5]. Combined with engineering experience of shield end reinforcement under complex geological conditions, this paper proposes an intelligent connection and reinforcement method mainly for wooden and stone components of ancient buildings, which optimizes the seismic performance and repair precision of structural joints and greatly improves the safety and protection efficiency of ancient buildings ^[6].

2. Project overview

The project is located in Zhangguying Village Ancient Building Complex, Zhangguying Town, Yueyang County, northern Hunan hilly area, with a core protected area of about 255 mu (46 hm²). The village features a “Feng”-shaped layout formed by more than 430 courtyards dating back to the Ming and Qing dynasties. Buildings are mainly composite structures of timber frames and 5-meter stone walls, with an average depth of 12–15 m and eave height of about 7 m. Due to long-term foundation aging, nearly one third of buildings have suffered settlement with the maximum settlement reaching 82 mm, and wall cracks mostly range from 5 mm to 30 mm. Site surveys show that the average width of main lanes is only 2.5 m, with the narrowest section less than 1.2 m, and the spacing between traditional dwellings is generally less than 1.8 m, making large construction machinery inaccessible. To avoid further settlement, pile foundation reinforcement technology is adopted. Micro-cast-in-place piles with a diameter of 300 mm and depth of 8–12 m will be arranged at key nodes to enhance foundation bearing capacity and control differential settlement. Segmented construction and lightweight equipment operation are adopted to preserve the original appearance and surrounding environment of the ancient building complex.

3. Optimization design of micro-pile drilling path

3.1. Path planning principles

For reinforcement of the Zhangguying Village Ancient Building Complex, the selection of micro-pile drilling paths directly determines construction feasibility and structural safety. As courtyard foundations are aged and load-bearing walls are generally 450–550 mm thick and densely distributed, drilling paths must avoid main load-bearing walls and traditional stone plinths. The drilling angle shall be controlled between 10° and 20°, ensuring sufficient bonding between piles and existing foundations, while the hole depth shall reach 8–12 m to meet the design requirement of foundation bearing capacity ≥ 160 kN. During construction, disturbance to ancient building foundations shall be minimized to prevent secondary damage caused by vibration or displacement.

3.2. Drilling path modeling and analysis

Combining actual site conditions including lane width (minimum 1.2 m) and building spacing (less than 1.8 m), 3D spatial modeling technology is adopted to digitally reconstruct typical courtyard foundations and simulate construction under different drilling paths. Comparison between vertical drilling and angled drilling schemes indicates that vertical drilling brings greater foundation disturbance and is hard to operate in narrow spaces despite high construction efficiency. In contrast, angled drilling allows flexible pile layout in limited sites, causing less disturbance to cultural relic structures. The technical flowchart from preliminary survey to

final construction scheme is shown in **Figure 1**.

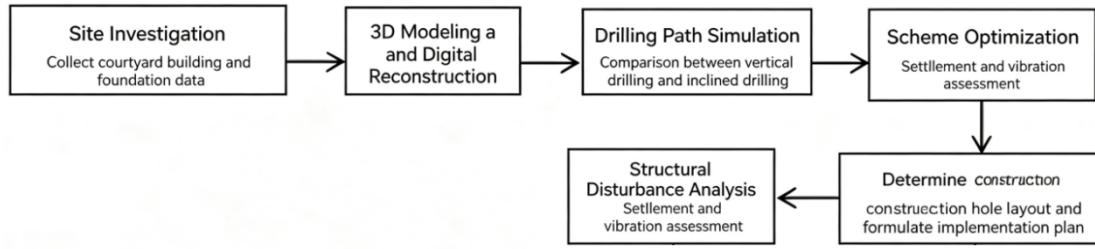


Figure 1. Flowchart of micro-pile drilling path optimization

3.3. Comparative analysis of different drilling paths

Table 1 compares vertical and angled drilling paths in terms of hole diameter, construction efficiency, structural disturbance, and applicability based on modeling results.

Table 1. Comparison of construction feasibility and structural disturbance of different drilling paths

Path Type	Pore Diameter Range (mm)	Construction Efficiency (holes/day)	Disturbance to Ancient Buildings	Applicability
Vertical Drilling Path	280–320	6–8	Severe (15%–20% settlement increment)	Open construction zones
Angled Drilling Path	260–300	4–6	Mild (settlement controlled at 5%–8%)	Narrow courtyards & dense wall areas

It can be seen that vertical drilling improves efficiency in open areas but carries high risks in dense ancient building zones. Although slightly lower in efficiency, angled drilling effectively reduces disturbance and is the preferred construction scheme for core-protected courtyards of this project.

4. Adaptation and improvement of pile implantation machinery

4.1. Selection of micro-drilling rig

Lightweight self-propelled micro-drilling rigs are selected for the narrow courtyards and lanes of Zhangguying Village^[10]. The total machine weight is about 1.8 t, with a length of 2.5 m and width of 0.9 m. It can pass through lanes as narrow as 1.2 m and operate in courtyards with an operation area less than 2 m². Adopting a hydraulic power system with maximum output torque of 450 N·m, the rig can drill holes 8–12 m deep in aged soil layers with bearing capacity below 160 kN/m² while maintaining high stability and safety^[11]. Compared with heavy traditional drilling rigs, the micro-rig requires no large-scale hoisting or ground reconstruction, making it more suitable for cultural relic protection sites.

4.2. Optimization of mechanical components

To adapt to complex strata and reduce disturbance to ancient buildings, the drill bit is made of wear-resistant alloy with a diameter range of 260–300 mm, capable of penetrating gravel, clay, and partially weathered rock with low abrasion. The machine body is equipped with a multi-stage vibration damping system combining hydraulic buffers and springs, which limits foundation vibration amplitude below 0.5 mm and effectively mitigates impact on courtyard walls during construction^[12]. For noise control, hydraulic system optimization and sound absorption covers reduce construction noise to about 65 dB, meeting site requirements for cultural

relic protection. The modular machine body can be disassembled into 3 main units, each weighing less than 600 kg, for easy transportation through narrow lanes and on-site assembly.

4.3. Field application case

A pilot courtyard of about 60 m² with surrounding walls 450 mm thick was selected for micro-pile implantation. The improved micro-rig completed 12 holes with a depth of 8 m and a diameter of 280 mm. Each hole took around 3 hours, with construction vibration amplitude ≤ 0.5 mm and settlement controlled within 5 mm. Conventional small drilling rigs take about 5 hours per hole, generate vibration up to 2 mm, and pose transportation and layout risks in lanes. Field results show that the improved micro-rig ensures structural safety and construction efficiency while drastically cutting disturbance to ancient building foundations, realizing efficient and safe micro-pile reinforcement in narrow-lane courtyards.

5. Structural protection design and construction coordination

5.1. Protection design principles

The principle of “protection prior to construction” is implemented for micro-pile reinforcement in Zhangguying Village Ancient Building Complex. For Ming and Qing timber-stone composite buildings with surrounding walls 450 mm thick and load beam span of about 3.5 m, temporary support systems must be installed before construction to control wall settlement within 5 mm during drilling and pile implantation. Vibration isolation measures combining rubber mats and damping plates are arranged around holes to reduce vibration transmission amplitude from 2.0 mm to less than 0.5 mm, fully protecting the integrity of aged foundations and timber beams^[13].

5.2. Implementation of protection measures

First, foundation underpinning is adopted for courtyards with severe settlement. The underpinning depth ranges from 0.8 m to 1.2 m to disperse bearing loads onto temporary piles or steel supports and maintain the bearing capacity of original foundations during drilling. Adjustable steel external wall supports with spacing ≤ 1.5 m are installed for 450 mm-thick surrounding walls to prevent lateral displacement and crack propagation. During drilling, polyethylene waterproof films are laid around holes to stop mud infiltration and local foundation softening. Enclosures lined with 30 mm-thick rubber vibration isolation mats are built around the rig operation zone to reduce vibration and noise, ensuring courtyard settlement ≤ 5 mm and vibration amplitude ≤ 0.5 mm^[14–15].

5.3. Effect analysis of protection measures

All protection measures achieved satisfactory results in the reinforcement project of Zhangguying Village. Foundation underpinning disperses loads to stable surrounding areas for courtyards with severe settlement, controlling foundation settlement within 5 mm and avoiding further damage to aged foundations. External steel supports spaced within 1.5 m successfully limit wall crack expansion to ≤ 1 mm and maintain the overall stability of Ming and Qing timber-stone composite structures. Polyethylene waterproof films laid around holes prevent mud penetration and local foundation softening during drilling. Enclosures and 30 mm vibration isolation mats control construction noise below 65 dB and vibration amplitude within 0.5 mm while guaranteeing the safety of buildings and residents. Detailed effects are shown in **Table 2**.

Table 2. Corresponding table of protection measures and effects for ancient building pile reinforcement

Protection Measure	Main Application Area	Construction Stage	Protective Effect
Foundation Underpinning	Courtyard foundations	Before pile hole construction	Settlement ≤ 5 mm
External Wall Bracing	Exterior & load-bearing walls	During pile hole construction	Crack expansion ≤ 1 mm
Waterproof & Anti-seepage Treatment	Drilling zones	During drilling	Prevent mud infiltration
Vibration Isolation & Enclosure	Operation zones	Rig operation	Vibration ≤ 0.5 mm, noise ≤ 65 dB

6. Conclusions

Based on 3D modeling analysis, micro-drilling rig improvement and on-site construction verification, conclusions on drilling path optimization, machinery adaptation and structural protection design for micro-pile reinforcement of Zhangguying Ancient Building Complex are drawn as follows:

An optimized angled drilling scheme is proposed by avoiding load-bearing walls, controlling hole diameter at 260–300 mm and hole depth at 8–12 m to balance construction feasibility and structural safety^[9]. In typical courtyards, angled drilling limits settlement to 5%–8%, about 70% lower than vertical drilling, and effectively mitigates disturbance to ancient building foundations.

The lightweight self-propelled micro-rig with wear-resistant drill bits, modular body, and vibration & noise reduction design can freely pass and operate in lanes as narrow as 1.2 m. Field tests reduce single-hole construction time from 5 hours to 3 hours and vibration amplitude from 2 mm to 0.5 mm, balancing construction efficiency and structural safety.

Systematic structural protection measures including foundation underpinning, external wall bracing, waterproof anti-seepage and operation zone vibration isolation ensure wall crack expansion ≤ 1 mm, vibration amplitude ≤ 0.5 mm and construction noise ≤ 65 dB. The applicability and reliability of micro-pile reinforcement for ancient building complexes are verified via protection effects and construction coordination.

The research proves that micro-pile reinforcement can be efficiently and safely implemented in narrow courtyard environments. The technical route combining drilling path optimization, improved micro-rigs and comprehensive protection design provides a replicable reference for the conservation of similar ancient building complexes.

Disclosure statement

The authors declare no conflict of interest.

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Analysis on the Application of Field Testing Technology for Cement Concrete Pavement Strength

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Abstract: As the core structure of road engineering, the strength performance of cement concrete pavement has a direct impact on the pavement bearing capacity, service life, and driving safety after later operations. This study combines the actual construction and operation needs of road engineering sites to conduct systematic research on three mainstream on-site testing technologies for concrete pavement strength. These techniques are the rebound method, ultrasonic rebound comprehensive method, and core drilling method. The purpose is to accurately grasp the physical quality of the road surface and effectively identify structural hazards. After expounding the core purpose and specification requirements of strength testing, this paper analyzes the working principle, supporting equipment, operation steps, and core technical points of the three technologies one by one. This paper also compares the parameters of the three technologies, so as to highly clarify the applicability of the technologies under different working conditions.

Keywords: Field detection; Cement concrete; Pavement strength; Rebound method; Ultrasonic-rebound method

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1. Introduction

Under the background of long-term road service, the road surface is frequently affected by multidimensional factors such as vehicle load compaction, rainwater erosion, alternating temperature and humidity changes, and construction process deviations. The road surface is prone to diseases such as cracking, hollowing, damage, and strength attenuation. This has a serious negative impact on the traffic quality and service life of the road surface. Strength, as the core indicator for evaluating the structural performance and quality status of cement concrete pavement, focuses on the systematic application analysis of three mainstream on-site testing technologies, and compares the advantages, disadvantages, and applicability of various technologies. This can effectively provide standardized and scientific technical support for on-site inspection work, and provide technical guarantees for the quality and long-term operational safety of cement concrete pavement

engineering^[1].

2. Purpose and requirements for strength testing of cement concrete pavement

2.1. Purpose of testing

On-site testing of cement concrete pavement strength is the core work of road engineering quality acceptance and later operation and maintenance control. The core purpose is to accurately determine the solid strength of pavement concrete and confirm whether it meets the design standards and relevant specifications. From the perspective of engineering construction, on-site inspection work can effectively identify potential local defects, insufficient strength, and other defects that may be reserved in multiple construction processes such as concrete pouring, vibration, and curing, achieving precise positioning of engineering quality hazards^[2]. From the perspective of road operation, under the erosion of the natural environment and long-term load, the strength of concrete pavement inevitably deteriorates slowly. Regular intensity testing will enable operating units to monitor the patterns of changes in road performance effectively. At the same time, combining strength indicators to determine the causes of pavement diseases provides data support for subsequent maintenance, repair, and reinforcement projects.

2.2. Testing requirements

The on-site testing of the strength of cement concrete pavement must strictly comply with national and industry standards such as the “Test Regulations for Cement Concrete Raw Materials in Highway Engineering” and the “Technical Regulations for Testing the Compressive Strength of Concrete by Rebound Method.” At the same time, the testing team needs to combine engineering design documents and construction standards to implement standardized and regulated operations for testing work, ensuring the accuracy, authenticity, and effectiveness of testing data. In addition, the inspection team needs to reasonably arrange the inspection points based on the scope of road construction, structural zoning, and disease distribution, strictly control the environmental conditions and operating procedures, and standardize the equipment operation procedures. The testing team ensures that the technical parameters of testing intensity, angle, and spacing are unified to prevent data deviation caused by human operation errors^[3].

3. On-site testing of cement concrete pavement strength

3.1. Strength testing of cement concrete based on rebound method

3.1.1. Technical principles and equipment

The rebound method belongs to the most widely used non-destructive testing technology in the current industry. The core principle of this technology is to estimate strength results based on the correlation between concrete surface hardness and compressive strength. The compressive strength of concrete materials is positively correlated with their surface elastic hardness. Under the action of standard spring elasticity, the rebound rod of the rebound instrument vertically impacts the flat surface of the concrete. During the impact, the surface of the concrete will undergo elastic deformation. The rebound value of the rebound rod of the equipment can directly reflect the hardness of the concrete surface^[4]. Based on a large number of experiments, a conversion curve between rebound value and concrete standard compressive strength can be established to calculate the compressive strength of the tested pavement concrete accurately. The core

equipment during the application of the rebound method includes a concrete rebound tester, a carbonation depth measuring instrument, and auxiliary tools such as sandpaper, a brush, and a record sheet.

3.1.2. Testing steps and key points

The steps for conducting strength testing of cement concrete pavement based on the rebound method mainly follow the standardized process of preliminary preparation, point layout, surface treatment, on-site testing, and data correction.

Step 1: Preliminary preparation. The testing team in this stage needs to verify the rebound instrument calibration certificate to confirm that the equipment performance is intact and meets the standards. During this process, the team can calibrate using a standard steel anvil to ensure that the calibration error is controlled within the allowable range of the specifications. On this basis, the road surface area to be measured is strictly cleaned to avoid special positions such as cracks, joints, pits, corners, etc., and the area to be measured is reasonably divided based on the area of the road section to be measured. The area of a single measurement area should be controlled at $200\text{mm} \times 200\text{mm}$, and the number of measurement areas for each pavement slab should be ≥ 10 . Step 2: Surface treatment of the survey area. In order to ensure the key step of detection accuracy, the monitoring team used sandpaper to polish the surface of the survey area and removed the floating slurry, stains, and peeling to ensure that the surface was smooth, solid, dry, and free of debris interference. Step 3: On-site bounce detection. During the operation, the team needs to place the rebound gauge perpendicular to the surface of the concrete pavement measurement area. The rebound gauge applies pressure slowly and uniformly. Read and record the rebound value after the impact rod completes the impact and rebound. Each testing area requires the rebound gauge to bounce continuously 16 times. After removing the 3 maximum and 3 minimum values, the team calculated the remaining 10 average values and used them as the effective rebound values for the measurement area. On this basis, the team used a carbonization depth measuring instrument to select 3 points for carbonization depth detection in each measurement area, and collected the average value as the final carbonization depth value of the measurement area. Step 4: Data correction. After completing the on-site testing, the monitoring team needs to use the concrete pouring process, curing age, and carbonation depth to effectively correct the original rebound data. The team then uses the standard conversion formula to calculate the estimated compressive strength of the concrete. This ensures that the test data closely matches the actual strength of the pavement structure.

