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Micro-disturbance Construction Technology of Ultra-close Rotary Drilling and Bored Pile

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Abstract: *A researching efficient, low-impact pile foundation construction technique under ultra-close distance conditions is particularly crucial. This study aims to explore methods for effectively minimizing micro-disturbance effects on adjacent tunnels during the full rotary drilling and bored pile construction process, thereby ensuring both safety and quality. First, we analyze the primary characteristics and challenges of full rotary drilling and bored pile construction under ultra-close conditions, with a specific focus on the potential risks posed to nearby tunnels. Then, based on relevant research findings domestically and internationally, we propose an optimized construction process for controlling micro-disturbances. This includes adjustments to drilling parameters, the application of slurry wall support, and selection and pouring techniques for concrete in bored piles. Results indicate that the ultra-close full rotary drilling and bored pile technology demonstrates high construction efficiency with minimal disturbance to surrounding tunnels, ensuring construction safety. By optimizing drilling parameters and controlling the construction speed, disturbances generated during construction can be effectively minimized. Field monitoring results show that, with the use of full rotary drilling technology, soil displacement around the site remains within permissible limits, causing no exceedance of standard-defined thresholds for the adjacent tunnels. Real-time monitoring during construction is essential for controlling micro-disturbances. By strategically placing monitoring points and utilizing advanced monitoring equipment, it is possible to detect anomalies in the construction process promptly, providing a basis for necessary adjustments.*

Keywords: *Ultra-close distance, Full rotary drilling, Bored pile, Micro-disturbance, Construction*

1. Introduction

With the rapid advancement of global urbanization, the utilization of underground space in cities has significantly increased. The construction of large-scale subway and tunnel projects, in particular, has brought the interaction between pile foundation construction and existing tunnels to the forefront of engineering concerns. Pile foundation construction can cause soil deformation and stress redistribution, which may compromise the safety and stability of existing tunnels. Numerous studies have focused on analyzing and controlling the adverse effects of pile foundation construction on existing tunnels, providing critical theoretical and technical guidance for practical engineering.

In terms of pile-tunnel interaction research, Asker et al. (2021) investigated the impact of tunnel construction on the pile foundation of elevated bridges through numerical analysis and proposed the use of a jet grouting wall to mitigate effects [1]. Shan et al. (2021) optimized displacement isolation pile design parameters between high-speed rail bridges and subway tunnels, analyzing pile-tunnel interactions from a vibration isolation perspective [2]. Song and Marshall (2020, 2021) examined the effects of tunnel excavation on pile foundations using centrifuge experiments and numerical simulations, revealing the influence of soil conditions on the interactions [3,4]. Some studies have focused on settlement and deformation caused by pile foundation construction, exploring the impact on surrounding buildings and facilities. Wang et al. (2021) proposed a simplified analytical solution to address settlement due to axial pile load during tunnel construction, providing theoretical support for micro-disturbance construction [5]. Ma et al. (2024) highlighted the significance of settlement monitoring during tunnel crossings near existing stations, where existing pile foundations significantly affected station settlement [6]. Li et al. (2020) compared protection schemes for piles near shield tunnels, assessing the impact of different schemes on settlement and deformation [7]. Experimental studies and numerical simulations can be utilized to analyze micro-disturbance issues in ultra-close pile construction. Zhang et al. (2021) presented a case study emphasizing effective measures taken during shield tunnel construction to reduce tunnel impact [8]. Lin et al. (2024) analyzed the effects of construction within subway protection zones on existing tunnels through field tests and numerical simulations, suggesting optimization strategies [9]. Song and Marshall (2020) provided experimental evidence through centrifuge tests and numerical simulations on the specific impacts of tunnel construction on surrounding piles [3,4]. Stress analysis and model construction of pile and underground structures enable investigations into stress variations during construction. Yan et al. (2024) proposed a simplified method for analyzing stress in transfer structures spanning multiple subway tunnels, offering a practical tool for stress assessment in micro-disturbance construction [10]. Zhang et al. (2024) studied the impact of full rotary steel-cased bored piles on adjacent tunnels, emphasizing the importance of structural safety assessment in micro-disturbance construction [11].

