Construction Technology and Quality Control for Shield Idling Through Mining-Method Tunnels Postprint

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Abstract

Shield tunneling, as a safe and efficient tunnel construction method, plays an active role in urban rail transit construction in China. However, local hard rock sections frequently occur within a tunnel interval, leading to difficult shield excavation, substantial cutter wear, and slow construction progress. When the length of hard rock excavation reaches a certain threshold, a composite construction method combining "shield tunneling" and "mining method" is typically adopted. Although this construction method can enhance construction speed and reduce construction risks, it may also introduce various issues. Based on the actual construction conditions of a subway interval in Wuhan, this paper presents the key technologies and quality control measures implemented during the shield arrival, shield advancement, and shield reception phases when the shield was pushed through a mining-method tunnel in moderately weathered mudstone strata, achieving favorable engineering outcomes and providing valuable references for similar projects.

Full Text

Preamble

Technology and Quality Control of Shield Empty-Pushing Through Mining Method Tunnel Construction

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Abstract: Shield tunneling construction, as a safe and efficient method, plays an active role in urban rail transit development in China. However, tunnel intervals often contain localized hard rock sections where shield excavation becomes difficult, cutter wear is significant, and construction progress slows substantially. When hard rock excavation reaches a certain length, a composite construction method combining “shield tunneling” and “mining method” is typically adopted. Although this approach can improve construction speed and reduce mining method excavation risks, it also creates numerous problems. Based on actual construction conditions in a Wuhan metro interval, this paper introduces key technologies and quality control measures for shield arrival, shield propulsion, and shield reception during empty-pushing through mining method tunnels in moderately weathered mudstone formations. The implementation achieved excellent engineering results and provides a valuable reference for similar projects.

Keywords: Shield Method; Mining Method; Empty Pushing; Key Technology; Quality Control

1 Project Overview

The Wuhan Rail Transit shield tunnel interval under consideration involves challenging geological conditions. The tunnel crosses moderately weathered limestone and quartzite strata with compressive strengths of approximately 33–58 MPa. Given the difficulties of shield tunneling in hard rock—including slow advance rates—this section adopted a composite “mining method + shield method” construction approach. The interval from the intermediate ventilation shaft to the Han River tunnel was constructed using this composite method, while the section from the Han River to the northern starting point used conventional shield tunneling.

The tunnel lining consists of C50P12 concrete segments with a ring width of 1.5 m, thickness of 350 mm, taper of 40 mm, outer diameter of 6,200 mm, and inner diameter of 5,500 mm. The mining method tunnel structure provides a clear width of 6,600 mm and clear height of 6,750 mm. The geological profile features silty clay (3-2) above the tunnel and moderately weathered mudstone (17a-1) below. The alignment includes a minimum curve radius of R=350 m, maximum longitudinal slope of 28‰, maximum burial depth of 37.2 m, and maximum water-soil pressure of 5 Bar. The main project quantities are summarized in , and the tunnel profile is shown in [Figure 1: see original paper].

Two slurry shields were deployed for the northern starting point to intermediate ventilation shaft interval. The shields launched from the northern starting point and advanced toward the intermediate ventilation shaft. After completing the shield tunneling phase and receiving the shields within the tunnel, the machines were empty-pushed to the intermediate ventilation shaft for removal.

2 Overall Construction Process and Methods

The overall construction process for empty-pushing through the mining method tunnel involves: guide platform construction → shield arrival → shield empty-pushing through the mining method tunnel section → shield reception.

2.1 Arc-shaped Guide Platform Construction

After completing the initial support of the mining method tunnel excavation, an arc-shaped concrete guide platform with a radius of 3,470 mm and thickness of 200 mm was installed within the bottom 90° range of the tunnel. The construction details are illustrated in [Figure 2: see original paper]. Precise control of guide platform construction accuracy is critical, as the platform serves as the lower support for the shield when passing through the hard rock tunnel. After positioning the formwork, measurement verification must be conducted, and elevation should be rechecked after concrete pouring to ensure construction accuracy within 0–+10 mm.