3.2. Strength testing of cement concrete based on ultrasonic rebound comprehensive method

3.2.1. Technical principles and equipment

The ultrasonic rebound comprehensive method belongs to a composite non-destructive testing technology that combines ultrasonic testing and rebound testing. It can not only effectively make up for the lack of detection accuracy of the single rebound method, but also solve the defect of insufficient stability of the single ultrasonic method. The technical principle of the ultrasonic rebound comprehensive method is that the compressive strength of concrete has a stable correlation with surface hardness and internal compactness values. The rebound value can reflect the surface hardness and strength state of concrete. The application of ultrasound reflects the internal density, porosity, and overall uniformity of concrete by propagating sound velocity inside the concrete. During the period of mutual supplementation and correction of two technical

parameters, a ternary conversion relationship of “rebound value—sound velocity—compressive strength” can be established to estimate the overall compressive strength of concrete accurately. The accuracy and reliability of the test results can be improved. The ultrasonic rebound comprehensive method is equipped with testing equipment that focuses on concrete rebound testers, non-metallic ultrasonic detectors, transducers, and coupling agents. The non-metallic ultrasonic detector is the core equipment. This device has data storage, sound velocity testing, and automatic correction functions, and is highly suitable for large-scale detection in concrete pavement engineering. The coupling agent is responsible for eliminating the air gap between the transducer and the concrete surface, and improving the stability of ultrasonic propagation ^[5].

3.2.2. Testing steps and key points

The ultrasonic rebound comprehensive method testing process covers four major steps: equipment calibration, measurement area layout, rebound testing and ultrasonic testing, and data integration and conversion.

Step 1: equipment calibration. In this stage, the monitoring team needs to carry out steel anvil calibration and acoustic time calibration for the rebound tester and ultrasonic detector, respectively, to ensure that the instrument accuracy meets the standard. Step 2: Test area layout. The team strictly cleans the testing area of the road surface, polishes and flattens the surface, and removes any floating slurry and debris. The team can maintain consistency with the rebound method for the layout standards of the testing area. The team evenly distributes the testing areas, and for each testing area, the team performs rebound testing and ultrasonic testing simultaneously. This ensures the matching of the two sets of data. Step 3: Rebound testing and ultrasonic testing. Among them, the operation process of rebound detection is consistent with the single rebound method. The team records the effective rebound average and carbonization depth values of each testing area to collect surface strength parameters accurately. During the ultrasonic testing period, the team used the matching method to arrange the testing points. The team symmetrically arranged the transducers on both sides of the testing area, and then evenly applied coupling agent to ensure that the transducers and concrete surfaces were tightly adhered without displacement or hollowing. The team started the instrument and emitted ultrasonic waves. They recorded the sound time and speed values of ultrasonic waves propagating inside concrete, and repeated the testing work three times in each measurement area. After removing abnormal data, they took the average value as the effective sound speed value. During the operation, in order to ensure the synchronization and matching of the two detection data, the detection position cannot be changed after confirming the detection point position in the same measurement area. At the same time, it is necessary to strictly control the spacing and detection angle of the transducers to ensure the stability of the ultrasonic propagation path. Step 4: Data integration and conversion. After completing the rebound and ultrasonic data acquisition, the computer combines the rebound value, sound velocity value, and carbonation depth value to estimate the compressive strength of concrete using a standardized ternary conversion formula.

3.3. Strength testing of cement concrete based on core drilling method

3.3.1. Technical principles and equipment

The core drilling method is the only “semi-damaged direct detection” technology in the strength testing of cement concrete pavement. It is also a recognized precision testing technology in the industry, often used as

a calibration basis for other non-destructive testing techniques. The core principle of the core drilling method is the use of drilling equipment. The team drilled standard cylindrical core samples from the pavement concrete slab and then conducted laboratory pressure tests to complete compressive strength tests on the core samples. Then they can directly determine the actual compressive strength of concrete. This technology does not require a parameter conversion process and can directly obtain strength data based on solid core samples. It can truly and intuitively reflect the overall strength state of concrete pavement from the surface to the interior. The core testing equipment of the core drilling method includes drilling and coring machines, which can be divided into electric water-cooled and gasoline-based coring machines. The supporting equipment includes core sample trimming equipment, diamond hollow drill bits, pressure testing machines, calipers, and maintenance water tanks ^[6]. Among them, the pressure testing machine is the core equipment in the laboratory, used to determine the ultimate compressive load of the core sample accurately.

3.3.2. Testing steps and key points

The core drilling method detection process includes four steps: point layout, drilling and coring, core sample processing, and laboratory pressure test strength determination. Due to its potential to cause minor damage to the road surface, it is necessary to strictly control the operating range during the operation ^[7].

Step 1: Point layout. Based on the distribution of road surface blocks, the team evenly selects core sampling points. This process needs to avoid road joints, damage, and steel reinforcement positions, while also avoiding the core areas of road traffic and driving. During the deployment period, the number of cores taken from a single detection section should be ≥ 3 to ensure the representativeness of the data. On the basis of confirming the location, the team strictly cleaned up the work area and ensured safety protection, fixing the core-taking machine equipment to ensure its horizontal and vertical stability. Step 2: Drilling and coring operations. Taking the water-cooled drilling method as an example, the team continuously supplies water to cool the drill bit during drilling, reducing the damage caused by high-temperature drilling friction to the core structure. At the same time, they strictly control the drilling depth, determining the depth based on the design thickness of the road surface to ensure the drilling of complete core samples and avoid core sample breakage, missing corners, or delamination. Step 3: Core sample processing. After the core extraction is completed, the team promptly seals the drilled holes on the road surface. They use specialized repair mortar for backfilling and compaction to ensure the restoration of road smoothness and integrity, avoiding damage expansion and water accumulation in holes. Subsequently, they labeled the extracted core samples with numbers and transported them to the laboratory for standard maintenance. After completing the maintenance work, they polished and leveled the end face of the core sample, effectively removing burrs and concave-convex defects on the surface of the core sample. Step 4: Determination of laboratory pressure test strength. The team places qualified core samples at the center of the pressure testing machine, and then conducts compressive tests on the equipment under constant loading. During the experiment, they strictly recorded the ultimate load of the core sample and calculated the compressive strength of the concrete based on the cross-sectional area of the core sample. During the experiment, it is necessary to take the average value of multiple core samples for testing as the detection result ^[8].

4. Comparison and applicability analysis of three testing technologies

In order to accurately distinguish the application advantages, monitoring efficiency, accuracy, and other

numerical values of various technologies, and ensure that they can adapt to the testing scenarios of different projects in practice, this study conducts a horizontal comparative analysis of the core performance indicators of the three testing technologies. The specific comparison of core parameters is shown in **Table 1**:

Table 1. Comparison of core technical parameters of rebound method, ultrasonic rebound comprehensive method, and core drilling method

Detection technology	Detection accuracy	Detection efficiency	Equipment cost	Degree of road damage
Rebound Method	General: The error is between 10% and 15%.	Extremely high, this method is suitable for large-scale surveys	Low, its equipment is portable and inexpensive	There was no damage
Ultrasonic Rebound Comprehensive Method	Higher: The error is between 5% and 8%.	Medium, the efficiency of this method is slightly lower than that of the rebound method	Medium, it has complete supporting equipment	There was no damage
Core Drilling Method	Very high: The error is less than or equal to 3%.	Low, this method has a complex workflow	High, its equipment and testing costs are high	There is a slight semi-damage

As shown in **Table 1**, from the perspective of technical performance and engineering applicability, the three technologies can form a complementary detection system that can effectively adapt to different detection scenarios. The rebound method has the advantages of high efficiency, convenience, low cost, and no damage. It is suitable for large-scale surveys of newly built road surfaces, screening of old road surfaces, and regular inspection of operation and maintenance work during later operation. However, this technology can only effectively reflect the surface strength, and the data is susceptible to external interference, resulting in limited accuracy ^[9]. The ultrasonic rebound comprehensive method will combine the advantages of the rebound method and ultrasonic method technology. It can simultaneously detect the surface hardness and internal compactness of concrete. Its data stability and accuracy have been improved, and it can avoid errors caused by carbonization and surface wear. As a precise benchmark detection technology, the core drilling method produces more authoritative and reliable detection results compared to other techniques. But it will cause slight damage to the road surface and have low detection efficiency. It is suitable for arbitration testing, engineering completion acceptance, and review of various non-destructive testing technology results for quality dispute sections ^[10].

5. Conclusion

In summary, this study systematically investigates the principles, equipment, operational procedures, and core points of three mainstream on-site detection techniques: rebound method, ultrasonic rebound comprehensive method, and core drilling method. This study clarified the performance differences and applicable scenarios of different technologies through comparison. Based on the research results, it can be concluded that the three detection technologies have their own advantages and complement each other. During actual engineering applications, the monitoring team should combine the engineering scenario, detection purpose, and accuracy requirements to reasonably match the detection technology and standardize the process of detection operations. In doing so, the team fully utilizes the inherent advantages of each method, avoids technical shortcomings, and improves the quality and efficiency of pavement strength detection. The team effectively supports the quality control of cement concrete pavement construction, post-maintenance and repair, as well

as the treatment of old road section diseases.

Disclosure statement

The author declares no conflict of interest.

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Evaluating Large Language Models in Green Building Design Decisions: A Case-Based Analysis of Energy, Water, and Material Trade-Offs

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Abstract: *Background:* AI has shown potential across technical professions, yet its application to green building design—navigating trade-offs between energy efficiency, water conservation, and materials lifecycle assessment (LCA)—remains unevaluated. No prior study has benchmarked frontier large language models (LLMs) using a professor-validated instrument combining multiple-choice question (MCQ) and True/False (T/F) items probing context-dependent sustainability reasoning. *Objective:* To comparatively benchmark four frontier LLMs—Claude, ChatGPT-5.2, DeepSeek-R1, and Gemini 3.1—on a validated 80-item instrument (40 MCQs and 40 True/False statements) derived from 20 green building design scenarios spanning materials, energy, water, and cross-domain lifecycle trade-off reasoning. *Methods:* 80 items from 20 original scenarios were validated by two professors. MCQs required selection of the optimal design alternative under competing sustainability constraints; True/False items used context-dependent partial truths (Statements 1–20: False via contextual override; 21–40: True) to evaluate resistance to overgeneralization. Items were grounded in LEED v4.1, ASHRAE 90.1, and ISO 14044. Each model was evaluated under identical zero-temperature conditions using binary scoring. Pearson Chi-square tests were applied for inter-model and inter-format comparisons. *Results:* Claude achieved the highest overall accuracy (95.00%; 95% CI: 90.22–99.78%), followed by DeepSeek-R1 (93.75%), ChatGPT-5.2 (88.75%), and Gemini 3.1 (83.75%). No statistically significant difference across chatbots was found ($\chi^2 = 7.251$, $df = 3$, $P = 0.064$). No significant MCQ-vs-T/F differential was observed for any model (all $P > 0.05$); pooled T/F accuracy (91.3%) marginally exceeded pooled MCQ accuracy (89.4%). *Conclusions:* This is the first study to benchmark multiple frontier LLMs in green building design using a purpose-built, professor-validated instrument evaluating both design-alternative selection and resistance to absolute sustainability heuristics. Consistent performance declines in cross-domain lifecycle scenarios reveal residual multi-framework integration limitations across all models. Findings support LLM integration into green building education and decision-support, while underscoring the need for expert oversight in complex design contexts.

Keywords: Large language models; Green building design; Sustainable architecture; Benchmark evaluation; Energy efficiency; Water conservation; LCA; LEED; Claude; ChatGPT; DeepSeek; Gemini

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1. Introduction

Frontier large language models (LLMs), such as Claude, ChatGPT-5.2, DeepSeek-R1, and Gemini 3.1, can interpret complex technical prompts, reason across multi-criteria problems, and generate expert-like responses ^[1–4]. In architecture and engineering, LLMs address questions spanning energy modeling, building regulation, and sustainability with moderate-to-high accuracy, though performance varies by model and domain ^[5–7].

Green building design demands simultaneous integration of ASHRAE 90.1, water management, ISO 14044 Lifecycle Assessment (LCA), and Leadership in Energy and Environmental Design (LEED) v4.1 ^[8–12]. Systematic reviews catalog broad sustainability uses of LLMs without addressing validated, mixed-format instruments grounded in multi-domain lifecycle reasoning ^[13–14]. Practitioners must navigate scenarios where individually optimal domain choices conflict—e.g., thermally superior insulation with high embodied carbon, or on-site renewables vs. envelope improvement. A critical artificial intelligence (AI) failure mode is applying absolute heuristics (e.g., “local materials always have lower impact”) without contextual adjustment. The True/False (T/F) component was engineered to target this failure: 20 False statements via contextual overrides and 20 True statements under established LCA principles.

No peer-reviewed study has evaluated LLMs on a professor-validated instrument combining MCQ design-alternative scenarios with high-difficulty True/False contextual partial-truth items across the full scope of green building domains (literature search: January 2023–August 2025) ^[5–7, 12]. This study aims to: (1) compare the overall accuracy of four frontier LLMs on 80 validated green building items; (2) assess performance differences by question format; and (3) identify domain-specific patterns of competency and limitation.

2. Methodology

2.1. Scenarios and questions

20 original green building scenarios were developed across four domains: materials and resources (Scenarios 1–5), energy efficiency (6–10), water conservation (11–15), and cross-domain lifecycle trade-off reasoning (16–20). Two MCQs per scenario (40 total; 4 options each) required integration of sustainability trade-offs rather than single-domain recall. 40 True/False items were constructed independently: Statements 1–20 were False via contextual override of general principles (all using “always”-assertions); Statements 21–40 were True under established LEED, ASHRAE, and LCA principles. Only text-based items were included.

2.2. Expert validation

Two professors independently assessed all 80 items against: (1) alignment with LEED v4.1, ASHRAE 90.1, and ISO 14044; (2) answer unambiguity within scenario context; (3) distractor plausibility / True/False contextual boundaries; and (4) difficulty appropriateness. Discordant ratings were resolved by structured consensus referencing primary technical standards.

2.3. Evaluation procedure

Each item was entered independently into all four chatbots using identical wording and format in fresh sessions to prevent prompt leakage. All models operated at temperature = 0. Three trials per item were conducted; modal responses were recorded for any inconsistency. Models were evaluated within a

consistent window to control for version confounds. The four LLMs represent diverse architectures: Claude (constitutional AI), ChatGPT-5.2 (RLHF), DeepSeek-R1 (mixture-of-experts with chain-of-thought pretraining), and Gemini 3.1 (Google DeepMind).

2.4. Assessment metrics

Binary scoring: correct = 1, incorrect = 0. Primary outcome: overall accuracy (80 items). Secondary: accuracy by format (MCQ vs. T/F). Pearson Chi-square tests for inter-model (χ^2 , $df = 3$) and intra-model format comparisons (χ^2 , $df = 1$). 95% CIs via the Wilson score method. Two-tailed; $P < 0.05$ threshold.

3. Results

Claude achieved the highest overall accuracy (76/80; 95.00%; 95% CI: 90.22–99.78%). DeepSeek-R1 followed (75/80; 93.75%), then ChatGPT-5.2 (71/80; 88.75%), and Gemini 3.1 (67/80; 83.75%), as shown in **Table 1**. Overall performance spread: 11.25 percentage points.