In summary, the impact mechanisms of pile foundation construction on existing tunnels are complex, involving soil deformation, stress redistribution, and tunnel structure response. Researchers have proposed various methods to mitigate construction-induced adverse effects through numerical simulations, field monitoring, and control measures. However, most existing studies remain theoretical, while engineering projects prioritize practical effectiveness. This study focuses on micro-disturbance construction technology using ultra-close full rotary drilled bored piles, based on an actual engineering project, to provide practical references for similar future projects.

2. Project Overview

In a major convention center project, a section crosses beneath the operational Metro Line 1, where shield tunneling construction with prefabricated segment structures was employed. The tunnel has a diameter of 6 meters, with a spacing of 5.8 to 6.6 meters between the uptrack and downtrack lines, and is buried at a depth of 12 to 14 meters in sandy silt. A total of 215 piles are planned within the subway protection zone, all constructed using a full rotary casing combined with a slurry wall supported by a rotary drilling machine. The minimum clearance between the newly constructed piles and the existing tunnel is 2.5 meters, requiring stringent control over the impact of pile foundation construction on the existing tunnel.

3. Technical Principles

An innovative technique utilizing a long steel casing bored pile has been developed to minimize micro-disturbances in surrounding strata. By rapidly assembling multi-section casings, a 32-meter ultra-long steel casing is created, isolating the operational metro from construction impacts and reducing disturbances within the intense influence zone (defined as within one tunnel diameter from the tunnel). This pile foundation follows a “micro-disturbance” principle, employing a full rotary drilled bored pile with an ultra-long steel casing as a load-bearing medium for the superstructure above the operational metro, thereby allowing the soil above the tunnel to avoid bearing loads.

Throughout the process, several control measures are employed, including precise pile positioning, enhanced design of the steel casing and cutting heads, real-time monitoring and adjustment of verticality, controlled sinking speed of the rotary casing, and optimal reserve of the soil column height within the casing. These measures effectively address challenges in ultra-close, ultra-long pile construction, such as soil plugging and hole collapse.

4. Process Flow and Key Operational Points

4.1 Process Flow

The micro-disturbance construction technique for ultra-close full rotary drilled bored piles is illustrated in Figure 1. The process primarily includes the following steps: optimization of construction parameters, construction preparation, measurement and layout, positioning of full rotary machinery, segmented rotary sinking and soil extraction for the steel casing, borehole formation for the bored pile, placement of the reinforcement cage, installation of the guide pipe and secondary hole cleaning, pile casting, and real-time monitoring of the operational metro throughout the process.

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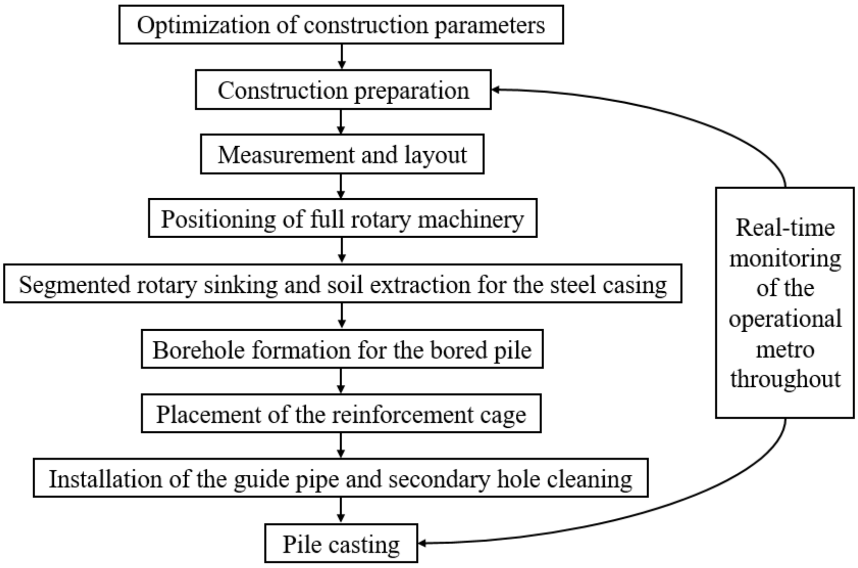

Figure 1: Construction Process Flow

4.2 Key Operational Points

4.2.1 Optimization of Construction Parameters

To minimize the deformation impact on the adjacent tunnel, a finite element optimization method [12-14] was employed to conduct a mechanistic analysis of ultra-close full rotary drilled bored piles. This analysis simulated the disturbance patterns of factors such as the thickness of the steel casing wall, surface loads, and rotation and downward pressure rates during construction on the surrounding soil. The final calculations determined that the steel casing wall thickness should be set at 12 mm, with surface loads maintained within the range of 15 kPa. The rotation speed and soil column height retained within the casing corresponding to the depth of single sinking, as shown in Table 1, were all kept within 11 meters.

