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APPLICATION AND CONSIDERATION OF PIPE-ROOF METHOD IN SHALLOW-BURIED MINED-TUNNEL PASSAGES

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Abstract: This paper investigates the application efficiency and key technical points of the pipe-roof method in shallow-buried tunnel-excavation passage projects. Taking the mined-tunnel passage for Exit No. IV of Fenghuang Xincun Station on Guangzhou Metro Line 8 as an engineering case, this study systematically reviews the whole implementation process of the pipe-roof method, covering design, construction and troubleshooting. Combined with literature review and field engineering practice, this paper documents typical construction problems including jacking difficulty, abnormal soil discharge and rock-stratum obstruction, and illustrates the countermeasures adopted, such as replacing large-tonnage jacks, optimizing drill-bit types, adjusting pipe-roof parameters and implementing reinforcement grouting. The results demonstrate that the pipe-roof method can effectively control ground surface settlement and deformation of surrounding structures. All monitoring data remained below warning thresholds, which guaranteed construction safety. It is concluded that the pipe-roof method delivers remarkable supporting performance and environmental-friendly advantages under complex geological conditions. Its successful application, however, relies on refined parameter design, dynamic construction adjustment and rigorous process control. The experience obtained provides important guidance for subsequent similar projects.
Keywords: Pipe-roof method; Shallow-buried tunneling method; Metro passage

1 INTRODUCTION

The pipe-roof method is a support technology that improves surrounding-rock stability and restrains its deformation by installing steel pipes or steel frames within the surrounding rock. Its primary mechanisms include the beam effect, arch effect, and surrounding-rock reinforcement effect. Specifically, the pipe-roof forms a load-bearing structure that effectively limits surrounding-rock deformation and enhances its self-stabilization capacity, thereby reducing the stress acting on the primary support and lining structures [1]. Initially adopted in tunnel engineering, this technique has gradually been extended to other underground-engineering fields, such as metro stations and under-ground access passages. The core of the pipe-roof method lies in constructing a high-strength supporting system via continuous arrangement of steel pipes, so as to effectively control stratum deformation and improve construction safety. Furthermore, the pipe-roof method presents favourable environmental benefits, which are particularly prominent in underground projects with strict environmental-protection requirements [2].

The applications of the pipe-roof method are mainly concentrated in tunnels, metro projects, mine roadways and other engineering fields. For instance, the long pipe-shed support technology was adopted for a mined metro tunnel in sandy-gravel strata. Based on theoretical analysis and field tests, the support performance under different circumferential spacings and pipe diameters was revealed, and the optimal support parameters were proposed, which provides an important reference for similar projects [3]. In addition, during the construction of Shifulu Station on Shenyang Metro Line 4, the small-diameter pipe-roof-beam method significantly reduced ground settlement and pipe-roof deformation, demonstrating the superiority of the pipe-roof method under complex geological conditions [4]. The Zhili Road Tunnel project in Chenghua District, Chengdu, employed large-diameter pipe-roof advance support to successfully complete tunnel excavation underneath the existing railway lines, while minimizing disturbances to urban roads and residents. Pipe-roof steel pipes with a diameter of Φ299 mm were adopted in this project. Construction safety and stability of the tunnel were guaranteed through the optimization of construction procedures and parameters [5]. In the Secondary Trunk Road I project of Beijing New Airport, the pipe-roof method was applied in shallow-buried mined tunnelling to realize partial excavation of a large-section flat-roof tunnel, whereby ground settlement was effectively controlled and waterproofing-drainage problems were addressed. Combined reinforcement of the pipe-roof and curtain grouting further improved tunnel stability [6]. For the Waitanyuan Block 33 project in Shanghai, advance steel-pipe pipe-roof support and horizontal excavation techniques were implemented to protect ancient trees. Construction-induced environmental impacts were effectively mitigated, which illustrates the advantages of the pipe-roof method in urban renovation projects involving historic buildings [7].