Table 1. Accuracy of AI chatbots ($n = 80$ items per model)

Model	Correct (of 80)	Accuracy (%)	SD	95% CI (%)
Claude	76	95.00	0.218	90.22–99.78
DeepSeek-R1	75	93.75	0.242	88.44–99.06
ChatGPT-5.2	71	88.75	0.316	81.83–95.67
Gemini 3.1	67	83.75	0.369	75.66–91.84

Note: SD = standard deviation. 95% CI = Wilson score confidence interval.

Pearson Chi-square across all chatbots: $\chi^2(3) = 7.251$, $P = 0.064$. The marginal non-significance is likely attributable to a moderate sample size ($n = 80/\text{model}$). All four models substantially exceeded random baselines (25% MCQ, 50% T/F).

Format analysis: Claude achieved 92.5% MCQs / 97.5% T/F ($P = 0.305$); DeepSeek-R1 92.5% / 95.0% ($P = 0.644$); ChatGPT-5.2 87.5% / 90.0% ($P = 0.723$); Gemini 3.1 85.0% / 82.5% ($P = 0.762$), as shown in **Table 2**. No significant MCQ-vs-T/F differential for any model (all $P > 0.05$).

Table 2. Performance by question format per chatbot

Model	MCQ Correct	MCQ (%)	T/F Correct	T/F (%)	Diff. (pp)	P-value
Claude	37/40	92.5	39/40	97.5	+5.0	0.305
DeepSeek-R1	37/40	92.5	38/40	95.0	+2.5	0.644
ChatGPT-5.2	35/40	87.5	36/40	90.0	+2.5	0.723
Gemini 3.1	34/40	85.0	33/40	82.5	-2.5	0.762

Note: T/F = True/False. All $P > 0.05$.

Pooled across all models: 143/160 MCQ responses correct (89.4%) and 146/160 T/F correct (91.3%). Three of four models performed marginally better on T/F than MCQ—indicating the high-difficulty True/False format did not systematically disadvantage models. Gemini 3.1 was the sole exception (T/F 82.5% vs. MCQ 85.0%), potentially indicating greater sensitivity to the contextual partial-truth framing.

All models performed strongest in materials and resources (Scenarios 1–5), with consistent accuracy decline through energy, water, and cross-domain scenarios. Cross-domain lifecycle trade-off scenarios (16–20) were the most challenging; Gemini 3.1 dropped to ~70%. Performance ranking—Claude > DeepSeek-R1 > ChatGPT-5.2 > Gemini 3.1—was stable across all domains.

4. Discussion

All four chatbots performed substantially above chance, with Claude achieving 95.00% and all models exceeding 83%, indicating that frontier LLMs encode meaningful LEED-aligned green building knowledge and can apply it reliably in structured text-based scenarios^[15–18]. Performance declined progressively from materials through energy, water, to cross-domain scenarios—consistent with increasing need for simultaneous integration of multiple technical frameworks—and this domain-ordering pattern was stable across all models.

The absence of significant MCQ-vs-T/F differentials for any model validates the mixed-format design, confirming both item types assess a consistent underlying competency construct. That three of four models performed marginally better on T/F (despite elevated design difficulty) indicates the contextual partial-truth format successfully assessed domain knowledge rather than a separate format-dependent skill. Gemini 3.1's slight T/F underperformance may reflect differential sensitivity to “always”-assertion constructions.

The professor validation process—two independent LEED AP BD+C-accredited experts reviewing all 80 items against LEED v4.1, ASHRAE 90.1, and ISO 14044, with structured consensus for discordant ratings—substantially strengthens internal validity over prior LLM sustainability evaluations using unvalidated question sets^[5, 7]. DeepSeek-R1's high performance (93.75%) may reflect its mixture-of-experts (MoE) architecture and chain-of-thought pretraining supporting multi-framework integration. Gemini 3.1's wider CI (75.66–91.84%) suggests less stable green building knowledge encoding.

Limitations: no human comparison group (LEED practitioners or students); exclusion of graphical content; risk that performance partly reflects training-data recognition. Post-hoc power analysis estimates 120–150 items per model needed for 80% power to detect the observed 11.25 pp differential at $\alpha = 0.05$. Future work should incorporate human benchmarks, diverse validated sources, and retrieval-augmented generation (RAG) coupling LLMs with structured green building knowledge bases.

5. Conclusion

Claude, DeepSeek-R1, ChatGPT-5.2, and Gemini 3.1 can accurately answer professor-validated, case-based green building design items across energy efficiency, water conservation, materials, and cross-domain lifecycle trade-off reasoning, with overall accuracies of 83.75%–95.00% across an 80-item instrument. This is the first study to benchmark multiple frontier LLMs in green building design using a purpose-built, professor-validated instrument simultaneously evaluating design-alternative selection and resistance to absolute sustainability heuristics. Although no statistically significant overall difference was found ($\chi^2 = 7.251$, $df = 3$, $P = 0.064$), and no significant MCQ-vs-T/F differential was detected for any model (all $P > 0.05$), consistent performance declines in cross-domain lifecycle scenarios reveal residual multi-framework integration limitations. These findings support further validation, larger datasets, and expert human oversight before autonomous LLM deployment in high-stakes sustainable building design contexts.

Disclosure statement

The authors declare no conflict of interest.

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Research on the Optimization of Bearing Capacity of Drilled Pile Structures Using Post-Grouting Technology

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Abstract: To study the improvement effect of post-grouting technology on the bearing performance of drilled cast-in-place piles under complex geological conditions, six drilled cast-in-place piles of a project in Yunnan are taken as research objects in this paper. Starting from field construction data collection, parameter measurement, and comparative analysis, the variation laws of key parameters such as grouting pressure and grouting volume during post-grouting construction are systematically investigated, which verifies that post-grouting technology can improve the bearing capacity of pile foundations. The research results show that cement slurry with a water-cement ratio of 1:0.6 is adopted for all six piles of this project. After primary grouting, secondary grouting, and supplementary grouting, the actual grouting volume of every single pile exceeds the designed value. Among them, the actual grouting volume of Pile SYZA2 reaches 10.7 tons, exceeding the designed value by 78.3%. The grouting pressure rises first and then stabilizes with the grouting time, while the cumulative grouting volume increases in a stepped manner as time elapses. The multi-stage grouting process can improve the uniformity of slurry diffusion. The research findings can provide parameter references and a practical basis for post-grouting construction of drilled cast-in-place piles under similar geological conditions.

Keywords: Drilled cast-in-place pile; Post-grouting technology; Bearing performance; Grouting parameters; Engineering practice

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1. Project overview and post-grouting construction scheme

1.1. Engineering geology and pile foundation design overview

The project is located in Yunnan, and the site geology is mainly a clay layer. The bearing stratum of Piles SYZA1, SYZA2 and SYZA3 is the ⑧₃ clay layer, while the bearing stratum of Piles SYZB1, SYZB2 and SYZB3 is the ⑦₃ clay layer, both of which are stable engineering geological layers.

All six test piles of this project adopt Φ1000 drilled cast-in-place piles, and the concrete strength grade of pile shafts is C50 underwater concrete. The detailed design parameters are shown in **Table 1**. The long pile

group (SYZA1\SYZA3) has a pile length of about 93\95 m with a designed single-pile grouting volume of 6 tons; the short pile group (SYZB1\SYZB3) has a pile length of about 71\73 m with a designed single-pile grouting volume of 5 tons. Cement slurry with a water-cement ratio of 1:0.6 is adopted for all test piles.

Table 1. Summary of core design parameters of six test piles of the Yunnan project

Pile No.	Pile Length (m)	Pile Diameter	Bearing Stratum	Concrete Strength	Designed Grouting Volume (t)	Water-Cement Ratio
SYZA1	94.91	Φ1000	⑧ ₃ Clay Layer	C50 Underwater Concrete	6	1:0.6
SYZA2	94.58	Φ1000	⑧ ₃ Clay Layer	C50 Underwater Concrete	6	1:0.6
SYZA3	93.25	Φ1000	⑧ ₃ Clay Layer	C50 Underwater Concrete	6	1:0.6
SYZB1	72.36	Φ1000	⑦ ₃ Clay Layer	C50 Underwater Concrete	5	1:0.6
SYZB2	71.92	Φ1000	⑦ ₃ Clay Layer	C50 Underwater Concrete	5	1:0.6
SYZB3	71.85	Φ1000	⑦ ₃ Clay Layer	C50 Underwater Concrete	5	1:0.6

1.2. Design of post-grouting construction technology

Pile tip post-grouting technology is adopted for all test piles of this project. The construction process includes hole forming, steel reinforcement cage installation, concrete pouring, grouting pipe installation, pipe opening, primary grouting, secondary grouting, supplementary grouting, and grouting termination ^[1].

Ordinary Portland cement P.O 42.5 is used for slurry preparation, and the water-cement ratio is strictly controlled at 1:0.6 to ensure slurry fluidity and consolidation strength and reduce the risk of slurry dilution by underground water.

Pipe opening construction: High-pressure water is used for pipe opening after concrete pouring is completed, with opening pressure controlled within 0.8~3.0 MPa to ensure unobstructed grouting pipes and lay a foundation for subsequent grouting operations.

Multi-stage grouting: A three-stage construction process consisting of primary grouting, secondary grouting, and supplementary grouting is adopted. Primary grouting serves as the main stage to complete most slurry injection; secondary grouting supplements weak areas left by primary grouting; supplementary grouting carries out final reinforcement according to grouting pressure and slurry diffusion conditions to ensure uniform slurry diffusion in soil at the pile tip ^[2-4].

Grouting termination criteria: Grouting shall be terminated when the grouting pressure reaches the designed termination pressure, the cumulative grouting volume exceeds the designed value, or the slurry injection rate keeps decreasing, so as to guarantee the grouting effect meets design requirements.

1.3. On-site data collection scheme

To fully understand the variation laws of parameters during post-grouting construction, real-time data collection is carried out for the whole grouting construction process of six test piles, and the collected contents are as follows:

Basic parameters: Design parameters including pile number, pile length, pile diameter, bearing stratum,

designed grouting volume and water-cement ratio;

Construction time parameters: Pipe opening time, grouting start time, grouting termination time and time nodes of each grouting stage;

Core grouting parameters: Grouting pressure, cumulative grouting volume and single-stage grouting volume at each time node;

Abnormality records: Records and treatment measures for slurry leakage, abnormal pressure and other faults during grouting.

All collected data are acquired in real time by sensors equipped on on-site grouting equipment, and special personnel conduct manual data review simultaneously to guarantee data accuracy and integrity, providing a reliable basis for subsequent parameter analysis and effect verification.

2. Measurement and variation law analysis of post-grouting construction parameters

2.1. Measured grouting parameters of single pile

Taking Pile SYZA1 as an example, measured analysis is conducted on core parameters of its three-stage grouting construction. The designed grouting volume of this pile is 6 tons, while the actual cumulative grouting volume is 7.9 tons, exceeding the designed value by 31.7%. The total grouting duration is 7 hours and 11 minutes, and the variation of grouting parameters in each stage is shown in **Figure 1**.

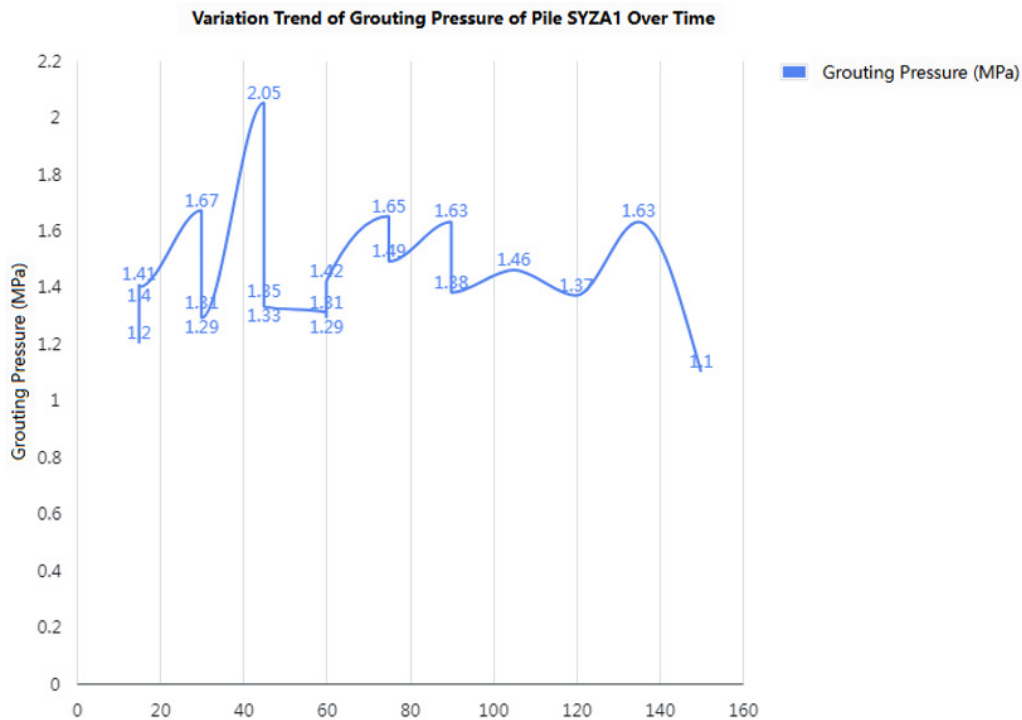


Figure 1. Variation trend of grouting pressure of pile SYZA1 with time (line chart)

From the variation trend of grouting pressure: In the primary grouting stage, the grouting pressure rises rapidly at first, then the growth slows down and finally stabilizes. The pressure reaches 1.2 MPa at the 15th

minute and peaks at 2.05 MPa at the 45th minute, then fluctuates between 1.1~1.65 MPa until the end of primary grouting. The cumulative grouting volume is 4.25 tons, accounting for 53.8% of the total grouting volume. In the secondary grouting stage, the grouting pressure basically stabilizes at about 1.29~1.41 MPa with slight fluctuation without an obvious peak value, and the cumulative grouting volume is 1.85 tons, accounting for 23.4% of the total volume. In the supplementary grouting stage, the grouting pressure rises slightly first and then levels off, reaching the maximum value of 1.49 MPa at the 75th minute, with a cumulative grouting volume of 1.8 tons, accounting for 22.8% of the total volume.

It can be seen from the variation trend of cumulative grouting volume that the cumulative grouting volume of Pile SYZA1 keeps increasing with the grouting time (**Figure 2**). The growth rate of grouting volume is the fastest in the first stage: 4.25 tons of slurry is injected within 150 minutes, with an average injection rate of 0.028 tons per minute. The growth rate slows down in the secondary grouting stage: 1.85 tons of slurry is injected within 60 minutes, with an average injection rate of 0.031 tons per minute. The growth rate remains basically unchanged in the supplementary grouting stage: 1.8 tons of slurry is injected within 90 minutes, with an average injection rate of 0.02 tons per minute. The three-stage grouting process enables continuous and uniform slurry injection and avoids local slurry accumulation caused by one-time single-stage grouting.

