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Research on Mechanized and Rapid Construction Technology for Chunmushan Extra Long Tunnel on Zhitong Expressway

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ABSTRACT: Mechanized construction methods offer a solution to reduce manual labor intensity and enhance work efficiency. They represent a prominent trend in the development of extra-long tunnels. To address the challenges associated with the mechanized construction of extra-long highway tunnels, this study employs the Chunmushan Extra-long Tunnel as a case study. It investigates the principles and strategies for mechanized support, workflow, and outlines a comprehensive approach. Additionally, advanced geological forecasting techniques are integrated, and seven sets of large-scale machinery for tunnel excavation, support, and drainage are thoroughly examined. The study provides an analysis of their operational efficiency. Moreover, the research offers insights into the potential development prospects for large-scale machinery operations, taking into consideration aspects such as informatization, intelligentization, and system integration. The results of this research carry significant theoretical and practical implications, offering valuable technical guidance for similar projects.

Key words: Extra-long tunnel; Large machine operation; Mechanized supporting facilities; Rapid construction

I. INTRODUCTION

Mechanized construction in tunneling is an approach aimed at enhancing construction quality and efficiency. It leverages new equipment, technologies, and processes to achieve mechanization and automation across various stages of tunneling, including excavation, support, and waterproofing. This approach effectively addresses concerns related to safety, environmental impact, and energy conservation in tunnel construction. China possesses one of the world's largest highway networks, with a total tunnel length exceeding 50,000 kilometers, signifying its significant standing in the world[1,2]. Mechanized operations in highway tunnel construction are expected to become the mainstream construction technology for tunnels in the present and future. By making extensive use of advanced equipment and technologies, conducting research and innovative applications, and enhancing the levels of mechanization and digital management in tunnel construction, the quality and efficiency of construction can be assured. Furthermore, this approach reinforces tunnel construction management and operational services, enabling digital management models that ensure safety and efficiency. Numerous experts and scholars have provided their perspectives on tunnel mechanization and the associated technologies. Hong[3] analyzed and discussed the development of tunnels in China in recent years, especially with regard to mechanized construction. Wang[4] examined issues encountered during the mechanized construction process of high-speed railway tunnels on the Zhengwu Railway. Tang et al.[5] conducted research on the mechanized configuration of tunnel construction under various surrounding rock conditions from an engineering economics perspective. Zhang[6] analyzed tunnel risk management from the perspective of tunnel accidents, proposing the use of advanced technology and equipment to ensure the safety and quality of tunnel construction. Han et al.[7], Zhou[8] and Cao[9] have all conducted research and discussions on tunnel mechanized construction.

The choice of tunnel construction methods is influenced by various factors, including geological conditions, tunnel cross-sectional shape, tunnel length, lining types, and the level of construction technology. Drill and blast methods are the most

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commonly used construction methods for highway tunnels, suitable for stable and uniform rock strata with good hardness. These methods offer advantages such as fast construction speed, low cost, and straightforward equipment. The New Austrian Tunnelling Method (NATM) is the most commonly employed approach under the drill and blast method, focusing on the surrounding rock mass and utilizing a rational sequence of excavation and support measures based on rock properties and stress conditions, aiming to maximize the bearing capacity of the rock mass itself[10-12]. Research into mechanized support for tunnels under this method is deserving of exploration.

Therefore, this study will be based on the Chunmushan Tunnel of the Zhitong Expressway, focusing on research into the rapid mechanized support technology for extra-long tunnels. This research will establish corresponding principles and plans for mechanized support, develop process flows, incorporate advanced geological forecasting techniques, and investigate seven sets of large-scale machinery for tunnel mechanized support. Furthermore, it will explore the development prospects for large machinery operations.