The pipe-roof method is applicable to various geological conditions, including sandy-gravel strata, weak rock strata and fractured rock masses [8]. It exerts minor environmental disturbance during construction and exhibits prominent advantages for projects with strict environmental-protection requirements [2]. Nevertheless, the pipe-roof method features high construction complexity and stringent technical requirements. Detailed geological investigation and design must be completed prior to construction, and all construction parameters should be strictly controlled throughout the construction phase. Therefore, further in-depth research is required to tackle technical challenges such as

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support-parameter optimization, construction precision control and ground-deformation management. Taking the pipe-roof construction of the mined access passage for Entrance/Exit No. IV of Fenghuang Xincun Station on Guangzhou Metro Line 8 as a practical case, this paper summarizes the difficulties encountered during construction, conducts cause analysis, presents corresponding countermeasures, and concludes key construction points and practical experience of the pipe-roof method, so as to provide guidance for subsequent similar underground projects.

2 PROJECT OVERVIEW

Fenghuang Xincun Station is located beneath the three-way intersection of North Gongye Avenue and Nantian Road in Guangzhou, and extends in the southeast-northwest direction. The mined-tunnel section of Entrance/Exit No. IV branches off from the connection opening on the first underground floor. This mined passage connects the existing station hall and the open-cut section of the entrance-exit. The mined passage is approximately 13.5 m long, 5.9 m wide and 5.2 m high. The primary support adopts I22b steel frames combined with C25 shotcrete at a thickness of 300 mm, with a steel-frame spacing of 0.5 m. The advance support consists of φ219 pipe-roof steel pipes, each 6 m in length, which are arranged in an overlapping circumferential pattern. The secondary lining is constructed of 500-mm-thick C30 reinforced concrete, with φ18 steel bars spaced at 150 mm on both the inner and outer circumferential sides. Approximately 3.2 m-thick miscellaneous fill overlies the passage, while the tunnel cross-section is mainly situated within <7> highly-weathered and <8> moderately-weathered argillaceous siltstone.

Beneath the mined passage lies the mined-tunnel platform tunnel for the left-track line of Fenghuang Xincun Station, with a vertical clear distance of 3.8 m. Its minimum horizontal clear distance to the viaduct piles of Inner-Ring Road is 3.35 m. North Gongye Avenue is located above the mined passage, and multiple critical pipelines run along the road, as listed in Table 1. Among these utilities, the 1200-mm-diameter storm-water pipe has the smallest vertical clearance above the mined passage, with a net distance of less than 80 mm.

Table 1 Parameters of Important Pipelines Underpassed by Mined Tunnel

Pipeline Category	Diameter/mm	Material	Buried depth/m	Vertical clear distance to tunnel/m
Water supply pipe	400	Concrete	1.18	2.20
Stormwater pipe	1200	PE	2.60	0.79
Medium-pressure gas pipe	529	Steel	1.27	2.08
Water supply pipe	800	Concrete	1.57	1.77
Sewage pipe	400	Concrete	1.99	1.30
Water supply pipe	150	Steel	0.69	2.59

3 PIPE-ROOF CONSTRUCTION TECHNOLOGY AND MAIN PARAMETERS

(1) A drill bit equipped with an LED light source and a spiral drill rod are inserted inside the steel pipe, assembled onto the pipe-jacking machine and well-connected. The power head of the pipe-jacking machine is driven to rotate by the hydraulic pump station, while the oil cylinder of the jacking machine slowly pushes the working steel pipe into the soil. Soil cuttings are discharged with the rotation of the spiral drill rod. Static-pressure pipe jacking is adopted so that soil discharge proceeds synchronously with jacking, which imposes minor disturbance on the stratum. An angle sensor is mounted at the front end of the steel pipe and connected to a display screen via signal cables, enabling real-time monitoring of the jacking angle. Corresponding measures are implemented for deviation correction and steering control.