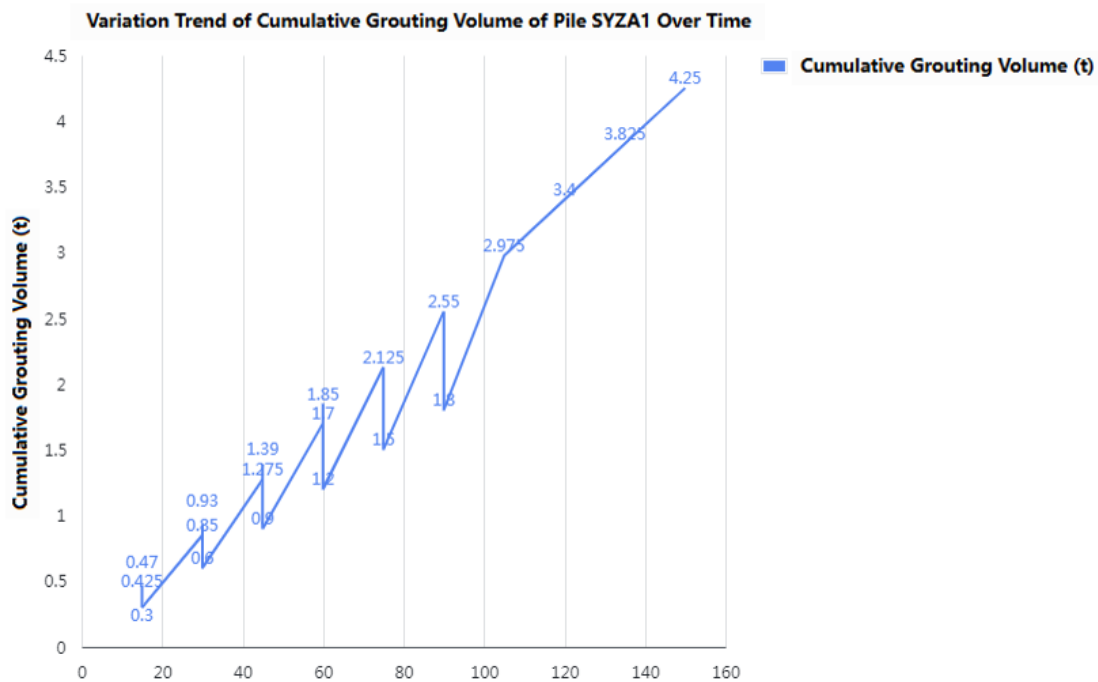


Figure 2. Variation trend of cumulative grouting volume of pile SYZA1 with time (broken line chart)

2.2. Comparative analysis of grouting parameters of multiple piles

The comparison between designed and actual grouting volumes of six test piles of the project is shown in **Figure 3**. The actual grouting volume of all test piles exceeds the designed value, presenting an obvious characteristic that “the grouting volume of long piles is larger than that of short piles.”

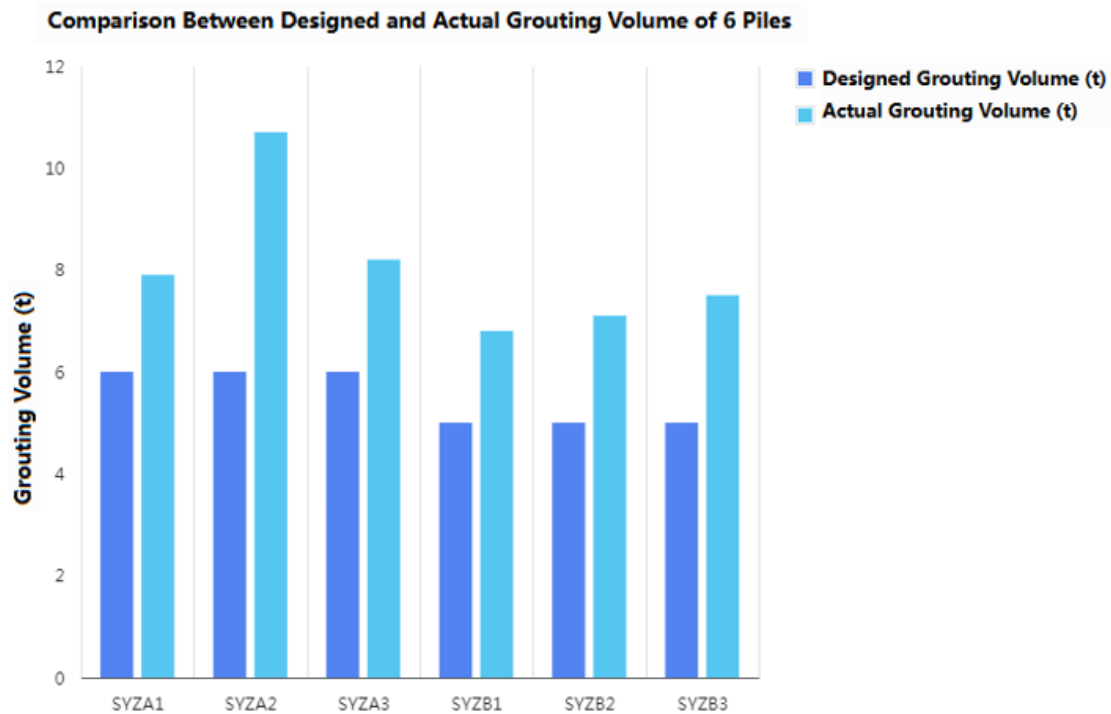


Figure 3. Bar chart of comparison between designed and actual grouting volumes of six piles

The comparison results show that the designed grouting volume of the long pile group (SYZA1~SYZA3) is 6 tons, and their actual grouting volumes are 7.9 tons, 10.7 tons, and 8.2 tons, respectively, with an average excess of 47.2% over the designed value. Among them, Pile SYZA2 has the maximum actual grouting volume of 10.7 tons, exceeding the designed value by 78.3%. This is mainly because slurry leakage occurred during its primary grouting stage; after supplementing 2.9 tons of slurry, secondary grouting was carried out to complete reinforcement. The designed grouting volume of the short pile group (SYZB1~SYZB3) is 5 tons, and their actual grouting volumes are 6.8 tons, 7.1 tons, and 7.5 tons, respectively, with an average excess of 42.7% over the designed value. Pile SYZB3 has the maximum actual grouting volume of 7.5 tons, exceeding the designed value by 50%.

Overall, the actual grouting volume of all six piles surpasses the designed value. The main reasons are as follows: The site of this project is covered by a clay layer with good soil permeability, so the actual slurry diffusion range is larger than expected in design. Meanwhile, to guarantee the pile foundation reinforcement effect, the grouting volume is appropriately increased during construction according to grouting pressure and slurry diffusion conditions. Therefore, the grouting effect of all piles meets the design requirements.

2.3. Summary of variation laws of grouting parameters

Based on the field-measured data of six test piles of this project, the variation laws of key parameters during post-grouting construction are summarized as follows:

Variation law of grouting pressure: The grouting pressure generally presents a trend of “rising first and then stabilizing” with grouting time. The pressure rises fastest in the primary grouting stage and is prone to peak values. At the initial stage of grouting, the gaps between soil particles at the pile tip are large with low slurry injection resistance; as slurry is continuously injected, soil gaps are filled, injection resistance

increases, and pressure rises accordingly. In the secondary and supplementary grouting stages, the soil has been preliminarily reinforced with stable slurry injection resistance, so the pressure remains generally stable without obvious drastic fluctuation.

Variation law of cumulative grouting volume: The cumulative grouting volume increases in a stepped manner. The growth rate of grouting volume is the fastest in the primary grouting stage, which completes more than 50% of the total grouting volume and serves as the main grouting stage. The growth rate slows down in the secondary and supplementary grouting stages, which mainly reinforce weak areas and ensure uniform slurry diffusion.

Correlation law between pile length and grouting volume: Under identical geological conditions, the longer the pile, the larger both the designed and actual grouting volumes. This is because the soil at the tip of long piles bears greater force and requires more slurry for reinforcement. In addition, long piles are equipped with longer grouting pipes, leading to large slurry loss during transportation and requiring a larger injection volume.

3. Analysis of optimization effect of post-grouting technology on pile foundation bearing performance

3.1. Correlation analysis between grouting parameters and pile foundation bearing capacity

The improvement of pile foundation bearing capacity by post-grouting technology is mainly realized by injecting cement slurry to fill sediment gaps at the pile tip and reinforce soil around the pile, so as to improve pile tip resistance and pile side friction resistance. The following conclusions can be drawn based on measured data of this project and pile bearing capacity theories:

Correlation between grouting volume and pile tip resistance: The larger the cumulative single-pile grouting volume, the more significant the improvement effect of pile tip resistance. The actual grouting volume of all six piles of this project exceeds the designed value, and Pile SYZA2 with the maximum cumulative grouting volume of 10.7 tons achieves the best improvement of pile tip resistance. Sufficient slurry injection can fully fill sediment gaps at the pile tip to form continuous cement stone bodies, greatly enhancing the strength and stiffness of soil at the pile tip and further increasing pile tip resistance.

Correlation between grouting pressure and pile side friction resistance: Stable grouting pressure can effectively improve pile side friction resistance. The grouting pressure of test piles of this project is controlled within 1.0~2.0 MPa. Stable grouting pressure ensures uniform slurry diffusion into surrounding soil to form cement-soil reinforced bodies, expand the contact area between pile shaft and soil, improve the shear strength of surrounding soil, and thus significantly increase pile side friction resistance.

Correlation between multi-stage grouting and bearing capacity uniformity: The three-stage grouting process can effectively improve the uniformity of pile foundation bearing capacity. Primary grouting completes major slurry injection, while secondary and supplementary grouting supplement weak parts to avoid local slurry accumulation and uneven reinforcement caused by single-stage grouting. The soil at the pile tip and around the pile can be fully reinforced, improving the overall stability and uniformity of pile bearing capacity.

3.2. Analysis of construction adaptability under complex geological conditions

The site of this project features a clay layer, a typical complex engineering geological condition with good soil permeability, which easily causes uneven slurry diffusion and slurry leakage and puts high requirements on post-grouting construction technology ^[5]. Construction practice of this project proves that post-grouting technology has good adaptability to such geological conditions, which is reflected in the following aspects:

Adaptability of slurry proportion: Cement slurry prepared with a water-cement ratio of 1:0.6 in this project has favorable fluidity, can diffuse uniformly in clay layers, and possesses certain consolidation strength. It can fill soil gaps and reinforce surrounding soil, avoiding insufficient slurry strength caused by an excessively high water-cement ratio and poor fluidity caused by an excessively low water-cement ratio.

Adaptability of multi-stage grouting process: The three-stage grouting process adopted in this project can solve the problems of slurry leakage and uneven slurry diffusion easily occurring in clay layers. Primary grouting completes most slurry injection; if abnormalities such as slurry leakage occur, secondary and supplementary grouting can be adopted for slurry supplementation to achieve the expected grouting effect.

Real-time adjustment of construction parameters according to measured grouting pressure and grouting volume to guarantee a stable grouting process. For instance, slurry leakage occurred during primary grouting of Pile SYZA2. Construction workers timely adjusted grouting pressure and supplemented slurry volume, and pile foundation reinforcement was completed after secondary grouting to guarantee the reinforcement effect. Post-grouting technology presents strong adaptability for pile foundation reinforcement under complex geological conditions.

3.3. Optimization suggestions for construction

Based on the construction practice and parameter analysis of six test piles of this project, the following optimization suggestions are put forward for post-grouting construction of drilled cast-in-place piles under similar geological conditions:

Grouting parameter optimization: For clay layer geology, the water-cement ratio shall be controlled within 1:0.5~1:0.7 to guarantee slurry fluidity and consolidation strength. The primary grouting pressure shall be controlled within 1.0~2.0 MPa, while the secondary and supplementary grouting pressure shall be controlled within 1.0~1.5 MPa, to prevent excessive pressure leading to an excessively large slurry diffusion range and insufficient slurry injection caused by excessively low pressure ^[6].

Construction technology optimization: Adopt the three-stage grouting process, where primary grouting accounts for 50%~60% of the total grouting volume, secondary grouting accounts for 20%~30%, and supplementary grouting accounts for 10%~20%, so as to ensure uniform slurry injection. For geological conditions prone to slurry leakage, pre-reinforce the surrounding soil before grouting, monitor grouting pressure and grouting volume in real time during construction, and adjust construction parameters in a timely manner ^[7-9].

Quality control optimization: Conduct comprehensive inspection of grouting pipes, sensors, and other equipment before grouting construction to ensure normal operation of all devices. Arrange special personnel to monitor the whole grouting process and record data during construction to guarantee data accuracy and integrity ^[10]. Analyze grouting data promptly after construction completion and evaluate the grouting effect to ensure the pile foundation bearing capacity meets design requirements.

4. Conclusion

Taking six drilled cast-in-place piles of a Yunnan project as research objects, this paper systematically analyzes the application effect of post-grouting technology in drilled cast-in-place piles and the variation laws of relevant parameters through field construction data collection, parameter measurement, and comparative analysis. During post-grouting construction, the grouting pressure rises first and then stabilizes with grouting time; the pressure rises fastest and is prone to peak values in the primary grouting stage, while the pressure remains basically stable in the secondary and supplementary grouting stages. The cumulative grouting volume increases in a stepped manner as grouting time elapses. Post-grouting technology can improve the bearing capacity of drilled cast-in-place piles: sufficient grouting volume can greatly increase pile tip resistance, stable grouting pressure can effectively improve pile side friction resistance, and the three-stage grouting process can enhance the uniformity and stability of pile foundation bearing capacity, presenting favorable adaptability under complex geological conditions such as clay layers. The research results are derived from full-process data collection of actual engineering sites and can provide operational references for parameter design, process improvement, and quality control of post-grouting construction of drilled cast-in-place piles under similar geological conditions. Subsequent research can combine static load tests and other detection methods to quantitatively analyze the improvement range of pile bearing capacity brought by post-grouting technology, and perfect the design theory and construction specifications of post-grouting technology.

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Research on the Whole-process Construction Management and Control System of Prefabricated Buildings Based on BIM Technology

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Abstract: Prefabricated buildings serve as the core carrier of industrialized and green construction. Nevertheless, they feature long construction chains, multiple participating entities, and high precision requirements. Traditional management and control modes are plagued by pain points such as low collaborative efficiency, high rework rate, and poor traceability, which can hardly meet the demands of refined construction. With technical characteristics including parameterization, visualization, collaboration, and full-life-cycle data connectivity, BIM technology provides core technical support for upgrading the construction management and control of prefabricated buildings. In view of this, this paper conducts in-depth research on the whole-process construction management and control system of prefabricated buildings based on BIM technology, so as to offer references for the high-quality construction of prefabricated buildings.

Keywords: BIM technology; Prefabricated buildings; Construction management and control; Whole-process construction management and control system

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1. Introduction

Alongside the industrial, green and digital transformation of China's construction industry, prefabricated buildings have become the primary approach to boost the high-quality development of the construction industry due to their advantages of high construction efficiency, low resource consumption and minor environmental impact^[1]. The Development Plan for the Construction Industry During the 14th Five-Year Period proposes to vigorously develop prefabricated buildings and raise their proportion in new buildings to more than 30% by 2025. Prefabricated buildings transfer a large number of on-site operations to factory prefabrication. Their construction links cover design, production, transportation, hoisting and acceptance,

involving multiple stakeholders including developers, design institutes, component factories, construction units and supervision companies, which raise higher requirements for refined, information-based and collaborative construction management and control ^[2].

Under traditional management and control modes, prefabricated buildings commonly suffer separation between design and production, inconsistent component information, disorderly hoisting procedures, frequent collision rework and difficult quality tracking, resulting in delayed construction schedules, cost overruns and severe hidden quality hazards, which hinder the popularization of prefabricated buildings. BIM technology integrates geometric, physical, functional and management information of the whole building life cycle by relying on 3D digital models. It boasts core strengths such as parametric modeling, visual simulation, collaborative management and traceable data, which are highly consistent with the inherent demands of prefabricated buildings for standardized design, factory production, assembly construction and information management ^[3].

In recent years, numerous domestic projects have explored the application of BIM technology in prefabricated buildings. However, most applications merely stay at the stage of visual demonstration for single links, without forming a systematic management and control system covering all construction procedures, and the value enabled by technology has not been fully unleashed. Therefore, starting from the adaptability between BIM technology and prefabricated building construction, this paper tests the application effect through engineering demonstration and constructs a whole-process construction management and control system, so as to provide practical references for improving the construction control level of prefabricated buildings.

2. Adaptive characteristics of BIM technology in prefabricated building construction

2.1. Parametric component attributes adapt to refined management demands

The core units of prefabricated buildings are standardized prefabricated components. A single project involves thousands of prefabricated wall panels, composite slabs, staircases, and other components, each with strict technical requirements on dimensions, steel reinforcement, and embedded parts as well as installation joints. Traditional 2D drawings cannot realize granular management ^[4]. BIM technology assigns a unique identity code to each prefabricated component through parametric modeling, integrating all information, including geometric dimensions, material parameters, production requirements, hoisting joints, and quality standards, to realize unified management via one model. Managers can quickly retrieve component information and accurately grasp technical requirements of each component through the model, fundamentally eliminating production errors and installation deviations caused by information mistakes, and satisfying the refined management demands for prefabricated buildings featuring massive and diversified components ^[5].