II. PROJECT OVERVIEW

The Chunmushan Tunnel is a critical and controlled project for the Huaihua City (Zijiang) to Tongren (Xiangqian Border) Expressway in Hunan Province. It is located in the border area between Zijiang County and Mayang County. The tunnel's entrance is situated approximately 50 meters to the northwest of Yangjiazhai in Wulangxi Township, Zijiang County, while the exit is approximately 380 meters to the northeast of Zhangmu'ao in Yaoshi Town, Mayang County. This is a separated extra-long tunnel designed for a four-lane bidirectional road with a standard design speed of 100 km/h. The tunnel spans from chainage ZK18+195 to ZK24+414 for the left line (with a length of 6,219 meters) and from chainage K18+158 to K24+351 for the right line (with a length of 6,193 m).

The contour of the tunnel main lining inside the Chunmushan Tunnel has been determined based on the requirements of the tunnel construction clearance, as well as the required space dimensions for cable ducts, drainage channels, tunnel ventilation, and electromechanical facilities, as shown in Fig. 1.

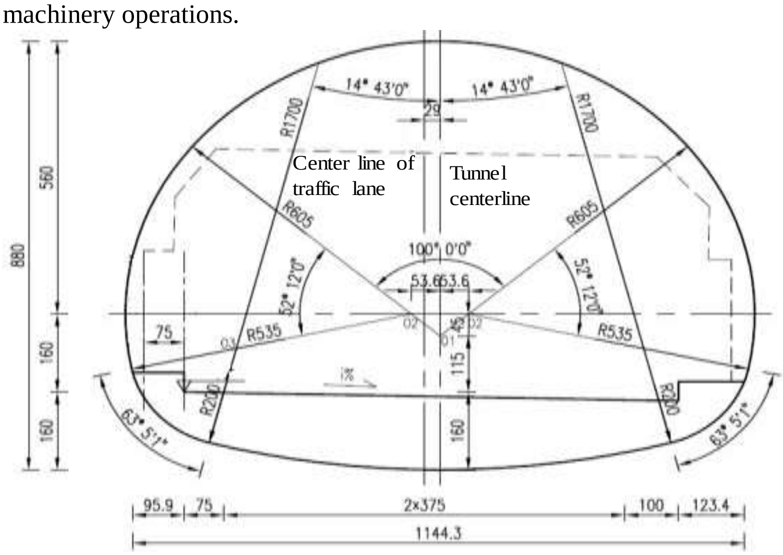

Fig. 1 Inner Contour Map of the Main Tunnel Lining

The Chunmushan Tunnel is a single-line tunnel with a total length of over 6 km. It is located in a region characterized by structural erosion in the middle and lower mountainous terrain. The surrounding rock of the tunnel consists of moderately weathered metamorphic sandstone and shale. While the majority of the rock mass is moderately weathered and relatively intact, there are some areas where it has experienced structural deformation and fragmentation. The stability of the surrounding rock is generally fair, and the geological conditions range from relatively soft rock to moderately hard rock. Joint and fissure development is significant, which affects the engineering performance. The entrance and exit slopes of the tunnel are relatively steep, and there are thick weathered layers in certain sections. A comprehensive analysis of the geological and hydrogeological conditions in the tunnel area indicates complexity. The stability of the surrounding rock inside the tunnel is not very favorable. The tunnel traverses a lengthy section through mountainous terrain, with developed valleys and extensive drainage areas. The rock mass exhibits significant joint and fissure development, high

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permeability, and a relatively shallow water table, making it less conducive to tunnel excavation and construction. The tunnel also passes through a faulted and fractured zone with extensive fissures, leading to fragmented rock mass. The presence of fractures in this area provides good conditions for water drainage, which could significantly impact the construction of the tunnel. The tunnel crosses the West Huangshan syncline, which provides favorable conditions for groundwater storage, but this also poses a significant influence on the tunnel's construction.