(2) Pipe-roof parameters: Hot-rolled seamless steel pipes of φ219 are adopted, with an outer diameter of 219 mm and a wall thickness of 12 mm. The steel grade is Q235-B. The circumferential centre-to-centre spacing of pipes is 270 mm, which can be fine-tuned on-site as required. The construction deviation of the pipe-roof axis shall not exceed 1 cm. Male-female interlocks are welded on the side of each pipe-roof steel pipe. The interlocks are fabricated on-site using hot-rolled unequal-leg angle steel, with each 6-meter-long member subject to a length tolerance less than 5 mm and a thickness tolerance less than 0.5 mm.

(3) Reaction wall: According to field conditions, the contractor shall calculate the load on the reaction wall based on the maximum jacking force of the pipe-roof driller. A reinforced-concrete structure can be adopted. Special construction schemes covering the design, construction and subsequent demolition of the reaction wall shall be compiled by the contractor and approved after review before implementation.

(4) Grouting parameters for cement slurry inside steel pipes: The socket-end of each installed pipe-roof steel pipe is sealed, with grouting holes and vent observation holes reserved. Each grouting hole has a diameter of φ42 mm and is fitted with a valve. The vent observation pipe is arranged above the pipe end face, with a diameter of φ42 mm and a height of no less than 2 m. The tunnel face must be sealed by shotcrete-rock bolt support. Quick-setting agent is applied to seal the interlock joints between adjacent steel pipes, and reserved vent hoses shall extend 2 m above the pipe interlocks. Cement slurry mixed with cement is injected to fill the interior of steel pipes, with a water-cement ratio of 0.8:1. The grouting pressure ranges from 0.2 MPa to 0.5 MPa. Grouting volume shall be no less than the theoretical grouting quantity, and grouting can be terminated when the liquid-level descent rate inside the vent observation pipe is less than 1 mm/min. Supplementary grouting shall be carried out 2 hours after the completion of primary grouting to ensure full filling inside the pipe. The filling-grouting inside pipes is constructed from bottom to top, and the crown steel pipes are filled at last. To realize synchronous grouting inside interlocks, grouting holes with an 8-mm diameter are drilled in the interlock angle steel at intervals of 1 m along each interlocked steel pipe.

(5) Directional grouting conduits shall be installed on steel pipes to realize targeted grouting for settlement-prone zones.
(6) Pre-grouting with φ42 steel flower pipes adopts single-fluid cement slurry. The relevant parameters are as follows: grouting pressure 0.1–0.5 MPa, water-cement ratio 1:1, cement strength grade P.O 42.5.
(7) Welding requirements: Double-sided welding is applied between interlocks and steel pipes. T-groove welding is adopted for connections between steel pipes. Inner pipe couplings (400 mm in length, 8 mm in wall thickness, 275 mm in diameter) and longitudinal stiffener plates shall be installed at welded joints.
(8) To improve the rigidity and reduce the deflection deformation of the pipe-roof, C30 micro-expansion fine-aggregate concrete is backfilled inside the pipe-roof.
(9) Construction standards for pipe-roof: Construction deformation shall be controlled within ±5 mm; the gradient of the pipe-roof shall be kept within 0.5 %; for filling grouting inside steel pipes, the water-cement ratio ranges from 0.9 to 1, grouting pressure is 0.2–0.5 MPa, and the grouting filling coefficient is 1.05.
For Entrance/Exit No. IV of Fenghuang Xincun Station, the φ219 pipe-roof method is adopted for reinforcement of mined primary support. Steel pipes are connected by angle-steel-welded male-female interlocks. The designed penetration depth extends 1 m beyond the end wall of the existing passage. A portal ring beam is constructed at the open-cut section opening for support and fixation. For pipe-roof jacking equipment, double-cylinder 50-ton jacks are initially selected. The safety coefficient of jacking force is set at 60 %, and the maximum safe thrust is 30 tons. As auxiliary equipment, a φ190 right-hand spiral soil-removal drill rod is preliminarily adopted, fitted with a light-source-equipped drill bit at the top and a positioning steering instrument at the tail. Jack operation and drill-rod advancement shall be carried out synchronously.

