Monitoring Technology for Underpinning Construction of Pile Foundations Under Elevated Bridge Piers of Subway Stations (Postprint)

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Abstract

With the sustained development of urban infrastructure, urban rail transit construction has experienced rapid growth. However, constrained by legacy urban planning, new subway construction will inevitably traverse the foundations of existing buildings (structures) to some extent. How to execute underpinning construction and risk control for existing building pile foundations has become an unavoidable technical and managerial challenge in subway construction. This paper presents a detailed discussion on the design of underpinning schemes, construction techniques, and safety monitoring, using the pile foundation underpinning of an elevated bridge pier at an urban subway station as a case study, thereby accumulating valuable experience for construction technology and safety risk management of existing bridge pile foundation underpinning under complex construction environments and geological conditions.

Full Text

Monitoring Technology for Pile Foundation Underpinning Construction Beneath Viaduct Piers in Metro Stations

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Abstract: With the continuous development of urban infrastructure, urban rail transit construction has experienced rapid growth. However, constrained by existing urban planning, new subway construction inevitably passes through the foundations of existing buildings and structures. How to conduct underpinning construction of existing building pile foundations and control associated risks has become an unavoidable technical and management challenge in subway construction. This paper examines a case of viaduct pier pile foundation underpinning for a metro station, providing a detailed discussion of the underpinning scheme design, construction technology, and safety monitoring practices. The valuable experience accumulated from this project regarding construction technology and safety risk management for existing bridge pile foundation underpinning under complex construction environments and geological conditions offers important guidance for future projects.

Keywords: Foundation Underpinning; Existing Bridges; Construction Technology; Data Monitoring; Construction Design

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2. Project Overview

2.1 Design Overview The subject city viaduct is a north-south elevated expressway with varying planned widths along the east-west direction. Piers 20# through 22# are each supported by two 1.20m-diameter bored cast-in-place piles spaced at 3.30m intervals. The designed pile length is 43.65m for all piles, while the actual constructed lengths are 43.51m, 43.55m, and 43.65m respectively, with all pile tips seated in silt and fine sand layers. The pile cap dimensions are 5,500 × 1,800 × 1,500mm (length × width × height). The minimum distances from the edges of piers 20# and 22# caps to the outer side of the station retaining structure are 5.3m and 3.28m respectively.

The metro station is a three-level underground island platform station with a 13m-wide platform, total length of 323.5m, and standard section width of 22.3m. Behind the station, double-track double-bay parking lines are provided. At the station centerline, the standard section excavation pit measures 22.3m wide with a depth of approximately 23.937m. Beneath the viaduct, the pit is about 23.6m wide and 24.6m deep. The main station structure beneath the viaduct is planned to be constructed using the cover-excavation method, with retaining support consisting of 1m-thick diaphragm walls plus four levels of concrete struts. The schematic diagram of the station and viaduct is shown in [Figure 1: see original paper].

2.2 Geological Conditions The site is located on a first-level terrace of the Yangtze River, belonging to a fluvial accumulation plain. The strata primarily consist of recent artificial fill (Qml), lacustrine deposits (Q4l), Holocene alluvial layers (Q4al), and alluvial-proluvial deposits (Q4al+pl). The bedrock is Silurian (S2f) mudstone with a generally gentle rock surface, though locally undulating.

As shown in [Figure 2: see original paper], layer 1-1 is miscellaneous fill, layer 1-3a is muddy silty clay, layer 3-1 is clay, layer 3-1a is brown-yellow silty clay, layer 3-1b is silt, layer 3-5 is silty clay interbedded with silt, layer 4-1 is silt and fine sand, and layer 4-2 (silt and fine sand) is distributed throughout as a massive thick layer with revealed thickness of 5.10–18.50m. Layer 20a-1 is strongly weathered mudstone, layer 20a-2 is moderately weathered mudstone, and layer 20a-3 is slightly weathered mudstone.