2.2. Visual simulation adapts to high-risk hoisting operations

On-site construction of prefabricated buildings mainly relies on component hoisting. The hoisting procedures of heavy prefabricated components are complicated, with high spatial precision requirements. Traditional construction depends on technicians' experience, which easily leads to chaotic hoisting sequences, spatial collisions, and large positioning errors, bringing significant safety and quality risks ^[6]. BIM technology can create 3D visual construction scenarios to conduct pre-simulation of hoisting procedures, mechanical paths,

and component positioning processes, predict risks such as spatial conflicts and blind areas in advance, and optimize hoisting sequences and mechanical positions. Construction workers can clearly identify hoisting points, sequences, and installation requirements via 3D models instead of traditional 2D drawing disclosure, reducing hoisting errors caused by inconsistent understanding and improving the accuracy and safety of hoisting operations.

2.3. Multi-terminal collaborative platform solves cross-stakeholder collaboration pain points

The construction chain of prefabricated buildings is lengthy with numerous participating units, and links including design, production, transportation, and construction are distributed in separate spaces. Traditional communication dominated by paper drawings and offline meetings delivers information with low efficiency and a high error rate, easily triggering collaborative problems such as delayed transmission of design changes and mismatches between production and on-site progress ^[7]. The cloud collaborative platform built based on BIM technology enables cloud sharing of models and data, allowing all participants to conduct collaborative work based on one unified model. Design institutes update design changes online, component factories receive the latest production demands in a timely manner, construction units upload on-site progress synchronously, and supervision companies conduct online quality acceptance, breaking information barriers between all stakeholders and realizing efficient cross-regional and cross-link collaboration, which significantly cuts management losses caused by information asymmetry.

2.4. Full-life-cycle data connectivity meets quality traceability requirements

Quality control of prefabricated buildings emphasizes traceability. Production records, transportation status, installation precision, and acceptance records of all components need to be retained. Traditional paper file management leads to scattered data and inconvenient retrieval, making it hard to quickly identify responsible links once quality problems occur ^[8]. BIM models can carry full-process data covering design, production, construction, and acceptance. Production records, transportation information, hoisting data, and acceptance materials of each component are bound to component codes in the model, forming a complete quality information chain. In case of quality defects, staff can rapidly retrieve full-process information through component codes to locate the source and responsible parties. The complete data chain also provides data support for later operation and maintenance phases.

3. Whole-process application of BIM technology in prefabricated building construction management and control

3.1. Deepening design stage: Forward design and collision inspection to control risks from the source

Deepening design serves as the first step of prefabricated building construction, and its accuracy affects the quality of subsequent production and installation ^[9]. Based on BIM technology, forward deepening design of prefabricated buildings can be carried out. Relying on architectural, structural, and electromechanical professional models, standardized splitting of prefabricated components is conducted, and component splitting schemes as well as joint connection designs are optimized to guarantee production feasibility and installation convenience. Meanwhile, a BIM collision detection function is adopted to conduct full-

professional collision inspection on embedded parts, reserved holes, and electromechanical pipelines of prefabricated components, identify design conflicts in advance, issue collision reports and optimize design schemes, so as to avoid on-site rework resulting from design defects from the source. In addition, each prefabricated component is assigned a unique RFID code during deepening design, which is associated with specifications, material properties, production requirements, and installation positions of components, establishing a one-component-one-code management system to provide data support for full-process traceability^[10].

3.2. Production and transportation stage: Linkage of BIM and Internet of Things to realize accurate matching between supply and demand

Component production and transportation act as an intermediate link connecting design and on-site construction, which influences on-site construction progress^[11]. The BIM model is connected to the component production management system to directly transmit component design parameters to the production end, reducing errors and workload from secondary drawing. During production, raw material inspection, production procedures, and quality test data of components are timely uploaded to the BIM model, realizing online visual control of production progress and quality. Managers can grasp the production status of each batch of components via the BIM model and adjust production plans according to on-site construction progress to match production with on-site demands. In the transportation link, component transportation batches and loading sequences are optimized based on the hoisting sequence in the BIM model, enabling components to be produced, transported, and hoisted in order, and cutting costs of on-site stacking and secondary handling. Real-time positioning technology of the Internet of Things is utilized to track the location of transport vehicles, and transportation progress is synchronized to the BIM collaborative platform, allowing on-site managers to make hoisting preparations in advance and improve construction connection efficiency^[12].

3.3. On-site hoisting stage: Visual management to ensure schedule, quality and safety

On-site construction constitutes a critical link for control. Relying on BIM models, the project built a centralized on-site construction management and control platform to conduct all-round and refined control over schedule, quality and safety^[13]. In terms of schedule control, the BIM model is linked to detailed construction schedules to generate a 4D construction schedule simulation, which can clearly and dynamically reflect construction tasks, process connections and component demands at each stage, so as to achieve full control over construction progress. During construction, actual on-site progress data is collected and uploaded to the system daily for automatic comparison and intelligent analysis against planned schedules. Once deviations occur, the system will send out early warning signals immediately, allowing the project team to promptly adjust resource allocation or construction schemes and ensure controllability of key construction milestones. For quality control, an innovative collaborative approach integrating BIM and mobile terminals is adopted. On-site managers can retrieve complete BIM information of components to be installed anytime via handheld mobile devices, accurately verify component models, specifications, and designed installation positions, and timely record key data such as hoisting positioning accuracy and connection quality. All detected quality defects are photographed, marked, and uploaded to the management and control platform right away to generate problem tracking forms, realizing closed-loop whole-process management

covering defect identification, assignment, rectification, and re-inspection. For critical processes with complex craftsmanship and stringent quality requirements such as sleeve grouting, 3D visualized technical disclosure based on BIM models is carried out to help workers fully grasp operation procedures, technical specifications, and acceptance criteria, fundamentally eliminating potential quality hazards. In terms of safety control, leveraging the pre-simulation advantage of BIM technology, simulated analysis of hazard sources and key safety protection points within hoisting operation areas is conducted in advance to optimize the layout plan of safety protection facilities. Meanwhile, collision simulation is performed for the operating radii and lifting paths of large hoisting machinery such as tower cranes, which effectively avoids interference risks between machinery units and between machinery and structures, and enhances the predictability and management capacity of on-site safety supervision.

3.4. Completion acceptance stage: Digital delivery to connect operation and maintenance management

During the completion acceptance phase, the project takes complete BIM models as carriers to integrate all data generated throughout construction, including partial and sub-item quality acceptance records, factory and on-site component test reports as well as design change and negotiation records, creating a digital completion model fully consistent with the physical building in geometric and attribute information ^[14]. This model completely replaces traditional scattered and vulnerable paper completion materials, greatly accelerating the retrieval, comparison, and verification of materials during acceptance, and guaranteeing the integrity, accuracy, and long-term traceability of engineering archives. The value of the completion BIM model does not end at acceptance; it can be directly delivered to the subsequent operation and maintenance phase as core data assets. It provides accurate and intuitive data support for equipment maintenance, space asset management, energy consumption management, and emergency plan formulation and simulation after building commissioning, realizing full-life-cycle data connectivity and value continuation covering design, construction, and operation across the whole construction industrial chain, and expanding the wider and deeper application scope of BIM technology in the construction industry ^[15].

4. Conclusion

Prefabricated buildings represent an inevitable trend of construction industrial upgrading, and BIM technology serves as the major technical means to raise the management and control level of prefabricated construction. Through analysis of adaptive characteristics and system construction based on engineering verification, this paper summarizes the adaptive advantages of BIM technology in parametric control, visual simulation, collaborative management, and full-life-cycle traceability, and verifies its prominent strengths in schedule, quality, cost, and collaboration. A whole-process construction management and control system covering deepening design to on-site construction and completion delivery is established. In the future, with the in-depth integration of digital twin, Internet of Things, artificial intelligence, and BIM technologies, the construction control of prefabricated buildings will develop toward higher intelligence and precision. The industry shall further deepen the full-life-cycle application of BIM technology, break data barriers across all sectors, promote the digital and intelligent construction of prefabricated buildings, and drive the high-quality development of the construction industry.

Disclosure statement

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Construction and Management of the Organizational Framework for the Review of Final Settlements for Hospital Engineering Projects

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Abstract: Hospital engineering projects bear the attributes of public buildings and medical specialties, containing a large number of special medical systems. Such projects feature numerous design changes during construction, diverse participating parties, and complicated pricing rules. The final settlement review serves as the last line of defense for project investment control, and it exerts a direct impact on the efficiency and compliance of construction fund utilization. At present, hospital project settlement reviews suffer from fragmented organizational structures, low professional matching degree, inadequate process control, and weak risk prevention, which lead to prolonged review cycles, pricing disputes, and unstable review quality. Establishing an organizational framework with clear power and responsibility, as well as professional collaboration, and forming a refined whole-process management mechanism constitute the core solutions to the above problems. In view of this, this paper conducts an in-depth analysis of the construction and management of organizational frameworks for hospital engineering final settlement reviews, aiming to provide references for the standardized implementation of such work.

Keywords: Hospital engineering; Final settlement review; Organizational framework; Risk management

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1. Introduction

With the continuous improvement of China's modern medical system and the development of medical and health undertakings, hospital construction projects at all levels are being advanced, with expanding construction scales and growing technical complexity ^[1]. Compared with general civil buildings, hospital projects integrate public building and professional medical attributes. Apart from conventional civil engineering and installation works, they cover multiple special systems including medical gas, smart medical care, and logistics transmission, which are subject to high technical standards and strong system coupling.

In addition, numerous design changes and visa records are frequently generated due to adjustments to medical demands during construction, bringing severe impacts on cost control. Final settlement review acts as a key link in hospital engineering projects, which directly affects the safety and utilization efficiency of construction funds.

At present, many hospital projects still adopt the traditional single-department-led review mode with outdated organizational systems and management mechanisms that fail to adapt to the complex characteristics of hospital engineering. Existing problems include inadequate special item reviews and loose quality control. These issues will not only delay the normal settlement procedures of hospital projects, but also trigger risks such as inflated project costs and non-compliance. Therefore, in light of the characteristics of modern hospital engineering, scientific and rational organizational frameworks for settlement reviews shall be constructed, and supporting management mechanisms shall be perfected to improve review quality and lay a solid foundation for the smooth handover of hospital engineering projects.

2. Core problems faced by hospital engineering final settlement reviews

2.1. Fragmented organizational structure and low cross-stakeholder collaboration efficiency

Hospital engineering settlement reviews involve multiple internal departments and external parties, yet a unified overall coordinating organization is generally absent, resulting in a fragmented overall layout^[2]. Internally, review work is mostly undertaken solely by audit or infrastructure departments, with low participation from finance, legal, medical affairs, and clinical departments. When communication is required to confirm functional demands, reconcile payments, and conduct compliance examinations, there are clear responsible persons and communication channels lacking. Cross-department communication costs remain high with long feedback cycles, and review progress is often hindered due to mutual buck-passing between departments. Externally, there is no unified scheduling mechanism among entities including construction enterprises, supervision institutes, design institutes, and third-party cost consulting agencies, and they adopt inconsistent statistical standards. There are many subcontractors for special medical works, while the rights and liabilities of general contractors and subcontractors remain ambiguous. The communication chain for review matters is overly long, leading to low efficiency in problem feedback and rectification. Moreover, most projects lack special docking modules for medical engineering reviews, and such works are often categorized as ordinary installation projects without professional coordination, forming bottlenecks hindering review progress.

2.2. Distinct professional characteristics with insufficient depth and precision of special reviews

The prominent medical specialty attributes of hospital engineering constitute major difficulties in settlement reviews and frequent sources of cost calculation errors^[3]. On the one hand, special medical works feature unique craft and high customization. Operating room purification, radiation protection, medical logistics, and other systems are governed by respective industry standards for construction techniques and materials. Most conventional cost reviewers lack expertise in medical engineering and only conduct reviews based on general installation quota standards, which easily cause misapplication of quotas and omitted items, failing to accurately judge the rationality of construction techniques and the degree of pricing matching. On the

other hand, a large number of customized medical equipment and special materials lack unified quotas and public market prices, making price inquiries difficult. Construction units often take advantage of information asymmetry to mark up prices, while reviewers cannot effectively cut high costs due to limited professional knowledge. In addition, special medical works contain numerous concealed works with incomplete construction records, making it hard to verify actual construction techniques and engineering quantities during post-completion reviews and increasing review difficulties.

2.3. Non-standard process management and unstable review quality and efficiency

Hospital engineering settlement reviews lack a standardized whole-process control system, and work quality and progress largely depend on the personal experience of handling staff, leading to unstable overall performance^[4]. Firstly, settlement documents are poorly managed. Some projects have completion drawings inconsistent with actual sites, incomplete change visa formalities, and missing records of concealed works, as well as backdated visas and documents without complete signatures and seals. Reviewers have to repeatedly check and supplement materials, greatly extending review cycles. Secondly, the review process lacks node control. No time limits are stipulated for document acceptance, engineering quantity verification, dispute settlement, and report issuance, resulting in backlogs. The settlement review cycle of some hospital projects lasts more than one year, hindering project final accounts and asset handover. Thirdly, no quality control system is established. Most projects lack a multi-level review system, so review results cannot be cross-checked, which may lead to errors in engineering quantity calculation, mismatched fee standards, and inappropriate application of policy documents, failing to guarantee review quality.

2.4. Weak risk prevention with prominent compliance and integrity risks

Hospital engineering involves large investment and numerous special works, bringing prominent compliance and integrity risks during settlement reviews. However, the risk prevention systems of most hospitals remain imperfect^[5]. First, change order and visa control is lax. Strict approval procedures are absent for some design alterations and on-site visas, and the practice of “construction first, formalities later” occurs frequently. Several unreasonable alterations are submitted directly without technical and economic demonstration, which leads to out-of-control project construction costs. Unreasonable changes are submitted without technical and economic argumentation, leading to out-of-control project costs and failure to verify the legitimacy and rationality of changes during reviews. Secondly, significant price control risks exist. Prices of special medical equipment and materials are unclear, and some projects involve designated brands and connected transactions with substantial room for price inflation, lacking a comparative pricing basis for reviews. Thirdly, the integrity prevention mechanism is absent. Double-person supervision and complete traceable records are not required for key pricing negotiations, which may trigger integrity risks involving artificial price manipulation. Fourthly, inadequate compliance examination. Many reviews only verify engineering quantities and prices without checking the performance of bidding documents and contract clauses, which may cause compliance risks where settlement results conflict with contractual agreements.

3. Optimized management strategies for hospital engineering final settlement reviews

3.1. Construct a three-level linked organizational framework and improve collaborative operation mechanisms

A scientific organizational structure serves as the foundation for the efficient operation of the settlement review process; accordingly, an organizational framework comprising a “decision-making layer,” an “executive layer,” and a “support layer”—each seamlessly coordinating with the others—should be established based on the hospital’s management structure and engineering characteristics, the responsibilities of each department should be clearly defined, and coordination issues should be resolved ^[6].

The decision-making level shall establish a Settlement Audit Working Group, with an executive leader overseeing infrastructure projects or auditing serving as the group leader; the heads of the Infrastructure Department, Audit Department, Finance Department, Legal Affairs Department, Medical Affairs Department, and core utilizing departments shall all participate in the group. The primary responsibilities of this working group include: reviewing and approving the audit work plan and the major pricing principles; coordinating and resolving opinions raised regarding the major pricing principles and the audit plan; making final decisions on the pricing results; and supervising the legality and impartiality of the work performed by all audit personnel.

A professional audit working group at the executive level will be established, adopting a hybrid approach that combines “internal audit personnel” with “third-party professional consulting firms.” Based on their respective specializations, the group will be divided into three specialized sub-teams: the General Civil Engineering & Installation Team is responsible for the quantity take-off, standard rates, and fee verification for civil engineering, decoration, as well as general plumbing, electrical, and HVAC systems; the Medical Specialized Team consists of cost estimation professionals with experience in hospital construction projects, dedicated to auditing various medical specialty projects—focusing primarily on whether the construction processes comply with regulations, whether the equipment parameters are appropriately matched, and whether the pricing is reasonable; and the Comprehensive Coordination Team is responsible for overall schedule management, documentation management, dispute resolution consultations, compilation of final results, and external liaison.