III. MECHANICAL MATCHING PRINCIPLES AND PLANS

3.1 Basical principles

(1) To enhance the efficiency and quality of tunnel mechanized construction, it is essential to allocate mechanical equipment reasonably based on the construction requirements, enabling them to adapt to different geological conditions and construction environments.
(2) Tunnel mechanized construction involves various types of machinery that need to work in synergy, forming an efficient construction process. Therefore, it is necessary to organize construction procedures rationally, coordinate the cooperation and scheduling of various equipment, and prevent situations where equipment idles or clogs.
(3) Tunnel mechanized construction requires mechanical equipment to have a high level of automation, enabling functions such as automatic control, regulation, and detection to reduce manual intervention and errors. Simultaneously, mechanical equipment should be characterized by energy efficiency, environmental friendliness, and high efficiency to decrease energy consumption and pollution while improving construction speed and quality.
(4) Safety is of paramount importance in tunnel mechanized construction. Thus, it is necessary to strengthen quality control during construction to ensure the safe operation of mechanical equipment. This includes conducting regular equipment inspections and maintenance, addressing malfunctions and hidden issues, assigning specialists to operate the equipment, adhering to operating procedures and safety standards to prevent accidents and losses.

3.2 Overall plan

The tunnel mechanized equipment is configured into four operation lines: excavation, support, lining, and cable duct.

To ensure the safety, quality, and progress of tunnel construction, the project department has increased the investment in production factors. They have established a "VR Safety Experience Center" that includes 34 scenario modules such as tunnel collapse, electric shock, mechanical injuries, and safety. Through real-life experiences, this center helps project personnel acquire knowledge and methods for safe construction, with the primary goal of accident prevention and safety as the highest priority. Furthermore, they have implemented access control systems, video monitoring systems, and intelligent AI systems. Through information technology and closed-loop management, these measures provide comprehensive support for the project's quality and safety, aiming to achieve the goal of "zero accidents." In terms of tunnel construction, a complete set of mechanized construction processes has been introduced. This includes advanced equipment such as intelligent double-arm rock drilling jumbos, wet spraying robotic systems, and automated secondary lining trolley systems. These large-scale, advanced machines effectively improve the working environment within the tunnel, alleviate construction risks and intensity, enhance safety measures, and ensure high efficiency and quality in construction.

Based on the specific characteristics of the Chunmushan Tunnel, the construction activities are centered around four major phases: excavation, concrete spraying, arch construction, and lining. Specialized tunnel equipment has been tailored for excavation, transportation, support, and lining. These are integrated to create a mechanized parallel production line, enabling fast, continuous, and balanced tunnel construction. The main machinery and equipment used for the entrance and exit of the Chunmushan Tunnel are summarized in

Table 1.

Table 1 Main mechanical equipment at the entrance and exit of Chunmushan Tunnel

Serial Number	Device Name	Specification	Quantity
1	Multifunctional drilling rig	C6xp-C	2
2	Double curved arm rock drilling	Boomer XL3D	4

	jumbo		
3	Wet spraying manipulator	HPS3016SG	4
4	Excavator		4
5	Loader	ZL50CN	4
6	Dump truck		6
7	Self-propelled inverted arch hydraulic trestle		4
8	Arch installation machine		4
9	Automatic fabric secondary lining trolley by layered window		4
10	Automatic waterproof board laying trolley		2
11	Self propelled cable tray trolley		2

IV. MECHANIZED SUPPORTING RAPID CONSTRUCTION TECHNOLOGY

4.1 Advanced geological prediction

Advanced geological forecasting results serve as the basis for optimizing construction plans. They assist construction personnel in promptly identifying and addressing adverse geological conditions, thus avoiding or mitigating construction accidents resulting from uncertain geological factors. A multifunctional geological drilling rig is a crucial tool for assessing the rock mass rating. It performs advanced drilling, core sampling, and testing during tunnel construction, providing essential information about rock types, structures, fractures, hydrology, and more. The rock mass rating serves as a foundation for construction operations, guiding personnel in selecting appropriate support methods and parameters to ensure tunnel stability and safety.

In consideration of the specific characteristics of the Chuanmushan Tunnel project, the following points are essential to be mindful of when conducting advanced geological forecasting:

(1) Combine geological survey data for both long-term and short-term joint predictions of geological conditions.

(2) Identify the likelihood and scale of potential tunnel collapse disasters in regions that are predicted to be at risk and propose corresponding preventive and remedial measures.

(3) In areas with abundant underground water, predict potential sudden water hazards, including the location, scale, and potential construction disturbances, and put forth relevant preventive and remedial measures.