4 PROBLEMS ENCOUNTERED DURING CONSTRUCTION AND COUNTERMEASURES

4.1 Problem 1: Jacking Difficulty Caused by Underground Obstacle

Double-cylinder 50-ton jacks were adopted in the early-stage construction of No. 16, No. 15 and No. 14 pipe-roof steel pipes. The excavation lasted for 8 hours with stable soil-removal efficiency and normal advance rate of pipe-roof installation. The designed length of each pipe-roof pipe was 13.6 m. Resistance was encountered when the excavation depth reached 7.6 m, accompanied by a sharp fluctuation in jacking force. Referring to the planar geophysical prospecting map, the obstacle was located at the position of a 500-mm-diameter storm-water pipe. According to the geological investigation report and preliminary core-drilling results, the working face consisted of clay-rich miscellaneous fill, which featured high plasticity and viscosity as well as poor water-induced shaping performance. No significant abnormal phenomena were observed during the overall jacking process (Figure 1 and Figure 2).
During the construction of the fourth pipe (Pipe No. 13), a sudden pressure change occurred at the excavation depth of 4 m, where the jack excavation pressure reached 100 % and the thrust overloaded the rated capacity of 50 tons. Preliminary analysis attributed the resistance to hard rock or construction waste. However, the drill rod could move forward and backward smoothly under independent jacking. To check potential risks such as weld cracking or separation of the male-female interlocks, the pipe-roof steel pipe was jacked out by reverse-pressure pushing, and no defects were found on pipe-roof components. Geological factors were then suspected, and branches, gravel fragments, garbage bags and other debris were detected in the excavated soil samples.
The following potential causes were identified through discussion and analysis: ① Existence of underground structures; ② Concrete lumps, rock fragments and extensive construction waste embedded in the stratum; ③ Insufficient jacking force; ④ Poor soil-breaking capacity of the drill bit and a large clearance (40 mm) between the drill rod and the pipe-roof pipe; ⑤ Increased resistance induced by opening deformation at the pipe front end due to weld failure of male-female interlocks; ⑥ Rising resistance caused by construction waste encountered at the front of male-female interlocks.
Causes ① and ② were excluded because repeated jacking of the drill bit encountered no hard obstruction, although considerable resistance occurred during pull-back. Cause ③ was considered possible, since the jack reached overload status without further advancement. Cause ④ was also regarded as a contributing factor: no reaming drill bit was adopted, so the interlock zone fell outside the excavation coverage, resulting in high jacking resistance. Cause ⑤ was ruled out after inspection of the withdrawn pipe-roof pipe, which showed intact male-female interlocks with no deformation or weld separation. Cause ⑥ was confirmed as one of the triggering factors, given the branches, gravel fragments and garbage bags recovered from excavated materials.
After technical discussion, the double-cylinder jack was replaced with a single-cylinder 200-ton jack with a safety efficiency of 70 %, yielding a safe jacking force of 140 tons. The bevel-edged drill bit was abandoned and replaced with a soil-breaking drill bit. As positioning equipment could not be installed, a total station was employed to monitor the gradient of the advancing pipe. The drill rod was pulled out every 4 m for re-measurement of pipe-roof attitude. Meanwhile, the original φ190 mm spiral soil-removal drill rod was replaced by a φ195 mm one. Pipe No. 13 was successfully jacked forward at a thrust of 75 tons with normal soil discharge. For the subsequent eleven pipe-roof pipes, the maximum jacking force reached 85 tons and all jacking operations proceeded smoothly.