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3. Risk Control Analysis of Pier Pile Foundation Underpinning Construction

3.1 Overall Underpinning Scheme Within the excavation pit area, as soil is unloaded, the side friction of bridge piles is lost. To compensate for the loss of friction and overall stability of pier 21# piles during excavation, underpinning is implemented before pit excavation. Prior to constructing the station pit retaining structure, two bored cast-in-place piles are installed on each side of the elevated bridge adjacent to the piles being underpinned. The underpinning piles are 53m long with tips embedded no less than 1m into the slightly weathered mudstone layer (20a-3). Afterward, the pit is excavated with sloping sides to the design elevation of the new pile cap bottom, where a new steel-reinforced concrete cap is constructed to envelop the existing cap. The interface between new and existing caps is treated with bonding agent and rebar planting. Once the new cap reaches design strength, excavation of the main pit beneath the viaduct proceeds.

Piles for piers 20# and 22# are located on both sides of the main station pit. To reduce the impact of diaphragm wall construction beneath the viaduct on these piles, high-pressure jet grouting reinforcement is applied to the wall trench surfaces in this area.

The main construction sequence for pile foundation underpinning is illustrated in [Figure 3: see original paper]: a) Symmetrical construction of underpinning piles b) Construction of new pile cap and main station structure c) Construction of station concrete base slab and partition walls d) Backfilling, pipeline restoration, and traffic resumption

3.2 Underpinning Pit and System Design 3.2.1 Underpinning Pit The underpinning pit is approximately 2.45m deep with a safety classification of Grade I. It adopts sloped excavation at a 1:1 gradient, with a 100mm-thick C20 plain concrete surface layer for slope protection.

3.2.2 Underpinning System Design An active underpinning scheme is adopted for pier 21# piles, where four new underpinning piles are installed along the bridge direction on both sides of the original piles, and a new cap envelops the original cap to form an integral unit.

(1) The underpinning piles are C30 bored cast-in-place piles, each 1,200mm in diameter and 53m long, with pile tips embedded no less than 1m into the slightly weathered mudstone layer (20a-3). Three 60mm-diameter grouting pipes are pre-embedded along the perimeter of each pile for post-grouting.

(2) The new pile cap uses C40, P8 waterproof reinforced concrete in a steel-reinforced concrete structure with dimensions of 8,000 × 6,400 × 2,300mm (length × width × height). The original cap surface is roughened and reinforced with planted rebars, then encased by newly poured concrete. Steel sections are installed above and below the original cap, connected by welded rebar to form a steel frame according to the four-pile cap design. This reduces excavation depth and impact on the viaduct during construction while minimizing effects on the main station structure.

3.3 Protection Design for Bridge Piles During Station Pit Excavation

Protection measures are designed for piers 20# through 22# during main pit excavation beneath the viaduct to reduce construction impacts.

(1) Trench Wall Reinforcement As shown in [Figure 4: see original paper], the pile foundations for piers 20# and 22# are located on both sides of the main station pit. Due to height restrictions beneath the viaduct, special machinery is required for diaphragm wall construction, resulting in long trenching times. The reinforcement cages must be installed in sections, requiring extended hoisting times. The walls are embedded to depth, requiring deep trench excavation. The site is located on a first-level Yangtze River terrace with high confined water pressure and a (1-3a) muddy silty clay layer in the side walls that has poor self-stabilization capability. These factors—long exposure time, deep excavation, and poor side wall geology—create potential for trench collapse. To reduce this risk to piers 20# and 22#, high-pressure jet grouting reinforcement is applied within approximately 40m of the wall trench on both sides, extending 47m below ground surface and at least 1m beyond the pile tips of piers 20# and 22#. After reinforcement, the unconfined compressive strength must be $ 1.0MPaandthepermeabilitycoefficientlessthan10^{-7}$ cm/s.