(4) For strata rich in gas, predict the location, concentration, and potential construction disturbances due to gas, and propose relevant preventive and remedial measures.

(5) Utilize geological drilling to forecast geological conditions approximately 30 meters ahead of the face. Forecasting criteria should consider drilling speed, pressure, water inflow conditions, and other factors.

4.2 Excavation operations

Chunmushan Tunnel employs smooth blasting based on the New Austrian Tunnelling Method (NATM) principles for excavation. The selection of the excavation method is a crucial factor influencing project quality, safety, and economic benefits. Different rock mass classifications correspond to distinct excavation methods, and thus, it is essential to choose the most appropriate excavation method according to the geological conditions. For instance, in Class III rock, the top-down benching method is commonly employed. In the shallow-buried segments of Class IV rock, a single-side drift method is typically utilized. In the deep-buried segments of Class IV rock, the three-bench method can be adopted. Finally, for Class V rock, the double-side drift method is a suitable choice.

After excavation, the debris removal within the tunnel is accomplished using a trackless transport method, which offers advantages such as high transport efficiency, wide applicability, strong climbing capabilities, simple track layout, and low transportation costs. Backhoe excavators are utilized for clearing the tunnel face, offering benefits including flexible operation, fast rotation speeds, and suitability for excavating materials with high water content, such as sandy soil or clay. Self-dumping trucks are employed to transport and dispose of the debris at designated storage areas. When used in conjunction with the loading equipment, these trucks provide significant transport capacity, high production efficiency, and excellent maneuverability. Lastly, the discarded debris can be utilized for stone filling in roadbed construction. This approach not only recycles waste rock but also conserves materials and reduces costs, ultimately enhancing project quality and efficiency.

4.3 Initial support work

Upon completion of tunnel excavation, the initial support phase is initiated, involving various activities such as the installation of steel arches, grouting within the advance shed, small advance pipes, and rock bolting support, collectively forming a comprehensive initial support system.

(1) Advance Shed and Grouting:

The tunnel advance shed is a commonly used tunnel support method, effectively controlling the deformation of the surrounding rock and stabilizing the working face. In this tunnel, seamless hot-rolled steel pipes with a diameter of 108mm and a wall thickness of 6mm are utilized. These pipes possess high strength, toughness, and corrosion resistance, making them suitable for various geological conditions. The pipes are arranged at a radial spacing of 40cm. During drilling, a principle of sequential upward hole drilling is employed to ensure drilling quality and accuracy. Once a complete shed structure is formed, grouting is carried out to enhance the bond and sealing between the shed and the surrounding rock.

(2) Advance Small Pipes and Grouting:

Advance small pipes are primarily used for pre-support in areas with soft and fractured rock. The construction equipment employed in the tunnel includes a multifunctional anchor bolt drilling machine with specific parameters, including an outer insertion angle of 12°, grouting pressure of 0.5-1.0MPa, and grouting speed of 50-100L/min.

(3) Selection and Quantity of Arch Installation Machines:

The arch installation machine is a tunnel support installation device designed for the mechanical installation of steel arches (including I-beam arches and grillage arches) and high-altitude work. The selection of this equipment primarily considers factors such as its working capacity, working flexibility, arch installation methods, and arch assembly capabilities. Among these, a single-arm single-basket arch installation machine has limited working flexibility and is not suitable for the installation of grillage arches with large deformations. It also lacks the functionality to perform mid-air assembly of arches, making it only suitable for the installation of I-beam arches. A two-arm arch installation machine has stronger working capacity and can perform multiple operations. It is suitable for both complete arch installation and sectional arch installation. During sectional installation, the two arms each handle one section of the arch, which are then joined by the two arms inside the tunnel clearance. Workers complete the connection of the joined arch sections using a hoisting basket. A three-arm, three-basket arch installation machine features three arms, three platforms, three grippers, dual diesel power, gravity self-adaptation, full-size fixtures, and more. This design makes it capable of handling a wide range of tasks, including full-section work, micro-benches, double benches, and performing tasks such as anchor installation, mesh installation, auxiliary tools, quality measurement, grouting, and the installation of tunnel equipment.