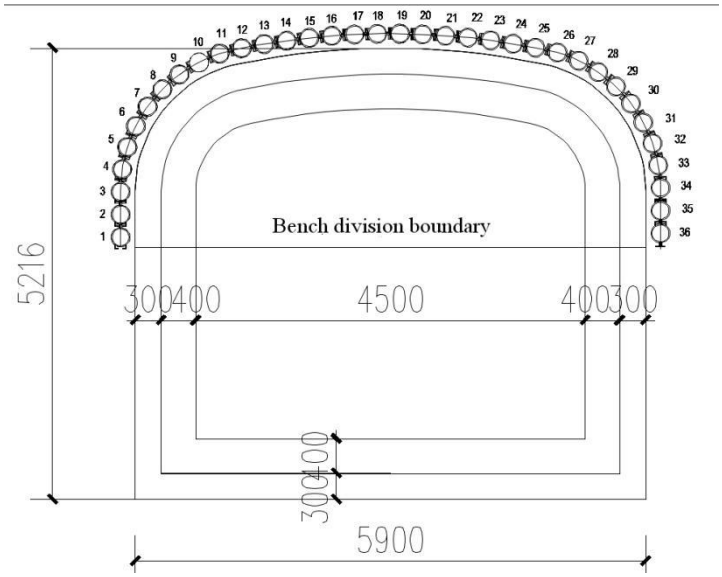


Figure 1 Pipe Curtain Numbering Plan



Figure 2 Soil Samples of Screw Mucking for Pipe Curtain Construction

4.2 Problem 2: Difficult Soil Discharge and Slight Stratum Uplift

During the construction of the 16th pipe-roof pipe, jacking proceeded normally while soil discharge suddenly ceased. Hollow cavities were initially suspected, and construction was continued accordingly. After successive installation of the 18th pipe, the jacking force reached 116 t. Meanwhile, ground monitoring detected a maximum upward stratum uplift of 1.6 mm, which was below the warning threshold, implying abnormal soil discharge during pipe-roof jacking. Construction was immediately suspended on-site.

Preliminary analysis indicated that after passing through the overlying miscellaneous-fill stratum containing construction waste, the pipe entered highly cohesive soil. The increased drill-rod diameter reduced the available space for soil transportation inside the steel pipe. The original spiral drill rod was reinstalled, which restored soil discharge, yet the discharged soil volume failed to fill the full cross-section of the pipe.

It was further hypothesized that the rock-breaking drill bit could not collect cohesive clay efficiently. The rock-breaking bit was replaced with the original bevel-edged drill bit. Soil-removal efficiency was improved, with the soil filling rate inside the drill rod reaching 80 %. No obvious ground uplift was observed thereafter.

4.3 Problem 3: Recurrent Jacking Difficulty When Entering Stratum <8>

Jacking resistance reappeared when the lower-row pipe-roof pipes penetrated into stratum <8>. Jacking became difficult after an advance of 5–6 m, and drill-rod fracture even occurred in some cases. After technical discussion, the following countermeasures were adopted. The fundamental construction principle remained unchanged, namely that the bottom of the pipe-roof system should extend into stratum <8>. A total of 36 pipe-roof pipes were designed for the mined passage of Entrance/Exit No. IV of Fenghuang Xincun Station, among which Pipe No. 4-33 had been completed. Based on spoil samples obtained during drilling, the bottom pipe-roof pipes had reached stratum <8>. The contractor was required to drill horizontal supplementary core-boreholes between Pipe No. 1-3 and Pipe No. 34-36. Design and

geological investigation institutes would determine the actual stratum conditions from core samples to define the final termination criterion for pipe-roof installation.

For completed pipe-roof pipes whose jacking length and male-female interlock arrangement failed to satisfy the original design requirements due to stratum variation, alternative reinforcement measures were implemented. The detailed conditions are summarized as follows. For Pipe No. 8-29, the 219-mm pipe-roof steel pipe was jacked to approximately 13.6 m, followed by insertion of an inner 110-mm pipe-shed advanced to 14.6 m and subsequent grouting (no male-female interlocks were installed for Pipe No. 12 and 13; for Pipe No. 16, after the 219-mm pipe had been jacked for 9 m, an inner 159-mm pipe-shed was installed to reach the designed depth). For Pipe No. 4-6 and 30-32, after the 219-mm steel pipe was advanced for a certain distance, an inner 110-mm pipe-shed was jacked to the designed position. Jacking of the 219-mm steel pipe for Pipe No. 7 stopped at 6 m, and the inner 110-mm pipe-shed could not advance further after reaching 10.5 m. The spiral drill-rod fractured at a depth of 4.5 m during the construction of Pipe No. 33.