(2) Vertical Connecting Beam Design As the pit beneath the viaduct is excavated, two concrete horizontal connecting beams are installed vertically along the bridge piles. These beams connect to existing bridge piles using planted rebars and to underpinning piles using reserved rebar couplers. The cross-sectional dimensions are 800 × 1,000mm for beam I and 600 × 1,000mm for beam II. The planar reinforcement layout of vertical connecting beams is shown in [Figure 5: see original paper].

(3) Groundwater Treatment The retaining structure beneath the viaduct uses embedded diaphragm walls with jet grouting seals at joints. Dewatering is performed inside the pit, with pressure relief wells installed outside to reduce the water head difference between inside and outside the pit.

(4) Backfilling Within Partition Walls The space between bridge pile foundations and main station partition walls is backfilled sequentially upward to the pile cap bottom elevation as the main structure is constructed.

4. Construction Monitoring Analysis

4.1 Monitoring Requirements

(1) The underpinning pit safety classification is Grade I, with deformation control also classified as Grade I. According to the *Technical Specification for Excavation Engineering* (DB42/T159-2012) and the *Technical Requirements for Line 6 Construction Design*, when important protected objects exist within one times the excavation depth, horizontal displacement control standards are $\delta \leq 40$mm, maximum horizontal displacement $\leq 0.15\%$h (and ≤ 30mm), and maximum ground settlement $\leq 0.15\%$h, where h is the excavation depth in meters. Through comparative calculation, the control standards are determined as: maximum horizontal displacement $\leq$ 3.75mm, maximum ground settlement $\leq 0.15\%$h (approximately 3.75mm). The underpinned and existing bridge piles jointly serve as permanent structures bearing upper loads. During underpinning and station construction, horizontal displacement of viaduct pile foundations must be controlled within 10mm and settlement within 20mm, with these bridge deformation control indicators subject to confirmation by the viaduct property owner. Protection plans require property owner approval before implementation.

(2) Given historical incidents of pile inclination in this viaduct, a condition assessment must be conducted before underpinning.

(3) Third-party monitoring must be implemented before main pit retaining structure construction to provide necessary basis for construction monitoring, emergency response, and potential disputes.

(4) Site monitoring and measurement must continue throughout the entire construction process. Monitoring frequency should be determined according to construction progress, with increased frequency when structural deformation is excessive or site conditions change, and continuous monitoring when accident signs appear. Monitoring reports and treatment recommendations must be submitted promptly after each monitoring session. In emergencies, monitoring should be intensified with corresponding measures taken and timely reporting.

(5) During underpinning pile construction, monitoring of viaduct pier deformation must be strengthened, with visual inspection of crack development on the bridge deck. Problems must be addressed promptly, with monitoring focused on piers 17# through 23#.

(6) Normal monitoring frequency for the underpinning pit is twice daily; during rebar planting and cap pouring, four times daily; during excavation beneath bridge piles, continuous monitoring is required.

(7) Monitoring alert values:

- Power and telecommunication pipelines: settlement and horizontal displacement must not exceed 10mm, with daily development not exceeding

2mm.

- Viaduct pile foundation horizontal displacement controlled within 10mm, settlement within 20mm (these alert values must be confirmed by the viaduct property owner).

(8) Construction requires approval from the viaduct property owner with early communication and coordination. If the property owner has special requirements, the supervisor and designer must be notified promptly to adjust the design scheme.

4.2 Analysis of Key Monitoring Data As shown in [Figure 6: see original paper], monitoring data from points Q05 through Q12 at three piers (20#, 21#, and 22#) are selected to illustrate variation patterns, with statistical analysis covering the period from December 15, 2014, to November 12, 2015. The corresponding cumulative surface settlement variations at these monitoring points are shown in [Figure 7: see original paper].