When using the arch installation machine for operations, a single machine can be employed to meet the operational requirements of two working faces, as shown in Fig. 2(a). Compared to traditional methods, the arch installation machine can enhance construction efficiency and safety, reduce labor and equipment input, and achieve high-quality and efficient tunnel support.

(4) Selection of Shotcrete Equipment

There are primarily wet shotcrete machines and wet shotcrete manipulators, as shown in Fig. 2(b). A wet shotcrete machine for tunnel construction is a device used for spraying concrete in tunnels. It consists of four main components: concrete mixture, compressed air from the wet shotcrete machine, atomization accelerator at the nozzle of the wet shotcrete manipulator, and the concrete mixture being sprayed onto the rock face. Compressed air from the wet shotcrete machine refers to air that is compressed by a compressor and then transported through pipes to provide the power for the spraying process. The atomization accelerator at the nozzle of the wet shotcrete manipulator refers to the installation of an atomizer at the nozzle outlet to atomize the accelerator, mixing it with the concrete mixture to accelerate the concrete's setting time and improve bond strength. The concrete mixture is sprayed onto the rock face at high speed through the nozzle, forming a uniform and compact concrete lining layer.

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(a) Arch installation machine (b) Wet spraying machine

Fig. 2 Equipment for First Lining

In the construction of the Chunmushan Tunnel, wet shotcrete construction should be employed. The mixing equipment used is a fully automatic computer-controlled concrete mixing plant with a production capacity of $75m^3/h$. The mixing time for each batch is approximately 2.5 minutes.

(5) Concrete Transport Equipment Selection:

Concrete transportation is a crucial step that directly impacts construction quality and efficiency. To meet the requirements of rapid and high-quality concrete transport, concrete transport equipment should have features like a large capacity, automatic mixing, and low waste discharge. In the Chunmushan Tunnel project, concrete transport vehicles with a capacity of 8 to 10m3 are typically chosen as the transport equipment.

4.4 Other mechanized equipment

In addition, the project also deploys self-propelled steel gantry cranes, automatic waterproofing board installation trolleys, hydraulic lining installation trolleys for the lining works, and in the later stages, cable trench trolleys for cable trench construction. The following are the advantages of these equipment in improving operational safety.

Fig. 3 Waterproof Board Laying and Hanging Trolley

(1) Self-Propelled Steel Gantry Crane:

a. Ensures pedestrian and vehicle safety during the backfilling phase, allowing safe passage while guaranteeing structural strength.

b. Facilitates compliance with specified requirements for backfilling strength before vehicular passage.

(2) Automatic Waterproofing Board Installation Trolley (as shown in Fig. 3):

a. Reduces the risks associated with personnel frequently ascending and descending trolleys at heights.

b. Provides better control over the proper tension and overlapping width of the waterproofing boards compared to manual operations, ensuring the quality of board overlap and the structural durability.

(3) Intelligent Hydraulic Lining Installation Trolley:

a. Supports approximately $211m^3$ of concrete with hydraulic support, ensuring safety during the pouring process while enabling convenient adjustments for lining thickness.

b. Utilizes a combination of flat vibrators and construction window-inserted vibrating rods to avoid issues of inadequate lining compaction, ensuring the linings are well compacted.

4.5 Concrete inverted arch and inverted arch filling

Following excavation, timely organizing the construction of the arch lining is crucial. The selection of excavation length should primarily be based on the rock mass classification, and it's advisable to adjust the maximum single excavation length to a maximum of 3 meters. Going beyond this value would increase construction control complexity. Immediately after the arch excavation, the initial spray sealing can be carried out. Considering the actual rock conditions, the spacing between the arch lining and the face should be adjusted accordingly.

The procurement of a 36-meter fully hydraulic self-propelled arch gantry crane facilitates fast and orderly construction, allowing the arch lining construction and excavation operations to proceed efficiently.