Table 1: Parameters Related to Steel Casing Rotation Pressure

Depth (m)	Soil Layer	Rotation Speed (m/h)	Height of Soil Column h (m)
0-2.5	Loose fill, sandy silt	≤5	/
2.5-12	Sandy silt	≤4	≤7
12-18		≤2	≤7
18-32		≤3	≤10

4.2.2 Construction Preparation

Before construction begins, a specialized construction plan should be developed to ensure the safety and reliability of construction techniques, and implementation should only proceed after review and approval. Detailed construction design drawings must be thoroughly studied prior to starting work. The technical supervisor should provide comprehensive written safety and technical briefings to management personnel and operators, along with maintaining records of these safety and technical briefings. Once site leveling is completed, the travel routes for machinery should be planned, and steel plates or subgrade boards should be laid based on geological conditions. If necessary, site hardening should be conducted to ensure construction accuracy.

As shown in Figure 2, the site should be leveled and hardened in advance based on the pile foundation positions, with the hardening dimensions for individual piles set at 8×8 meters and a thickness of 30 cm to ensure the load-bearing capacity of the full rotary drill's base. All temporary facilities within a 30-meter radius of the subway tunnel should be removed, and surface construction loads should be controlled to around 10 kPa.

Figure 2: Site Leveling and Hardening

4.2.3 Measurement and Layout

Control points for the axis at the construction site should not be affected by pile foundation construction to allow for verification of pile positions during construction operations. When determining pile positions, control lines should be established on-site according to the construction grid, and each pile should be numbered based on the design pile position map. The positions of the piles should be set according to their corresponding axis and dimensions, with sample piles placed for drill positioning. The determined pile positions should undergo a secondary verification to ensure accuracy before construction begins.

4.2.4 Positioning of Full Rotary Machinery

The steel casing full rotary drill should be centered using lifting techniques to ensure that the drill's rotating table center aligns with the pile center point. Based on the established center points, the edges of the pile should be marked using white lime according to the designed pile diameter. As illustrated in Figure 3, the main positioning plate should be suspended above the pile position, ensuring that the center of the positioning plate's cross aligns with the pile center point. Measurements should be re-checked, and if no deviation is found, the full rotary drill should be lowered into position.

Figure 3: Positioning and Centering of the Full Rotary Drill

4.2.5 Steel Casing Segmented Rotary Sinking and Soil Extraction

The steel casing has a wall thickness of 12 mm and an outer diameter of 1 m, consisting of five segments totaling 35.5 meters, with the first four segments each measuring 8 meters and the fifth segment measuring 3.5 meters. The first segment (the bottom segment), equipped with a cutting head, should be inserted while ensuring that the cutting head does not collide with the main body of the machine. The casing's cutting head should be clamped and fixed at a height of 100 mm above the ground, with horizontal and vertical alignment continuously checked using a theodolite or plumb bob.

The sinking speed for the first segment of the steel casing should be controlled at 5 m/h for the 0-2.5 m depth range and at 4 m/h for the 2.5-8 m depth range, as shown in Figure 4. The verticality of the casing should be continuously adjusted in real-time using a verticality device on the drilling machine to ensure precision.

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Figure 4: Real-time Correction of Steel Casing Sinking Verticality

When the top of the first casing segment is approximately 1.0 m from the operating platform of the full rotary drill, drilling operations should stop. The casing should be secured, and a guiding point should be welded at its top. The second segment of the steel casing should then be lifted onto the first segment, joined using shear plates, and fully welded around the circumference. After passing a quality inspection 20 minutes post-welding and allowing the seam to cool, sinking operations can continue. The second segment of the steel casing should be sunk at a speed of 4 m/h for the 8-12 m depth range and at 2 m/h for the 12-16 m depth range, with soil extraction conducted (with a soil height $\leq$ 7 m retained within the casing).

The remaining segments (three to five) of the steel casing should be sunk sequentially, with a speed of 2 m/h for the 16-18 m depth range (soil height $\leq$ 7 m), and at 3 m/h for the 18-32 m depth range, maintaining a soil height of 10 m within the casing. Once the ultra-long steel casing has been sunk to the design elevation, the full rotary drill should be relocated, and the fifth segment of the steel casing should be severed.