The support team comprises all functional departments of the hospital as well as the participating construction units: the infrastructure department and the supervision department verify the authenticity of on-site conditions and documentation; the finance department cross-checks the project payment data; the legal department reviews compliance matters; clinical departments confirm the implementation of functional requirements; and the design unit provides answers to technical questions; together, all these departments provide comprehensive support for the review process.

Additionally, three operational mechanisms are implemented: the unified export mechanism, the consultation and analysis mechanism, and the three-tier quality control mechanism ^[7]. First, the unified export mechanism: all formal external opinions shall be forwarded by the Comprehensive Coordination Group to prevent fragmented communication; second, the consultation and analysis mechanism: for complex or contentious issues, multi-party consultations shall be conducted to produce written minutes that serve as the basis for review; third, the three-tier quality control mechanism: a three-stage quality control system is adopted, comprising initial review by reviewers, re-review by the responsible professional, and final approval

by the project leader, ensuring rigorous quality oversight at each stage.

3.2. Strengthen professional capacity building to address pain points of special reviews

To tackle difficulties in reviewing special medical works, support shall be enhanced from personnel, data, and resource dimensions to improve review accuracy ^[8].

First, build a compound review team. Regular training on special medical engineering knowledge shall be organized for internal reviewers, with hospital infrastructure engineers and technical staff from equipment manufacturers invited to lecture on construction techniques and industrial standards to make up for knowledge gaps. A talent pool for special reviews shall be established, prioritizing professionals with hospital cost experience for major projects.

Second, establish a hospital-exclusive construction cost database. Classify, organize, and accumulate data, including the unit construction cost of completed special medical projects, prices of core equipment and materials, and cost reduction rates, to build a special cost index system. This can provide price references for subsequent project reviews and mitigate information asymmetry.

Third, employ professional third-party cost consulting institutions. For technically complex special medical works, select consulting firms with hospital project track records to participate in reviews, leveraging their professional experience and industrial data to deepen review depth. A performance appraisal system for consulting institutions shall be implemented to dynamically evaluate review quality and efficiency.

3.3. Standardize whole-process control to boost review quality and efficiency

Implementing standardized, node-based full-process management can shorten the review duration while ensuring work quality ^[9]. First, implement a pre-review of settlement documentation by establishing a standardized checklist for hospital engineering settlement documents; this checklist shall specify the formats, signature/certificate requirements, and completeness standards for each type of document—particularly for concealed records of medical specialty projects, equipment parameter data, and acceptance reports. Documents lacking complete information or incomplete procedures will not be formally accepted, thereby reducing the time loss caused by repeated supplementary submissions at the source. Second, refine the control of review process nodes by developing a detailed review progress plan that breaks down the entire workflow—including document acceptance, engineering quantity calculation, account reconciliation and communication, dispute resolution, and final report issuance—into specific time-bound milestones. Regular progress updates should be provided to each professional discipline; when a milestone falls behind schedule, timely early warnings should be issued, followed by prompt coordination efforts. Third, strictly enforce the on-site verification system: for key items such as large-scale modifications, concealed works, and installation of core medical specialty equipment, joint on-site verification must be conducted by the review team, supervision team, and construction team; photographic evidence and verification records must be retained to ensure that the settlement content accurately reflects the actual site conditions. Fourth, establish a hierarchical dispute resolution mechanism: general professional disputes shall be resolved through negotiation among the corresponding specialized groups; if negotiation fails, the Comprehensive Coordination Group shall organize multi-party negotiations; major disputes shall be submitted to the Leading Group for collective decision-making; all dispute resolution processes must be documented, and no ambiguous handling or oral agreements shall be permitted.

3.4. Improve risk prevention system to consolidate compliance and integrity bottom lines

Establish a comprehensive risk prevention and control system by integrating risk management into all stages of the audit process to mitigate compliance and integrity risks^[10]. First, create a list of key risks by identifying high-risk areas within hospital engineering settlement audits—specifically, the pricing of medical special projects, large-scale change orders, pricing for non-standard equipment, and fee standards—thereby defining specific risk points and corresponding control requirements; for high-risk items, implement a dual-person review and a focused re-examination process. Second, strengthen the compliance review of change orders: during the audit phase, the quantity of work specified in the change order must be verified, and the approval procedures, technical necessity, and economic rationality of the change must be traced; change orders with incomplete documentation or insufficient justifications shall be rejected, thereby curbing the increase in unreasonable construction costs at the source. Third, strictly implement integrity risk controls by enforcing an interest avoidance policy, requiring audit personnel to proactively avoid any conflicts of interest with participating construction units; core pricing negotiations and on-site inspections must involve two or more staff members; all audit adjustments and communication opinions must be documented and archived through formal channels, and private contact or verbal promises are strictly prohibited. Fourth, standardize the management of audit results and archives: audit reports must provide detailed records of all increases and decreases, the resolution status of disputes, and any outstanding issues; such reports may only take effect after undergoing a three-tier review process and approval from the Leading Group; all settlement documents, process files, and final audit outputs shall be uniformly archived in a standardized manner to ensure that the entire workflow is traceable and verifiable.

4. Conclusion

The final settlement review of hospital engineering is a systematic project requiring high professionalism and extensive collaboration. Scientific organizational frameworks and complete management mechanisms constitute the fundamental guarantee for high-quality and efficient reviews. In response to existing problems including fragmented organization, insufficient professional matching, and loose process control, this paper proposes a three-level organizational framework with overall decision-making coordination, professional execution, and supporting collaboration, alongside supporting measures of professional capacity development, whole-process control, and comprehensive risk management. These measures can effectively resolve prominent difficulties in hospital settlement reviews and improve the accuracy, efficiency, and compliance of review work.

As hospital construction advances toward intelligence and specialization, settlement reviews will face growing difficulties. In the future, further research shall be conducted on the application of BIM and cost big data in settlement reviews, organizational modes and management mechanisms shall be continuously optimized, and a complete review management system adapted to hospital engineering characteristics shall be gradually formed. This will effectively strengthen investment control, ensure safe and efficient utilization of construction funds, and provide solid support for high-quality hospital development.

Disclosure statement

The authors declare no conflict of interest.

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Application of Artificial Intelligence Technology in Digital Design of Building Interior

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Abstract: This paper focuses on the application of artificial intelligence technology in building interior digital design. Firstly, it discusses the significance of the application of artificial intelligence technology in building interior digital design, such as helping to improve the efficiency of interior design and promoting the iteration of architectural industry design ecology upgrade. Then, several application measures are put forward, including indoor space intelligent analysis and preliminary survey application, AI intelligent scheme generation and space optimization design application, and intelligent modeling and virtual simulation design application. Artificial intelligence technology allows designers to provide more innovative ideas, promote the transformation of interior design from empirical creation to data-driven, precise, and intelligent creation, provide practical references for the intelligent upgrade of architectural interior digital design, and help the architectural interior design industry achieve high-quality, sustainable, and digital innovation development.

Keywords: Artificial intelligence technology; Digital design of building interior; App; Application

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1. Introduction

With the deep integration of the digital economy and the construction industry, the field of architectural design has officially entered the key stage of digital and intelligent transformation. Traditional architectural interior design has long relied on designers' manual drawing, experience, conception, and repeated revision, which has some problems, such as a long design cycle, poor man-machine adaptability, and large landing error, and it is difficult to better meet the diversified and personalized interior design needs of modern buildings. Against the background of rapid iteration of big data, artificial intelligence, digital modeling, and other technologies, artificial intelligence technology, with its advantages of efficient operation, intelligent deduction, and data optimization, has become the core driving force to promote the digital and intelligent upgrade of architectural interior design, providing an important path for the innovative development of the architectural interior design industry. With the application of artificial intelligence technology in building interior

digital design, intelligent analysis, scheme generation, parameter optimization, and risk prediction can be carried out based on massive design data, which can shorten the design cycle, reduce the design cost, and create an interior design scheme that meets the needs of users, space conditions, and modern aesthetic standards.

2. The significance of the application of artificial intelligence technology in building interior digital design

2.1. It is beneficial to improve the efficiency of interior design

The traditional interior design of buildings mainly depends on the manual operation of designers, from site survey, hand-drawn conception, modeling and drawing to rendering optimization and drawing proofreading. The whole process is complicated and time-consuming, and the design of complex apartment and commercial spaces takes several months; repeated revisions will lengthen the project schedule. However, in the digital design of building interior, the application of artificial intelligence technology can realize the automation and intelligent upgrade of design process, and rely on the functions of three-dimensional intelligent surveying and mapping, automatic scheme generation, one-click modeling and rendering, intelligent drawing checking, etc., which can compress the work that originally took several days to be completed by manpower to several hours and shorten the design cycle. At the same time, AI can iterate the scheme, replace the style, and optimize the layout in real time according to the needs of users, solve the problems of repeated revision of traditional designs, improve the speed of project design and delivery efficiency, and help the design industry adapt to the fast-paced and high-quality construction needs of modern architectural projects.

2.2. It is conducive to promoting the iteration of ecological upgrading in the design of the construction industry

There have been some problems in building interior design for a long time, such as shallow digitalization, disjointed data across all links, disjointed design and construction, and information faults across all links of design, modeling, construction, and operation and maintenance, which are likely to lead to construction rework. However, the application of artificial intelligence technology in building interior digital design can not only break through the data barrier of the whole chain of interior design, but also realize the data exchange and linkage update of space survey, scheme design, modeling and simulation, drawing output, construction check, and later operation and maintenance, and establish a full-life digital design system. At the same time, the standardized design output mode of AI unifies the standards of design results, avoids the arbitrariness of manual design, promotes the transformation of the interior design industry, helps the overall digital upgrade of the construction industry, and optimizes the development ecology of the industry.

3. The concrete application of artificial intelligence technology in digital design of building interior

3.1. The intelligent analysis of indoor space and the application of preliminary survey

The preliminary indoor survey and spatial analysis are an important foundation of the design work, which determines the rationality and feasibility of the follow-up scheme. The full application of artificial intelligence technology realizes the digitalization and intelligent upgrade of indoor space survey and analysis, and improves the accuracy and comprehensiveness of the preliminary design work.

The first is to realize three-dimensional intelligent mapping and data reconstruction of indoor space. Combined with AI vision recognition, laser scanning, and 3D reconstruction technology, the indoor blank space and existing reconstruction space can be fully automatically surveyed and modeled. Compared with the traditional manual measurement mode of tape measure and level, AI intelligent surveying and mapping equipment can quickly collect all-round spatial data such as indoor apartment size, wall structure, beam-column position, door and window openings, pipeline arrangement, etc., automatically avoid the blind area of manual measurement and accurately capture the subtle structural deviation of space ^[1]. At the same time, relying on the artificial intelligence three-dimensional reconstruction algorithm, the collected discrete data can be automatically integrated to generate a high-precision, one-to-one restored indoor digital space model. Because this model can directly connect with the subsequent design software, it does not require the designer's secondary modeling, which solves the tedious problem of traditional survey data and provides an accurate database for the subsequent digital design.

The second is to complete indoor ambient intelligence detection and parameter analysis. Modern interior design not only pays attention to the spatial form, but also pays attention to the living environment indicators such as lighting, ventilation, sound insulation, temperature and humidity, air quality, and so on. Traditional environmental analysis mainly relies on manual calculation and empirical prediction, with low data accuracy and a single analysis dimension. However, using artificial intelligence technology and various intelligent sensing devices, environmental data such as natural lighting duration, illumination uniformity, air circulation rate, noise decibels, space temperature, and humidity can be collected around the clock, and the environmental data can be intelligently analyzed and judged using deep learning algorithms ^[2]. Aiming at the problems of insufficient lighting, poor ventilation, and noise interference, an AI system can automatically mark the problem areas and quantify the environmental defect parameters, which provides important data support for designers to optimize the window opening position, partition layout, and wall material, and ensures the comfort of interior design.

The third is to realize the analysis of spatial function and intelligent deduction of people flow. According to different indoor scenes such as office space, commercial space, and residential space, artificial intelligence can combine the characteristics of space area, apartment structure, and users to carry out intelligent crowd simulation and functional adaptation analysis. By importing a large number of similar space design cases and usage data, AI algorithms can deduce the trend of people flow and space congestion areas under different layout modes, and accurately identify the problem of space waste ^[3]. Based on the analysis results, the optimization direction of space function, such as the optimization of counter layout in commercial space and the adjustment of station layout in office space, is automatically output, so that early space design can get rid of pure aesthetic conception and realize the adaptation of function, people flow, and space.

3.2. AI intelligent scheme generation and spatial optimization design application

Scheme design is the core link of digital interior design. Traditional scheme design mainly depends on the designer's personal experience, which has the problems of a long creative cycle and a single optimization dimension. However, the application of artificial intelligence technology, relying on massive design databases and deep learning algorithms, can realize intelligent generation, automatic iteration, and precise optimization of interior design schemes and improve the efficiency of scheme design, which is the core application of intelligent interior design at present.

The first is to realize the intelligent generation of multi-style and personalized schemes. By learning a large number of excellent domestic interior design cases, the artificial intelligence system covers a variety of design styles and accumulates a perfect database of color matching, material combination, soft decoration layout, and modeling design ^[4]. In the specific design process, designers only need to input the indoor space model, apartment parameters, owners' needs, style preferences, budget standards, functional requirements, and other parameters into the AI system, and the system can automatically generate multiple sets of differentiated indoor design schemes in a short time. The scheme covers a number of complete design contents, such as the overall spatial layout, the top surface modeling of the wall, the floor paving, the matching of soft cloths, the color system, etc., which changes the traditional mode of repeated modification of a single scheme. At the same time, AI can adapt accurately according to the individual needs of the owners and automatically match humanized design details for special scenes such as old people's rooms, children's rooms, and office spaces to meet the personalized design needs of different people and different scenes.

The second is to complete the parametric intelligent optimization of indoor space. Using artificial intelligence parametric design technology, multi-dimensional collaborative optimization is realized. By building an intelligent algorithm model, space size, daylighting standard, pedestrian flow law, energy consumption index, and aesthetic norms are set as constraint parameters, and the initial scheme is automatically iteratively optimized ^[5]. In terms of space utilization optimization, AI can fine-tune wall partitions, furniture sizes, and layout positions through algorithms, reduce idle areas of space, and improve the use efficiency of small-sized and irregular spaces; In terms of aesthetic optimization, AI relies on visual aesthetic algorithms to automatically adjust the spatial proportion, color contrast, and modeling symmetry to avoid visual imbalance. In terms of energy-saving optimization, the layout of doors, windows, and partitions is optimized by combining natural lighting and ventilation data, so as to reduce the energy consumption of artificial lighting and air conditioning and realize the green energy-saving design of indoor space. Compared with manual optimization, AI parametric optimization can take design indexes into account at the same time, with higher optimization accuracy and more comprehensive dimensions.

3.3. The application of intelligent modeling and virtual simulation design

Digital modeling and effect simulation are important links in indoor digital design. The integration and application of artificial intelligence technology, digital modeling, and virtual simulation technology have realized indoor modeling automation, multi-dimensional simulation, accurate effect prediction, and improved the landing of digital design.

The first is to realize intelligent rapid modeling and lightweight processing of indoor models. Using artificial intelligence modeling technology to realize automatic model generation, relying on the spatial data of previous three-dimensional surveys, the AI system can automatically identify structural components such as walls, beams and columns, doors and windows, ground and top surfaces, and build high-precision indoor foundation models. According to the design scheme, model materials such as furniture, lamps, soft clothes, and decorative components can be automatically imported, and the proportion adaptation, position alignment, and detail splicing of components can be automatically completed ^[6]. Aiming at complex special-shaped space and surface modeling design, AI algorithms can automatically optimize the model structure, solve the problems of artificial modeling surface distortion, and improve the modeling accuracy. In addition, for high-precision models, AI can carry out intelligent lightweight processing, compress model data on the basis of retaining core design details, ensure the smooth operation of the model, and adapt to subsequent rendering, simulation, and display requirements.