Around April 20, 2015, to reduce the risk of trench collapse affecting piers 20# and 22# during diaphragm wall construction beneath the viaduct, high-pressure jet grouting reinforcement was applied within approximately 40m of the wall trench on both sides. Isolation piles were also installed in the pre-reinforcement zone of piers 20# and 22#. Due to the high pressure from grouting and pile installation, all bridge piles experienced upward heave, particularly at monitoring point Q07, which reached a maximum heave of 12.56mm on May 10.

After reinforcement completion, as underpinning pile construction began, the bridge piles started to settle gradually. By June 10, when underpinning pile construction was completed, the earlier heave from trench wall reinforcement and settlement from pile construction had essentially neutralized each other. At this stage, the maximum heave was 6.59mm at Q07, while the maximum settlement was -1.33mm at Q12.

On July 18, construction of the diaphragm wall beneath the viaduct commenced. Due to space restrictions, deep trenching, long construction duration, extended trench exposure time, and poor side wall geology, soil disturbance during excavation caused water and soil loss, leading to varying degrees of settlement in the bridge piles. The monitoring data analysis shows that pier 20# monitoring point Q12 experienced the most significant settlement, reaching a maximum cumulative settlement of -7.29mm by September 6 when the diaphragm wall construction was completed.

Thus, it is evident that soil pressure from trench wall reinforcement and base reinforcement causes pile heave, while underpinning pile (bored cast-in-place piles) and diaphragm wall construction easily lead to water and soil loss, causing ground settlement.

Conclusions

Based on the actual construction of pile foundation underpinning beneath viaduct piers for a metro station, this paper presents a comprehensive risk control analysis of underpinning construction technology, which facilitates orderly construction progress and provides valuable experience for similar future projects.

The following conclusions are drawn:

(1) During metro construction, attention must be paid to surrounding environmental conditions. Effective protection of the construction environment through proper monitoring point placement and reasonable construction process design, combined with technical measures appropriate to actual hydrogeological conditions, provides good control of construction risks.

(2) Embedding monitoring points at different site locations effectively expands the safety monitoring scope, enabling early warning and feedback of impending risks during construction and allowing site personnel to take timely measures to effectively avoid hazardous situations.

(3) Statistical analysis of actual monitoring data from viaduct pier pile foundation underpinning construction reveals that certain monitoring items require special attention. For example, surface settlement around piers 20#, 21#, and 22# during construction is significantly greater than at other piers, necessitating increased monitoring frequency and focused attention on data changes at monitoring points around these piers to implement effective preventive measures.

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Application of Viaduct Metro Construction

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Abstract: Railway construction has been developed rapidly. But during the construction of a new subway, the tunnel will inevitably pass through the foundation of buildings. How to control the risk of underpinning construction and protect existing buildings becomes an inevitable challenge. The paper focuses on the management and technology used in Viaduct Pile foundation underpinning, elaborates the design, construction technology and safety monitoring work. The provided valuable experience of bridge pile foundation underpinning construction in complex environments and geological conditions is helpful to security risk management.

Key Words: Foundation Underpinning; Existing Bridges; Construction Technology; Data Monitoring; Construction Design

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Influence of Empty Shield Tunneling Segment Pushed Ahead Through on the Existing Tunnel

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Abstract: Wuhan Metro Line 6 has to go under an existing station of the 2nd line by the method of in advance tunneling construction. This article describes the construction process in advance of shield tunneling segment through a series of problems existing in the corresponding solutions, and analyzes the track surface during construction on the 2nd line of settlement and the existing station building subsidence case of using shield empty push impact on the existing tunnel. Based on Wuhan metro Line 6 tunnel, this article carries out a systematic analysis on the early application of the existing tunnel excavation method and the shield push with no-load. On this basis, the article discusses the shield tunneling segment results from the rail surface settlement of the existing track and station building cumulative settlement. The project also uses a special precipitation and strengthening programs to reduce the impact of the construction process on the existing line operator and provides a useful reference for similar engineering.

Key Words: Shield Tunneling; Undercutting Method; Push Forward with No-load

Note: Figure translations are in progress. See original paper for figures.