2.2 Shield Arrival

Shield arrival construction begins when the cutterhead reaches 30 m from the interface between the shield tunnel and mining method tunnel, and concludes when the cutterhead passes the interface and the tunnel breakthrough is achieved. This project employed a water arrival method, with the construction flow shown in [Figure 3: see original paper].

2.2.1 Water Retaining Wall Setup To ensure construction safety, a 500 mm thick reinforced concrete water retaining wall was constructed 10 m from the interface within the mining method tunnel section built from the intermediate ventilation shaft side, as shown in [Figure 4: see original paper]. The wall' s horizontal and vertical main reinforcement used \$ \$20 threaded steel bars at 200 mm spacing, welded to pre-embedded bars in the mining method tunnel' s initial support. Bracing bars of \$ $10steelwerearrangedina400\times$\$400 mm staggered pattern, with all connections welded.

Two \$ \$100 steel pipes with gate valves were installed at the top and bottom of the wall. Clean water was injected into the storage chamber through the top pipe before tunnel breakthrough. After breakthrough, slurry and wastewater were pumped out through the bottom pipe into the drainage system, followed by wall demolition and site cleanup.

2.2.2 Secondary Grouting Behind Segments After the shield advanced to the interface, excavation stopped and the slurry circulation was closed. Secondary supplementary grouting was then performed on 4–6 rings of segments behind the shield tail.

2.2.3 Connection of Last 10 Segment Rings Strict implementation of a three-stage bolt tightening system was required for the last 10 rings. After the cutterhead contacted the tunnel face and the machine stopped, the last 10 rings' circumferential bolts were retightened. To prevent segment joints from opening and causing water leakage after breakthrough when transverse forces suddenly decreased, transverse tensioning devices were installed between these rings. These devices used 14b channel steel sections bolted with M30 bolts at lifting nut locations, installed before shield thrust removal or at the rear shield segment position.

2.3 Shield Empty-Pushing Through Mining Method Tunnel Section

After arrival completion (tunnel breakthrough), slurry and wastewater in the storage chamber were discharged through the wall' s lower drainage pipe, the water retaining wall was demolished, and the site was cleaned to prepare for shield empty-pushing through the mining method section. The construction flow is shown in [Figure 5: see original paper].

2.3.1 Shield Propulsion Since no reaction force exists ahead of the cutterhead during empty-pushing, shield attitude control is challenging. To maintain tunnel alignment, each propulsion cylinder group's stroke was adjusted based on the relationship between the cutterhead and guide platform, advancing along the design line at 30-50 mm/min. A dedicated inspector monitored shield propulsion conditions ahead of the shield, checking for initial support intrusion into the cutterhead profile, contact between the shield front and guide platform, and compaction of gravel backfill. The empty-pushing operation is shown in [Figure 6: see original paper].

2.3.2 Segment Assembly Segment assembly followed the same process as normal tunneling. Segment type selection was based on shield tail clearance, cylinder stroke differences, and shield attitude to ensure proper installation. By controlling the gap between the shield tail and segment outer surface, assembly quality met design requirements. After each segment was installed, connecting bolts were initially tightened manually; after completing each ring, all bolts were tightened with pneumatic wrenches; and after segments cleared the shield tail, they were retightened again.

2.3.3 Segment Backfilling Segment backfilling involves compactly filling the void between segments and the mining method tunnel' s initial support through three components: rice stone spraying, shield tail synchronous grouting, and supplementary grouting.

(1) Rice Stone Spraying

Granite rice stone with 5-10 mm continuous grading served as backfill material, applied during segment assembly in two stages:

First Stage: Every 4.5-6 m, sandbags were used to create a cofferdam around the shield cutterhead within a 60°-300° range to prevent forward migration of rice stone and mortar. Two shotcrete machines (50-type) were connected to spraying pipes on the shield shell, simultaneously blowing 5-10 mm gravel aggregate from both sides at 0.25-0.3 MPa pressure. When a natural slope formed between the shield shell top and sandbag cofferdam top, spraying stopped.

Second Stage: After segments cleared the shield tail, rice stone was blown through segment grouting holes to further fill voids between segments and the mining method tunnel.