4.2.6 Formation of Bored Piles

Before commencing work with the rotary drilling machine, the pile positions should be calibrated and verified to ensure there is no deviation. As shown in Figure 5, the rotary drilling machine should be positioned, and the drill bucket and drill rod should be lowered, with slurry replenished and the borehole drilled to completion. The bottom of the hole should be processed to ensure it is flat and free of loose debris, sludge, and sediment layers, with the embedded depth into the rock layer meeting design requirements. Following the completion of the first cleaning operation, a timely inspection should be reported to the resident supervising engineer.

Figure 5: Formation of Bored Piles with Rotary Drilling

4.2.7 Hoisting of Reinforcement Cages

Before hoisting the reinforcement cages, the surface must be cleaned of debris, mud, and other contaminants. The reinforcement cages are fabricated in segments, each measuring 12 meters in length, with adjacent longitudinal bars staggered by 1 meter. The first segment of the reinforcement cage is inserted into the pile hole, supported and fixed in place using steel pipes, leaving a height of 2-3 meters to connect mechanically with the next segment. The lower reinforcement cage is connected through hoisting. When connecting the two reinforcement cages, the adjacent bars must be staggered by 35 diameters (35d).

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As shown in Figure 6, after completing the connection, the quality of the connection should be inspected. Once deemed satisfactory, the above steps are repeated for the next reinforcement cage. After the reinforcement cage has descended to the design elevation, it should be immediately secured to prevent any movement.

Figure 6: Hoisting of Reinforcement Cages

4.2.8 Placement of Conduits and Secondary Cleaning of Boreholes

After the hoisting of the reinforcement cage is completed, the conduit for pouring concrete should be installed. The conduit should utilize flange connections or spiral threaded joints. The water-seal ball used should be meticulously crafted, with its diameter and ovality meeting usage requirements, and its length should be less than 200 mm. After the installation of the reinforcement cage and concrete conduit is completed, a second cleaning of the borehole is performed. During this process, the drilling fluid should be continuously replaced, and the thickness of the sediment at the bottom of the borehole should not exceed 50 mm, until underwater concrete can be poured.

4.2.9 Pouring of Piles

Different lengths of conduits should be configured based on the depth of the borehole, with the bottom of the conduit maintained 0.3-0.5 m above the bottom of the borehole. It is essential to ensure that a sufficient initial volume of concrete is poured, with the conduit embedded to a depth exceeding 2 meters. Concrete pouring should generally not exceed 4 hours, with any intermediate pauses not exceeding 30 minutes. Continuous measurement of the concrete surface height and frequent withdrawal of the conduit should be conducted to ensure that the concrete work proceeds continuously, avoiding any leaks or empty pulls. The pouring should be uninterrupted and completed in one go. Once the concrete has been poured to a height of 500 mm above the design elevation, the drilling fluid and excess slurry should be expelled before proceeding with mechanical vibration compaction.

4.2.10 Real-Time Monitoring of the Entire Subway Operation

Table 2: Statistics of Maximum Cumulative Variations in Subway Monitoring Projects

Item		Cumulative Maximum Variation (mm)		Control Indicators (Cumulative)		
		Section	Variation	Warning Value (mm)	Alarm Value (mm)	Control Value (mm)
Up Line	Bed Settlement	K45+182	1.1	1.2	1.6	2.0
	Tunnel Horizontal Displacement	K45+182	0.6	1.2	1.6	2.0
	Tunnel Convergence Deformation	K45+182	0.7	1.2	1.6	2.0
Down Line	Bed Settlement	K45+182	0.9	1.2	1.6	2.0
	Tunnel Horizontal Displacement	K45+182	0.5	1.2	1.6	2.0
	Tunnel Convergence Deformation	K45+182	0.8	1.2	1.6	2.0

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To ensure the safety of the shield tunnel and maintain structural stability, an automated monitoring system is employed to oversee the subway protection zone. The monitoring focuses on several key parameters: tunnel bed settlement, horizontal displacement of the tunnel, and horizontal convergence of the tunnel. The monitoring results are summarized in Table 2. These results are continuously tracked and compared against control indicators, ensuring that all data remain below the predefined alert thresholds. The maximum deformation increment of the tunnel is controlled within a range of 1.2 mm.