For rock masses classified as IV and V, which exhibit relatively poor stability, reinforcement with steel bars should be implemented at the crown arch and arch walls. In the case of rock mass classification III, leveling layers can be poured using plain concrete to facilitate construction activities. The construction of the crown arch should be carried out in a segmented manner, ensuring precise control of the arch concrete pouring timeline. It is essential that the crown arch pouring is completed before the arch wall pouring, with each section typically ranging from 6 to 8 meters in length.

Excavating the crown arch can be a challenging task. Opting for drill and blast excavation method is a suitable approach. To handle the shattered rock, supporting excavators can be used, and for areas that are difficult for construction equipment to reach, workers can utilize tools such as pneumatic hammers. Excavators and loaders can collaborate to remove the debris, and self-dumping trucks can transport it to designated storage areas. For the concrete pouring, C25 plain concrete is used. Prior to this, the area to be poured should be thoroughly cleaned of any water and debris. Formwork should be installed at segment ends, construction and expansion joints should be established, and these joints should be waterproofed. During the pouring, strict control of the concrete face's height is necessary to ensure it matches the measurement lines without deviations, and vibration compaction methods should be employed to enhance the concrete's density. Attention should be paid to the protection of crown arch reinforcement components. The crown arch should be filled with concrete once its strength reaches the required design specifications. For filling, C15 plain concrete can be chosen. The construction requirements should specify the position for side trenches.

4.6 Water channel and cable trough platform vehicle

Traditionally, tunnel water channels and cable troughs were constructed using small steel formwork modules, which posed challenges such as high labor intensity, difficulty in controlling construction quality, and issues with formwork misalignment. Presently, some tunnels have adopted the use of water channel and cable trough platform vehicles for construction. These vehicles come in two main types: self-propelled and track-mounted.
(1) Self-Propelled Vehicles: These vehicles are interconnected through an integrated gantry and can work on both the left and right sides simultaneously. They offer higher construction efficiency and make it easier to control construction quality, meeting the requirements for efficiency and aesthetics.
(2) Track-Mounted Vehicles: These vehicles are designed with integral steel formwork, which provides excellent formwork stability, effectively preventing form misalignment issues. They incorporate adhesive vibrators on the steel formwork, ensuring proper vibration effects and minimizing defects like honeycombing and surface roughness. In contrast to traditional formwork construction, where each cycle takes about 3 days, track-mounted vehicles have reduced the construction cycle to just 1 day. Overall, this approach has significantly enhanced both quality control and construction efficiency.

4.7 Intelligent grouting machine

In 2018, China Railway Construction Heavy Industry (CRCHI) developed the first domestically produced tunnel intelligent grouting equipment. This equipment is composed of a chassis, powder unit, grouting unit, and other components, integrating loading, weighing, slurry preparation, grouting, and control into one system. It exhibits a high level of automation, high operational efficiency, and ensures excellent construction quality.

4.8 Tunnel dust removal equipment

Tunnel dust removal and purification equipment primarily consists of the following components: a walking system, dust absorption system (including dust online monitoring device, induced draft fan, exhaust gas absorption telescopic arm, exhaust gas purification box, recirculating water pump, etc.), lighting system, control system, and air curtain. Typically, air curtain isolation technology is employed to effectively control dust dispersion and enhance the construction environment.

V. COMPARATIVE ANALYSIS OF TRADITIONAL CONSTRUCTION METHODS AND COMPLETE MECHANIZED CONSTRUCTION

5.1 Comparison of construction personnel investment

Taking the example of the benching method for IV-grade rock in the Chunmushan Tunnel, it is observed that when the tunnel is constructed using the traditional drilling and blasting method, the working face should not have more than 9 people

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working at the same time, and one cycle of drilling on the bench requires 9 people working simultaneously for 5 hours. To shorten the

Table 2 provides data on the number of personnel required for one cycle when using the traditional drilling and blasting method.