The filling standard required the mining method tunnel initial support profile to exceed the segment outer diameter by 15 cm, creating a 9.5 m^3 void per ring (including 1.6 m^3 for the guide platform). Rice stone was sprayed within the bottom 120° range to prevent segment settlement, with a minimum fill rate of 35% (ratio of rice stone volume to void space), requiring at least 2.8 m^3 per ring (adjustable based on actual spraying speed). Synchronous spraying from both sides was mandatory, with elevation differences controlled within 0.8-1.0 m to prevent segment displacement from pressure differentials. The rice stone spraying process is illustrated in [Figure 7: see original paper].

(2) Shield Tail Synchronous Grouting

Synchronous grouting used cement mortar with 8-hour initial set and 10.5-hour final set. Applied after each ring' s rice stone backfilling, injection was uniform based on advance speed, starting with shield propulsion and ending when propulsion stopped. To ensure filling effectiveness while preventing mortar migration ahead of the cutterhead, grouting pressure was maintained at 0.05-0.08 MPa. Since the shield shell periphery was open with minimal pressure variation, pressure was not used as the control criterion. Grouting ended when volume reached 80% of theoretical quantity. After installing 10 rings, grouting effectiveness was checked every 4 rings through openings at segment grouting holes, with supplementary grouting applied as needed.

Theoretical grouting volume per ring was calculated as:

$$Q = V \cdot \lambda$$

where λ is the grouting rate (1.5-2.5, with higher values for curved sections and sandy strata), and V is the shield tail annular gap (m^3/ring):

$$V = \pi[(6.52/2)^2 - (6.2/2)^2] \times 1.5 = 4.8\,\mathrm{m}^3$$

Thus, $Q = 7.2\text{–}11.0\,\mathrm{m}^3$ per ring.

(3) Supplementary Grouting

First Stage: Conducted to fill voids behind segments, particularly at the crown. During shield advance, synchronous grouting effectiveness was checked every 4 rings through segment grouting holes. If voids existed, single-liquid cement grout (cement:water = 1:0.8) was injected at 0.3-0.4 MPa pressure through holes at 37.9° or 322.1° positions (avoiding the key segment location). Pressure served as the single control criterion.

Second Stage: After the shield passed through the mining method tunnel, dual-liquid grout (cement-sodium silicate) was used for water sealing based on leakage conditions. The mix ratio was cement:sodium silicate = 1:1, injected at 0.2-0.3 MPa pressure with flow rate not exceeding 10 L/min, controlled by pressure alone.

2.4 Shield Reception Construction

Shield reception begins when the cutterhead reaches the reception shaft portal and ends when the shield tail completely clears the portal and moves onto the reception frame. The reception flow is shown in [Figure 8: see original paper].

2.4.1 Portal Seal Installation Before shield arrival at the reception shaft, a portal sealing device was installed to contain rice stone and mortar backfill behind segments, ensuring void filling effectiveness. The sealing arrangement is shown in [Figure 9: see original paper].

2.4.2 Backfill of Segment Annular Void When the cutterhead reached the portal, rice stone could no longer be sprayed from ahead of the cutterhead. Instead, it was injected through segment secondary grouting holes, with mortar applied synchronously through the shield' s built-in grouting system during advance. During reception, rice stone spraying occurred every 3 m. After the shield tail cleared the portal, backfill effectiveness was inspected, with supplementary grouting applied where insufficient. Surface sleeve valve pipe grouting was also an option, involving drilling from the surface through the tunnel crown after shield passage. Drilling depth was strictly controlled to penetrate only the mining method tunnel initial support. Grouting completion was controlled by both volume and pressure: 灌注量不小于壁后间隙的 65% (minimum 4 m^3 per ring average), with pressure controlled by the grout pump and verified through core drilling.

2.4.3 Connection of Last 20 Segment Rings During assembly of the last 20 rings, segments were promptly connected into an integral unit to prevent loosening when thrust was minimal or absent. Tensioning connectors used 14b channel steel sections bolted with M30 bolts at lifting nut positions, installed before thrust removal or at the rear shield segment position.