5. Quality Control

The quality acceptance of the ultra-small clearance full-rotation bored pile micro-disturbance construction must comply with current national and industry standards. During the construction process, quality control should meet the requirements shown in Table 3. Additionally, when positioning the casing, the deviation between the casing center and the pile center in the plane should be controlled to less than 50 mm, with an inclination of less than 1%. Once the casing is embedded, its center should be re-measured. The deviation of the conduit axis should not exceed 0.5% of the hole depth and should not be greater than 10 cm.

Table 3: Pile Quality Control Requirements

No.	Construction Step	Quality Control Standard	Quality Control Requirements
1	Construction Preparation	100% Personnel Briefing	Brief on-site construction personnel.
2	Equipment Positioning	Ensure a cushion thickness of 200 mm, verify design requirements; positional deviation ≤ 1 cm	Strictly follow acceptance procedures and conduct technical verification.
3	Casing Fabrication, Hoisting, and Rotating In	Casing wall thickness ±1 mm; vertical deviation 1/1000; ovality deviation 0.5 mm	Rigorously check incoming acceptance to ensure compliance with design requirements; select a 100T crawler crane.
4	Casing Lengthening and Rotating In	Weld height above casing ≤ 1 mm; butt joint casing centerline deviation ≤ 1 mm; soil column height not exceeding 11 m.	Use bevel welding for butt joints; set positioning devices for casing lengthening; use a 1080 rig-lock drill; measure soil column height before casing lengthening to ensure proper flow.
5	Hole Cleaning	Mud density ≤ 1.25; sediment thickness ≤ 50 mm	Measure actual mud density; have the supervisor witness the measurement of sediment thickness.
6	Lowering Reinforcement Cage	18 m long reinforcement cage uses straight thread connections; single-side welding length and quality compliance rate 100%.	Select a 100T crawler crane; the length of the reinforcement cage sections is 18 m, with single-side lap welding for connection.
7	Secondary Cleaning	Mud density ≤ 1.2; sediment thickness ≤ 50 mm.	Measure actual mud density; have the supervisor witness the measurement of sediment thickness.
8	Concrete Pourin	Initial pour volume ≥ 0.8 m³; slump: 180±20; conduit embedment depth ≥ 6 m	Calculate initial pour volume; test slump for each pile; determine embedment depth based on conduit length and concrete volume.

6. Benefit Analysis

The implementation of the developed micro-disturbance long steel casing pile construction effectively mitigated the disturbance impact of pile construction on the tunnel within the highly affected zone (defined as one tunnel diameter). The maximum cumulative deformation increment of the tunnel was only 1.1 mm, which did not exceed the deformation warning value. By adhering to the "micro-disturbance" principle, the use of ultra-long steel casing full-rotation bored piles as load transfer media for the operational subway structure allowed for the upper soil layers of the tunnel to remain unloaded. Through precise positioning of the piles, in-depth design of the steel casing and cutting heads, and real-time monitoring and adjustment of verticality, various control measures effectively addressed challenges such as soil blockage and hole collapse during the construction of ultra-long piles in ultra-small clearances. This technology not only protects the safety and stability of the subway tunnel but also significantly enhances construction efficiency and quality. Furthermore, it aligns with national circular economy development requirements and is compatible with the sustainable development of the

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construction industry, laying a foundation for future similar engineering projects and demonstrating high potential for widespread application.

7. Conclusion

This paper explores the micro-disturbance construction technology of ultra-small clearance full-rotation bored piles within the context of practical engineering, focusing on analyzing the characteristics of micro-disturbance during construction and its impact on adjacent tunnels. The research findings provide valuable references for similar projects and lead to the following conclusions:

(1) The ultra-small clearance full-rotation bored pile technology exhibits excellent construction efficiency and minimal tunnel disturbance during the construction process, ensuring operational safety.

(2) By optimizing drilling parameters and controlling construction speed, the disturbances generated during construction can be effectively reduced. Field monitoring results indicate that after adopting full-rotation drilling technology, the displacement of surrounding soil remains within acceptable limits and does not adversely affect the adjacent tunnel beyond the prescribed standard values.

(3) Real-time monitoring during the construction process is crucial for controlling micro-disturbance. By strategically placing monitoring points and utilizing advanced monitoring equipment, abnormal conditions during construction can be promptly identified, providing a basis for necessary construction adjustments.

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