Targeted solutions were formulated. For Pipe No. 7, the priority scheme adopted pilot-hole drilling by a geological drill rig followed by 110-mm pipe-shed casing advancement. If this scheme was not feasible on-site, closely spaced 110-mm pipe-sheds would be installed on the outer side between adjacent Pipe No. 6 and 8, jacked to 14.6 m and grouted. Densely arranged φ42 mm grouting steel flower pipes were installed on the outer side between Pipe No. 30-33, advanced to 14.6 m and grouted. Additional φ42 mm grouting steel flower pipes were laid on the outer side of Pipe No. 12, 13, 16 and their adjacent Pipe No. 11, 14, 15, 17, jacked to 14.6 m and grouted.

4.4 Construction Performance

The pipe-roof construction was successfully finished, and the secondary lining of the mined passage has been completed. During the whole construction period, the displacements of overlying pipelines, underlying existing-line tunnel, deformation of the Inner-Ring Road viaduct, tunnel clearance convergence and crown settlement of the mined tunnel were all kept below warning thresholds. The results demonstrate that the pipe-roof method provides remarkable advance-support effects for this project, and the subsequent adjustment of construction schemes was reasonable.

5 CONCLUSIONS AND REFLECTIONS

5.1 Optimization of Technical Parameters

① The jacking thrust is directly affected by the friction between the pipe-roof and surrounding soil, the friction force between male-female interlocks, and the content of construction waste in the stratum. Therefore, jacks with large jacking capacity shall be prioritized when site-construction conditions permit.

② The drill-rod parameters should be adjusted dynamically according to stratum conditions. Theoretically, close contact between the drill rod and pipe-roof pipe yields higher soil-removal efficiency, whereby a larger drill-rod diameter is preferred. Nevertheless, for highly-cohesive soil strata, the soil-transport friction inside the pipe may exceed the thrust provided by the spiral drill rod. Consequently, a certain clearance should be reserved between the drill rod and the inner wall of the pipe-roof steel pipe.

③ Improvement of male-female interlocks. The male-female interlocks adopted in this project caused considerable jacking resistance due to their relatively large width during field construction. To facilitate jacking operations, an alternative interlock configuration illustrated in Figure 3 is proposed, with closed cutting edges machined on the jacking-end section. This improved pattern features compact dimensions, low jacking resistance and flexible interlock overlap, which can serve as a technical improvement direction for future similar projects. (Pilot application on Pipe No. 5 and No. 6 verified that jacking resistance was reduced by 10–20 %.)

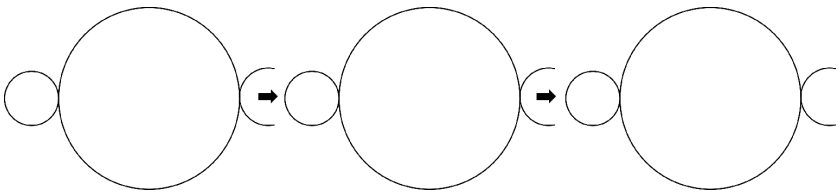


Figure 3 "Snap-Fit" Male-Female Lock Pipe Curtain

5.2 Construction Precision Control and Intelligent Construction

(1) Close attention shall be paid to the following key indicators during construction: jacking thrust, soil-removal efficiency of the inner spiral drill rod, positioning of the first pipe-roof steel pipe, and axial-line control in the course of pipe advancement.

(2) Digital-based and intelligent improvement measures: Precise positioning constitutes a critical procedure for pipe-roof construction. Directional equipment was adopted at the initial construction stage in this project, yet unsatisfactory performance was obtained owing to the lack of rock-breaking capacity of the drill bit. Lessons drawn from this practice suggest that the drill bit can be redesigned with a detachable structure, so that different drill bits can

be switched to adapt to varied geological strata. Each drill bit shall be equipped with a light source (a laser emitter is recommended for higher-precision measurement). Optical signals can be transmitted to the receiving terminal through the hollow spiral drill rod, and real-time images can be displayed on the control-computer screen. During casing advancement, deviation correction for each pipe-roof pipe can be implemented by tracking the laser spot shown on the display.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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