3 Quality Control

3.1 Shield Attitude Control

Given the shield machine's large size (10.5 m length, 6.52 m cutterhead diameter) and heavy weight (350 tonnes), attitude adjustment is difficult. The following measures were implemented across construction stages:

(1) Guide Platform Construction Stage Control guide platform construction precision. As the lower support for shield passage through hard rock tunnels, platform accuracy directly determines shield attitude. After formwork positioning, measurement verification and post-pouring elevation rechecking ensured accuracy within 0–+10 mm.

(2) Shield Arrival Stage Adjust shield attitude before tunnel breakthrough. Before entering the hard rock tunnel from the shield tunnel, the shield’ s exit attitude was adjusted to ensure roll value was less than \$±\$3 mm/m. During guide platform propulsion, roll was maintained below \$±\$5 mm/m.

(3) Shield Empty-Pushing Stage Optimize segment selection and installation. Combining shield attitude, shield tail clearance, and cylinder stroke differences, appropriate segments were selected to control cylinder stroke differences and maintain shield deviation within \$±\$20 mm and shield tail clearance around 70 mm, ensuring relatively uniform thrust on segments and preventing extrusion by the shield tail inner shell.

3.2 Segment Dislocation

(1) Shield Empty-Pushing Stage - Conduct manual attitude surveys every 3–5 rings, selecting segment types based on results combined with shield tail clearance. - Enhance inspection of rice stone backfill effectiveness to ensure compaction density in voids between segment bottoms and hard rock tunnel initial support, providing adequate lower support.

(2) Shield Reception Stage During advance on the reception frame, the portal temporary sealing device was tensioned every 2 rings. Rice stone was sprayed once per ring through segment secondary grouting holes, with quick-setting grout injected through the synchronous grouting system to fill the annular gap, ensuring correct segment attitude.

3.3 Segment Flotation

Due to limited rice stone and synchronous grouting quantities behind segments in the empty-pushing section, combined with accumulated water and ungrouted mortar, segment upper portions remained essentially void, allowing water and grout buoyancy to cause segment flotation and movement.

(1) Shield Empty-Pushing Stage Based on water inflow rates in the mining method tunnel, water was drained through lifting holes below segment waists in the completed tunnel to prevent flotation from excessive water accumulation. Wastewater was pumped to the intermediate ventilation shaft and then to the surface. Manual attitude surveys were conducted promptly, with auxiliary measures applied based on results.

(2) Shield Reception Stage Drilling and water release continued during grouting operations to prevent excessive water pressure from causing segment displacement or flotation.

3.4 Segment Waterproofing

During shield passage through hard rock tunnels, friction between the shield shell and guide platform is approximately 100 tonnes, between segments and shield tail brushes about 20 tonnes, and the towing force for backup equipment is 75 tonnes, requiring 195 tonnes of reaction force for forward propulsion.

To ensure waterproofing effectiveness:

(1) Shield Empty-Pushing Stage - After bolt tightening for each ring, bolts on the previous ring were retightened to ensure tight connections between segments and rings. - After segments cleared the shield tail, bolts were promptly retightened again.

(2) Shield Reception Stage The last 20 rings were tensioned every 2 rings using the portal temporary sealing device. Rice stone was sprayed once per ring through secondary grouting holes, with quick-setting grout injected to fill the annular gap, ensuring proper segment attitude and waterproofing.

Conclusions

Based on the actual implementation of shield empty-pushing through mining method tunnels in this project, the following conclusions are drawn regarding key technologies and quality control measures:

(1) **Shield Arrival Stage:** The water arrival method offers advantages over traditional approaches, including faster construction, lower cost, and easier removal of the water retaining wall.

(2) **Shield Empty-Pushing Stage:** With the shield shell periphery open, grouting was controlled by achieving 80% of theoretical volume. Key control factors included segment assembly quality, tunnel axis deviation from design, segment dislocation, segment flotation, shield attitude, shield tail clearance, and guide platform construction precision.

(3) **Quality Control Focus:** The primary quality concerns were segment dislocation, flotation, shield attitude control, shield tail clearance, and guide platform precision. Effective measures included proper segment selection, strict bolt tightening procedures, adequate backfilling, and water pressure management.

These measures successfully ensured construction quality and provide a valuable reference for similar projects.

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