The second is to carry out intelligent simulation of indoor light and color. The artificial intelligence simulation technology is used to realize all-weather dynamic light and shadow simulation. According to the building orientation, floor height, window position, sunshade structure and other parameters, the indoor light intensity and light and shadow projection range at different time periods in the morning, noon, evening and night are automatically simulated, and the problems such as insufficient lighting, dead angle of light and shadow, glare and glare are accurately predicted, and the layout of lamps, window size, shading material and indoor light and shadow experience are automatically optimized ^[7]. Through an AI color simulation system, the color presentation effects of walls, floors, and soft clothes under different lighting color temperatures and natural light environments can be simulated, and problems such as color matching conflicts can be predicted, and color matching can be adjusted intelligently to ensure the harmony and unity of the indoor color system.

3.4. Application of intelligent rendering and digital achievement optimization

The rendering of design results is the final link of indoor digital design, and high-quality renderings and animations are the core carriers of scheme display and floor disclosure. Using artificial intelligence rendering technology, the rendering mode of interior design is innovated, and digital output with high efficiency, high definition, and intelligence is realized.

The first is to realize one-click intelligent HD rendering. AI rendering system has built-in massive rendering parameter templates, which are suitable for all kinds of interior design styles and scenes. Designers do not need to manually debug complex parameters such as light, shadow, and materials. As long as a three-dimensional model is built, high-definition renderings, panoramic views, and indoor roaming animations can be generated with one click through the AI system. Compared with traditional rendering, AI intelligent rendering can complete high-definition drawing in a short time and improve rendering efficiency ^[8]. AI algorithms can intelligently optimize the details of the picture, automatically correct problems such as fuzzy material texture, light and shadow faults, and ensure high-definition, true, and unified rendering quality. The second is to complete the intelligent adaptation and optimization of material texture. Artificial intelligence can accurately identify the physical characteristics of all kinds of building materials and soft-packed materials through image recognition technology, automatically match the corresponding rendering parameters, and truly restore the texture and appearance of materials. AI can intelligently fine-tune the light and shade and reflective intensity of materials according to the spatial light and shadow environment, so that the materials can adapt to the overall spatial atmosphere and improve the authenticity of the renderings ^[9]. The third is to realize intelligent standardization and optimization of design results. AI system can optimize the composition, color brightness, and picture proportion of renderings according to industry design standards and display specifications, and unify the style and texture of the whole set of design results. Automatically generate supporting design instructions, dimensioning, material list, and process instructions, and carry out data linkage among three-dimensional models, renderings, and construction drawings to ensure the high uniformity of drawings, effects, and parameters, and provide high-quality digital results for scheme reporting and construction disclosure ^[10].

4. Conclusion

To sum up, the application of artificial intelligence technology in building interior digital design can not only realize the automation and standardization of the design process, but also reduce labor cost and material loss, and combine the requirements of human settlement environment, ergonomics, and green energy saving to carry out multi-dimensional optimization design to improve the comfort of indoor space. Using artificial intelligence technology, designers can pay more attention to creative expression, humanistic shaping, and

personalized needs, and enhance the artistic value of design works. In the future, with the continuous maturity of algorithm models and iteration of digital technology, the application scenarios of artificial intelligence technology in building interior digital design will be more abundant, which will continue to promote the development of the building interior design industry in the direction of digitalization and intelligence.

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Application Research of Intelligent Technology in Bidding Management of Road, Bridge, and Tunnel Inspection Projects

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Abstract: This study focuses on intelligent technology and investigates its application in the bidding management of road, bridge, and tunnel inspection projects. Based on the application demands and strategic framework for intelligent technology in such bidding management, the paper analyzes the key application points across four critical stages: tender preparation, bid preparation, bid opening and evaluation, and award decision and archiving. Practical implementation demonstrates that intelligent technology yields significant results in this context. With appropriate optimization, it can further enhance the level of bidding management and is expected to provide a reference for subsequent research and practice.

Keywords: Intelligent technology; Road, bridge, and tunnel inspection; Bidding; Intelligent evaluation; Intelligent decision-making

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1. Introduction

As a critical implementation guarantee for road, bridge, and tunnel inspection projects, the effectiveness of bidding management directly affects project quality and fund utilization efficiency. Under the traditional manual mode, bidding management for such projects suffers from numerous deficiencies, including inefficient bid document preparation, omissions in qualification review, difficulties in identifying bid rigging, subjective evaluation, and a lack of traceability throughout the entire process, as well as insufficient risk early-warning capabilities ^[1]. To address these drawbacks, this study introduces intelligent technology, systematically analyzes its application points, and verifies its effectiveness through practical implementation, aiming to provide a reference for future applications.

2. Application demands and strategic framework for intelligent technology in bidding management of road, bridge, and tunnel inspection projects

2.1. Application demands

Bidding for road, bridge, and tunnel inspection projects is characterized by strong professionalism, high qualification standards, and extremely demanding technical requirements, which distinctly differentiate it from general civil engineering tendering. Consequently, the demands for intelligent technology application are also rather specific. Under traditional manual management, oversights such as missing enterprise-specific inspection qualifications, staff certificates, and project performance records are common, making it difficult to prevent disqualification or performance fraud. The large volume of technical parameters renders the review of testing plans inefficient and prone to human error^[2]. Moreover, practices such as bid rigging, collusion, and malicious low-price bidding are often covert, and the traditional post-hoc supervision model fails to detect and control them in a timely manner. To address these challenges, management must rely on intelligent technology to automatically perform compliance verification, streamline processes, enable dynamic monitoring, and support scientific evaluation and decision-making, thereby providing refined and standardized management support for the entire bidding process of road, bridge, and tunnel inspection projects.

2.2. Strategic framework

In the bidding management of road, bridge, and tunnel inspection projects, the application strategy of intelligent technology is to leverage supporting technologies such as big data, blockchain, and artificial intelligence to build an intelligent system for full-process control covering tendering, bidding, evaluation, and award decisions. During the tendering phase, intelligent document preparation and self-compliance checks are implemented; during the bidding phase, intelligent bid preparation and risk self-inspection are carried out; the evaluation phase employs AI-based intelligent identification of irregular behaviors; and the final award decision is made through an intelligent evaluation model^[3]. This ensures the adaptability of the intelligent system to the entire bidding process, facilitating a scientific transformation from human-led operations to full-process digital and intelligent decision-making.

3. Basic application points of intelligent technology in bidding management of road, bridge, and tunnel inspection projects

3.1. Intelligent preparation and compliance risk control during the tender preparation phase

During the tender preparation phase, the core objective of intelligent technology is to improve the professionalism and efficiency of tender document preparation while effectively mitigating compliance risks. Therefore, management should rely on standardized databases and artificial intelligence technologies to enable standardized compilation and risk control. First, a dedicated template library for tender documents for road, bridge, and tunnel inspection projects should be established, integrating comprehensive data including regulatory provisions, industry standards, and model texts from previous similar projects. This library can then automatically match templates based on the specific project type, scale, and other actual conditions, intelligently filling in key content such as basic project overview, qualification requirements, and evaluation criteria, thereby reasonably shortening the document preparation cycle^[4]. Second, an intelligent compliance

review system should be built, incorporating relevant laws, regulations, qualification standards, and risk control clauses to form a comprehensive database. On this basis, intelligent technology can be used to automatically identify various specialized items—such as evaluation indicators, inspection qualifications, and test precision calibration—automatically flag risks, and provide intelligent modification recommendations. Finally, the intelligent system classifies and archives the entire trace of the tender compilation and review process, automatically generates compliance review reports, and ensures full traceability, effectively eliminating professional loopholes and compliance risks at the source.

3.2. Intelligent preparation and self-check during the bid preparation phase

In the bidding phase, the purpose of applying intelligent technology is to conduct efficient bid compilation and comprehensive self-inspection, taking into account the characteristics of bid documents—namely, data complexity, high error rates, significant non-compliance risks, and strong professionalism^[5]. In practice, management should rely on AI models adapted to the road, bridge, and tunnel inspection field, interfacing with industry technical standard databases. According to the tender requirements, the system automatically reviews key technical components such as implementation plans, testing procedures, personnel arrangements, equipment configurations, and quality assurance systems, ensuring that the specialized technical parameters of road, bridge, and tunnel inspection align with acceptance standards, and preventing issues like homogenized solutions and insufficient professionalism. Simultaneously, the intelligent system's full-dimensional self-inspection function should be used to check each responding clause of the bidding documents, automatically verifying all key materials—including enterprise qualifications, project performance, personnel certificates, and quotation sheets—so that problems such as expired qualifications, missing quote items, and inconsistent personnel information are accurately identified, and an intelligent rectification list is generated. During this process, intelligent technology can also compare the similarity between the bidding text and existing project bid documents to self-check for duplication, and evaluate quotation reasonableness based on industry big data, thereby issuing timely warnings for abnormally high or maliciously low bids. In this way, various risks can be effectively avoided, the risk of bid rejection is significantly reduced, and the bid documents become more compliant, reasonably enhancing competitiveness.

3.3. Intelligent evaluation and precise assessment during the bid opening and evaluation phase

Bid evaluation is a core link in bidding management. Introducing intelligent technology into this phase can significantly improve work efficiency, reduce subjective bias, and prevent delayed identification of bid rigging, thereby establishing a standardized evaluation system that combines machine preliminary review with expert re-evaluation for road, bridge, and tunnel inspection projects. Using intelligent systems, various tender documents can be automatically parsed and processed, converting unstructured data—such as enterprise qualifications, inspection performance, bid prices, personnel and equipment, and technical parameters—into standardized ledgers, and replacing manual verification, thus greatly enhancing the efficiency of bid-opening data organization^[6]. For key quantitative indicators such as qualification grade, performance scale, equipment configuration, and quotation reasonableness, the intelligent system can apply predefined review rules to automatically score and calculate, completing the evaluation in a fully unattended mode to avoid undesirable phenomena such as favoritism or subjective deviations. For nonquantitative content

like inspection techniques and quality control plans, AI technology can employ semantic interpretation and professional comparison methods to intelligently assess the scientific soundness and completeness of the solutions, marking existing issues and weaknesses to provide a reference for subsequent expert review. Additionally, the intelligent system can dynamically monitor risks throughout the bidding process based on multiple indicators—such as bid price differences, text similarity, and IP associations—thereby comprehensively enhancing the fairness and accuracy of this process.

3.4. Intelligent decisionmaking and closedloop supervision during the award decision and archiving phase

The award decision and archiving phase is the concluding yet crucial step in the bidding management of road, bridge, and tunnel inspection projects. In this phase, intelligent technology should focus on scientific decisionmaking, fullprocess traceability, and closedloop supervision, building a comprehensive management system for the entire bidding process. Specifically, management should integrate multidimensional data—including evaluation scores, enterprise credit, historical inspection quality assessments, and past performance records—into the intelligent system, and establish an intelligent decisionmaking model. This model can compare and analyze the comprehensive strength and performance risks of shortlisted candidates, automatically generate reference reports for award decisions, and provide intelligent technical support to effectively avoid lowprice awards that might compromise inspection quality, thereby ensuring the scientific and rational nature of the final decision ^[7]. Simultaneously, the intelligent system should record all information from the approval and discussion processes of the award decision, ensuring the verifiability and traceability of the decisionmaking process. In contract management, the system can intelligently extract core tender and bid clauses, automatically generate a standardized contract draft for the inspection project, and perform consistency checks between tender and bid terms, enabling timely identification and early warning of risks concerning construction period, pricing, quality, and liability for breach, thereby preventing issues such as yinyang contracts or conflicting clauses. For archiving and supervision, blockchain technology can be leveraged to encrypt and store all types of documents from the entire bidding process, ensuring data immutability and supporting fullprocess traceability, so that subsequent audit verifications and dispute resolutions have reliable evidence ^[8]. Finally, the project data accumulated by the intelligent system can be used to build a standardized bidding database for the road, bridge, and tunnel inspection industry, providing data support for intelligent bidding management of similar future projects, thereby forming a complete closed loop for the entire management process.

4. Practical application of intelligent technology in bidding management of road, bridge, and tunnel inspection projects

4.1. Case introduction

To verify the effectiveness of the proposed application points of intelligent technology in bidding management for road, bridge, and tunnel inspection projects, this study conducted a practical application of the intelligent technology system based on the bidding process of a special inspection project for a transportation infrastructure facility. This project involved multiple provincial highways, bridges, and tunnels within the region, encompassing special disease inspections and annual routine inspections. The main inspection contents included road roughness, bridge structural bearing capacity, structural cracks, and tunnel

surrounding rock stability, among others. In practice, 42 bidding enterprises participating in this project were introduced, and evaluation indicators such as enterprise qualifications, technical solutions, performance capability, bid prices, and personnel and equipment were adopted. A localized intelligent management system was utilized to carry out intelligent management of tender compilation and review, bid selfinspection, bid evaluation assistance, early warning of bid rigging and collusion, and blockchainbased evidence storage. This approach replaced the traditional manual management model and achieved fullprocess digital and intelligent control in an unattended mode, thereby providing a practical implementation scenario for the application of intelligent technology in bidding management of road, bridge, and tunnel inspection projects.

4.2. Application effects

Under the project scenario of bidding management for road, bridge, and tunnel inspection, the practical application of the intelligent technology scheme yielded relatively significant results. Key indicators—including time spent on bid document preparation and review, accuracy of qualification and performance verification, identification rate of bid rigging/collusion and abnormal quotations, subjective deviation rate in bid evaluation, and incidence of process compliance issues—all showed marked improvement compared with the traditional manual management model. The comparison is presented in **Table 1**.

Table 1. Comparison of effects between intelligent technology and traditional manual management in the context of bidding management for road, bridge, and tunnel inspection projects

No.	Indicator	Intelligent technology	Traditional manual mode	Improvement
1	Bidding document preparation and review time (working days)	2-3	7-10	70.60%
2	Qualification and performance review accuracy (%)	99.6	82.3	21.02%
3	Identification rate of collusive bidding and abnormal quotations (%)	98.2	68.5	43.36%
4	Subjective deviation rate in bid evaluation (%)	1.5	11.2	86.61%
5	Incidence of process compliance issues (%)	1.1	9.7	88.67%

Based on the comparison of the practical application data above, it is evident that the rational application of intelligent technology has enabled reasonable optimization of bidding management for the case project of road, bridge, and tunnel inspection. It can effectively circumvent traditional issues under the manual review mode—such as oversight, subjective bias, and irregular transactions—achieving multidimensional control effects including cost reduction, efficiency enhancement, quality improvement, and safety assurance. Moreover, the entire bidding process under this model leaves traceable data footprints, which further enhances the transparency and credibility of bidding activities, creating favorable conditions for selecting the best bidder and ensuring the quality of engineering inspections.

4.3. Existing shortcomings

Despite the notable effectiveness demonstrated in the practical application of intelligent technology in this roadbridgetunnel inspection project case, certain shortcomings remain, leaving room for further improvement. First, the current intelligent technology system development is based solely on general bidding scenarios, inevitably lacking specificity in niche subdivisions such as specialpurpose testing and specialized inspections, and both the evaluation models and technical standards require further refinement ^[9]. Second, the intelligent bidding management system does not fully achieve data sharing with inspection qualification

databases, enterprise credit platforms, and transportation engineering inspection supervision platforms; updates to qualification, performance, and credit data cannot be synchronized in real time, which imposes certain limitations on intelligent evaluation and risk control within bidding management.

4.4. Optimization strategies

In light of the existing shortcomings in the application of intelligent technology to bidding management for road, bridge, and tunnel inspection projects, the following optimization measures can be adopted in subsequent practice. (1) Leverage the vast amount of historical project bidding data in the field of road, bridge, and tunnel inspection, classify detection scenarios into routine, emergency, and specialized types, and carry out targeted optimization of the AI evaluation models according to different scenario types, while reasonably incorporating specialized niche inspection indicators into the models, thereby comprehensively enhancing the professionalism and adaptability of the intelligent technology system^[10]. (2) Build an integrated platform to enable data interoperability between the intelligent bidding management system and other relevant databases and platforms, thereby breaking down data silos among various platforms, allowing synchronized updates of enterprise qualifications, performance records, credit evaluations, and other data, and establishing a full-dimensional linkage control system for bidding risks.

