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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 hm^2). 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**.

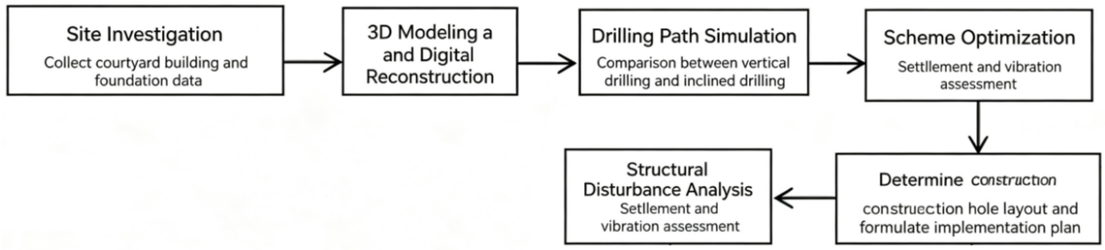

Figure 1. Flowchart of micro-pile drilling path optimization

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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