5. Concluding remarks

This study focuses on the pain points in the current bidding management of road, bridge, and tunnel inspection projects and constructs a complete system for intelligent technology application throughout the entire process. The research and practical results demonstrate that, with the support of advanced intelligent technologies such as big data, blockchain, and artificial intelligence, the entire bidding process for such projects can be better managed, comprehensively addressing the shortcomings of traditional management models in terms of efficiency, quality, fairness, and supervision, and achieving efficient, standardized, and refined management for such project bidding. In future management, the intelligent evaluation models should be continuously optimized, data barriers among various platforms should be fully removed, and intelligent technology should be deeply integrated into bidding management, so as to provide intelligent technical support for both the bidding management and the overall quality improvement of road, bridge, and tunnel inspection projects.

Disclosure statement

The authors declare no conflict of interest.

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Research on Detection Technology for Connection Joints of Prefabricated Concrete Bridges

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Abstract: Rational inspection is crucial for ensuring the quality of connection joints in prefabricated concrete bridges. Based on a specific prefabricated concrete bridge project, this study established a detection framework according to the inspection requirements for its connection joints and developed a combined application scheme for multiple detection techniques. Practical application demonstrates that the proposed detection scheme yields significant results and is expected to serve as a reference for subsequent research and practice on quality inspection technologies for connection joints of prefabricated concrete bridges.

Keywords: Prefabricated concrete bridge; Infrared thermography; Ultrasonic nondestructive testing; Electromagnetic induction testing; Rebound hammer testing

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1. Introduction

Prefabricated concrete bridges offer higher construction efficiency and environmental benefits compared with traditional cast-in-place concrete bridges, and have thus become a mainstream technical direction in bridge engineering. The most critical loadbearing points of such bridges are the connection joints, which play a decisive role in the overall bearing capacity, stability, safety, and durability of the bridge. However, existing inspection techniques suffer from shortcomings such as insufficient refinement, weak specificity, and poor adaptability, making it difficult to accurately detect hidden defects in connection joints^[1]. To address these issues, this study draws upon an actual engineering case and adopts a combination of multiple advanced detection techniques for joint inspection, with the aim of providing a reference for similar projects in the future.

2. Project overview

The main superstructure of a certain prefabricated bridge project consists of prefabricated prestressed concrete box girders. The bearing pads, bent caps, and pier columns are all factory-prefabricated components and transported to the site for assembly after passing inspection. The connection joints include various types, such as bearing connection nodes, bent cap splicing seams, pier column grout sleeve connections, and box girder wet joints. The total bridge length is 186 m, the deck width is 24 m, and the design speed is 50 km/h. The bridge primarily serves urban road traffic while also fulfilling urban landscape functions. Given that the entire bridge is constructed using prefabricated concrete techniques, the connection structures are fairly representative, and the number of joint nodes is considerable. To prevent connection misalignment during construction or operation, the project owner imposed stringent requirements on the inspection techniques for connection joints. This paper focuses on the practical application of these inspection technologies.

3. Inspection requirements and framework for connection joints

3.1. Inspection requirements

Based on the fundamental structure and operating conditions of the prefabricated concrete bridge in this project, the connection joints are subject to prolonged influences from thermal stress, vehicle loads, and environmental erosion, making them susceptible to hidden defects. Accordingly, the following main inspection requirements are established for the connection joints (**Table 1**).

Table 1. Main inspection requirements for connection components

No.	Connection Location	Inspection Requirement	Inspection Purpose
1	Pier column sleeve	Detect whether grouting is compact, whether there are voids, and whether rebar anchorage is insufficient, etc.	Ensure vertical loadbearing connection performance
2	Wet joint of precast components	Detect whether concrete has hollowing, cracking, water leakage, or poor bonding, etc.	Ensure transverse connection performance
3	Bearing connection joint	Detect whether there is void, displacement, bolt loosening, or aging deformation, etc.	Keep the force transmission of the bridge uniform
4	Splice joint	Strengthen detection of joint carbonization, crack expansion, and steel reinforcement corrosion, etc.	Achieve reasonable evaluation of structural durability

3.2. Testing approach

Based on the general overview of the project and the primary testing requirements for the connection joints of prefabricated concrete bridges, the testing organization has designed an overall technical strategy that follows the principles of comprehensive nondestructive testing, localized verification, and full-process refinement. First, visual inspection and infrared scanning are used for a general survey of the connection joints to achieve preliminary identification of suspected defect areas. Subsequently, nondestructive testing techniques such as ultrasonic testing, electromagnetic induction, and rebound hammer testing are applied to conduct specialized inspections on suspected defective locations, so as to accurately determine the defect location, size, and severity ^[2]. Finally, a small number of borehole verification tests are carried out on difficult and critical points to ensure the accuracy and reliability of the test data. This entire set of technical procedures effectively balances testing precision and efficiency, adapts well to the actual conditions of the project, and thus enables comprehensive testing of all connection nodes.

4. Application practice of connection joint testing techniques

4.1. Visual inspection and infrared thermography survey

To enable rapid identification of both apparent and hidden defects in the connection joints of prefabricated concrete bridges, the testing organization adopted visual inspection and infrared thermography as the fundamental survey techniques. The selected equipment included a portable infrared thermal imager and a highdefinition industrial camera, with a temperature measurement range of $-20\text{ }^{\circ}\text{C}$ to $150\text{ }^{\circ}\text{C}$ and an accuracy within $\pm 0.05\text{ }^{\circ}\text{C}$. Prior to testing, dust, debris, and standing water on the surface of the test areas were thoroughly cleaned to keep the testing surface flat and clean, thereby preventing environmental interference with the test results. The connection nodes of the entire bridge were then divided into several test units according to different zones, and each unit was numbered to avoid omissions or duplicate testing^[3]. Following that, the formal testing process commenced. In this step, visual inspection was first performed to examine each connection joint for apparent defects, including component misalignment, bolt loosening, water seepage, and joint cracking, with precise recording of defect locations and sizes, and retention of photographic documentation. Next, infrared thermal imaging equipment was used for scanning inspection, with the vertical distance between the device and the test surface controlled at 0.8–1.2 m and the scanning speed kept at $\leq 0.2\text{ m/s}$, so as to comprehensively collect temperature field data for each area. By comparing the temperature difference characteristics between normal areas and defective areas, hidden defects such as joint hollowing and grouting voids could be accurately identified, thereby completing the preliminary screening of defects and suspected locations.

4.2. Ultrasonic nondestructive testing for density

For the sleeve connections and wet joints of the prefabricated concrete bridge in this project, the testing organization primarily employed ultrasonic nondestructive testing to examine their density, enabling accurate identification of internal defects such as concrete loosening, hollowing, and bond failure^[4]. The testing equipment used was an ultrasonic tester, with a measurement range of 0.5–5 m and a timeofflight accuracy of $0.1\text{ }\mu\text{s}$. The first step in testing was to rationally arrange test points according to the inspection areas. For the sleeve areas, test points were arranged in four columns along the perimeter of the pier columns, with spacing controlled at 20 cm; for the wet joints, test points were arranged in a staggered doublerow pattern with spacing at 15 cm to ensure full coverage of the inspection. The second step was to uniformly apply a couplant on the test probes to eliminate air gaps and ensure stable ultrasonic wave transmission, with the couplant thickness controlled at 1–2 mm. The third step was to calibrate the equipment parameters on intact concrete areas, so as to determine the reference wave velocity, frequency, and amplitude. The fourth step involved using dual probes placed stably and closely against the test points to transmit ultrasonic waves and receive echoes; each test point was measured three consecutive times, and the average value was recorded as the final test value. Defect determination was made by comparing the measured data with the reference parameters. If the ultrasonic amplitude attenuation at a test point reached 20% or more, or if abnormal prolongation of the travel time occurred, the corresponding location was determined to be defective. Further crosscomparison of multipoint data was then performed to accurately pinpoint the specific location, defect burial depth, and size.

4.3. Electromagnetic induction testing for reinforcement connections

In this project, the testing organization mainly utilized electromagnetic induction testing to conduct a specialized inspection of the reinforcement connection effectiveness inside grouted sleeves, so as to

accurately determine defects such as insufficient anchorage length, misalignment, and displacement of rebars, thereby preventing compromised joint stiffness and bearing capacity due to poor internal reinforcement connections ^[5]. A portable rebar scanner was selected as the testing device, with a detection depth range of 0–120 mm and an accuracy of ± 0.5 mm, which matched the actual testing requirements for the $\phi 25$ and $\phi 28$ connecting rebars used in the connection joints of this prefabricated concrete bridge. Onsite testing commenced with precise marking of the specific test areas for the sleeves, while avoiding embedded pipes or metal components that could interfere with the testing signals. The equipment was then turned on, preheated for 5 minutes, and zero-calibrated; key parameters such as the reinforcement specifications and cover thickness at the connection joints were entered into the device as reference values. Subsequently, the probe was placed parallel and flush against the concrete surface, and scanning was performed both horizontally and vertically at a speed of 0.15 m/s, enabling continuous acquisition of reinforcement distribution data inside the connection joints. The equipment automatically generated core parameters such as anchorage length and spacing of the rebars; by comparing these with the preentered standard values, defects such as rebar misalignment or insufficient anchorage could be promptly detected. Finally, for any abnormal data points identified, two additional scans were performed with the electromagnetic induction device to verify the defects, thus effectively eliminating environmental and equipment interference and ensuring true and accurate determination of reinforcement connection defects ^[6].

4.4. Rebound hammer testing for joint compressive strength

For the compressive strength of concrete at the wet joints and splicing joints of the prefabricated concrete bridge, the testing organization selected rebound hammer testing as the preferred method in this project, using this technique to assist in evaluating the concrete pouring and curing quality at the joints, thereby achieving precise identification of hidden weak connections. A concrete rebound hammer with standardized impact energy was used as the basic testing device, and the standardized operating procedures were strictly followed according to the equipment instruction manual. In each wet joint area, 16 rebound test points were uniformly arranged, with spacing controlled at 30 mm or more, and care was taken to avoid areas with damage, honeycombing, or surface roughness that could interfere with the test results. Before testing, the test point surfaces were ground smooth using a grinding wheel; after treatment, loose aggregates, oil stains, and laitance were thoroughly removed to ensure a solid and flat testing surface ^[7]. The tester then held the rebound hammer perpendicular to the testing surface and applied pressure slowly, uniformly, and vertically; after the pointer locked, the reading was recorded. Each test point was subjected to a single rebound test only, to avoid repeated operations that could reduce testing accuracy. At the same time, the measured data were reasonably corrected using parameters such as carbonation depth and testing angle. Finally, the conformity of the joint quality was determined by comparing the measured data with the designed concrete strength parameters.

4.5. Local borehole verification testing

For the connection joints of the prefabricated concrete bridge in this project, in order to compensate for the limitations of the above nondestructive testing techniques and to address high-risk points that could not be precisely determined by NDT methods, the testing organization adopted local borehole testing as a minimally invasive auxiliary verification measure, thereby further improving the accuracy of joint defect detection. During the actual testing, small drilling machines, high-definition endoscopes, and precision depth gauges were used as basic auxiliary equipment, and the auxiliary retesting was carried out strictly in accordance

with the following operational procedures and technical measures ^[8]. First, the internal voids and density anomaly points identified during infrared and ultrasonic testing were screened out. Second, 1–2 borehole test points were set at each selected location according to the actual conditions; lowspeed drilling was performed using a $\phi 10$ mm drill bit, with the drill bit kept perpendicular to the component surface throughout, and the drilling depth extended approximately 5 cm beyond the suspected defect depth. Drilling force was carefully controlled to prevent violent drilling from enlarging the damage at the connection joints. Third, after drilling was completed, the testing personnel promptly cleaned the dust from inside the boreholes. Fourth, the endoscope was inserted into the borehole to directly visualize the actual condition of defects such as grouting compactness, looseness, voids, and rebar corrosion. Fifth, the defect burial depth and size were accurately measured using the depth gauge, and the specific measurement data were completely recorded simultaneously. After the verification testing was completed, the testing organization used fixed repair mortar to patch the boreholes and strengthened the curing of the repaired areas, thereby maintaining the structural integrity of the components and reasonably restoring their structural performance ^[9]. In this way, both the testing accuracy of the connection joints could be ensured, and the overall integrity of the prefabricated concrete bridge structure could be maximally preserved.

5. Application effectiveness of connection joint testing techniques

For the prefabricated concrete bridge selected in this study, after the fulldimensional quality testing of its connection joints using the above technical scheme, the problems of traditional manual testing—such as numerous loopholes, poor accuracy, and lack of specificity—were comprehensively addressed. As a result, full coverage and refined defect detection of all connection joints across the entire bridge were achieved. Moreover, both testing accuracy and efficiency were significantly improved compared with traditional manual testing methods, thus providing more accurate testing data support for subsequent quality acceptance, bridge operation and maintenance, and defect treatment. Practical application revealed that, compared with traditional manual testing techniques, the testing scheme applied in this project did not cause extensive structural damage, thereby achieving a balance between testing quality and costeffectiveness. Through a comparison of key core indicators (including detection rate of hidden defects, accuracy of test data, defect localization error, total bridge inspection time, and component damage degree), it can be seen that the testing effectiveness of this scheme was significantly superior to that of traditional testing techniques. The comparison of basic data is shown in **Table 2**.

Table 2. Comparison of core indicator parameters between the testing technical scheme used in this project and the traditional testing scheme

No.	Indicator	Proposed technology	Conventional technology	Improvement
1	Detection rate of hidden defects (%)	97.5	68.2	42.96%
2	Data accuracy rate (%)	98.1	82.5	18.91%
3	Defect localization error (mm)	± 3	± 15	80.00%
4	Full-bridge inspection time (d)	4	7	42.90%
5	Component damage degree (%)	0.1	3.2	96.88%

The comparison of the above testing data demonstrates that the technical testing scheme applied in this project outperforms traditional manual testing methods across all indicators, achieving a significant

improvement in detection accuracy, further reducing testing time, and minimizing component damage. This confirms that the integrated technical scheme delivers notable practical results and exhibits excellent adaptability and feasibility. If this scheme is reasonably applied to subsequent similar projects, with appropriate detailed adjustments made according to actual conditions, it can also achieve favorable outcomes and provide transferable experience for future projects ^[10].

6. Conclusion

In summary, this paper, grounded in the practical project of testing connection joints in prefabricated bridge engineering, has established a comprehensive testing technology system through the integration of survey screening, precision testing, and minimally invasive verification, while rationally detailing the operational procedures of the overall testing process. Practice has confirmed that the combined application of nondestructive testing techniques can substantially enhance both the accuracy and efficiency of quality inspection for connection joints, and the final minimally invasive verification further ensures testing precision, thereby creating favorable conditions for quality control, safe operation, and maintenance of the overall prefabricated concrete bridge project. In the future, testing organizations may also consider introducing artificial intelligence technologies and corresponding equipment based on actual needs, or integrating advanced technologies such as digital twins and big data, to enable intelligent identification, rating, and early warning of various defects at connection joints, thereby achieving further optimization of the entire testing workflow.

Disclosure statement

The authors declare no conflict of interest.

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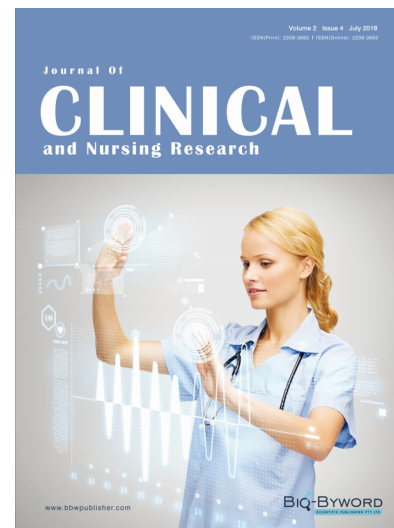
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