By replacing it with a complete mechanized

Table 2 and

Table 3 reveals that using a complete mechanized construction can reduce the number of

construction period, the labor force may increase the number of workers to reduce the working time, which increases the risk of safety production.

construction, the number of personnel required for one cycle was calculated and the data collected are shown in

Table 3. Analysis of

personnel in tunnel construction crews, leading to a decrease in the number of personnel in high-risk areas, reducing labor costs, and lowering the probability of risk occurrence.

Table 2 Number of Workers in Traditional Construction Methods

Serial Number	Teams	Number of people engaged in traditional construction methods within one cycle (person)														
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15
1	Excavation team	15	14	13	14	15	15	14	13	13	12	14	13	11	12	15
2	Initial support team	10	10	10	10	10	10	10	10	9	10	10	10	10	10	10
3	Inverted arch team	6	6	7	7	5	6	6	6	6	8	6	7	6	6	7
4	Second lining team	25	27	25	24	25	25	26	26	28	24	25	25	24	24	26
5	total	56	57	55	54	55	56	56	55	56	54	55	55	51	52	53

Table 3 Number of Workers in Tunnel Mechanized Operation

Serial Number	Teams	Number of people engaged in the complete set of mechanized chemical method operations within one cycle (person)														
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15
1	Excavation team	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
2	Initial support team	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
3	Inverted arch team	6	7	7	7	6	6	6	6	6	5	6	5	6	6	6
4	Second lining team	17	18	19	17	18	18	17	18	19	18	18	18	17	18	17
5	total	34	36	37	35	35	35	34	35	36	34	35	35	34	35	34

5.2 Comparison of required working hours

By considering excavation up to the next round of excavation as one cycle of operation, the required time for one cycle was statistically analyzed, and the data collected are presented in

Table 4.

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Analyzing

Table 4 reveals that using a

complete mechanized construction approach can reduce the number of cycles required for tunnel construction. This leads to a decrease in the time needed for each cycle, thereby improving efficiency, ensuring timely support operations, promptly closing the ring, reducing support delays that may cause rock deformation and settlement, and ultimately enhancing safety.

Table 4 Working hours per cycle

Serial Number	Teams	Labor hours required per cycle (h)														
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15
1	Blasting method	17	17	16	17	18	17	17	17	16	16	21	20	17	18	17
2	Mechanized construction	13	13	14	15	13	12	12	14	12	13	14	12	13	14	13

5.3 Overall quality comparison

Tunnel construction quality is a crucial factor affecting both the construction process and the overall stability of the tunnel upon completion. Employing a complete mechanized construction process allows for more effective control of construction technical specifications and quality standards compared to traditional construction methods.

The three-arm rock drilling jumbo effectively controls over- or under-excavation in the tunnel. It ensures the thickness of initial support and secondary lining during subsequent construction phases, preventing issues such as misalignment in the arch frame caused by under-excavation. This, in turn, ensures that the lining and support are subjected to uniform loading as per the design, resulting in greater stability.

The wet spraying mechanical arm addresses the quality deficiency related to the initial support cavity, guaranteeing safety in the process.

The multi-function arch trolley enables precise adjustment of arch installation, controlling the spacing, inclination, and installation deviations, thus ensuring the thickness of the protective layer. It also facilitates the installation of connecting rebars to ensure that the arch is subjected to reasonable forces.

The self-propelled steel gantry ensures that the backfilling of the invert arch reaches the required strength before opening for traffic, avoiding issues like cracking that might affect structural integrity.

The waterproof board trolley effectively controls the width of waterproof board overlaps, preventing issues related to insufficient overlaps that could lead to debonding.

The hydraulic double-lining trolley ensures the compactness of the lining's rear surface through thorough vibration compaction, ensuring the overall strength of the concrete lining and enhancing safety. Its inherent rigidity also helps maintain the smoothness of the wall surface.

5.4 Overall safety comparison

Complete mechanized tunnel construction equipment can provide comprehensive and multi-angle safeguards for tunnel construction safety:

(1) Reduced personnel in high-risk areas: By minimizing the number of workers in hazardous zones and keeping them at a safe distance from the face of the tunnel, the management complexity is reduced. This helps mitigate the risk of falling rocks

and debris, enhancing the safety of the construction environment.

(2) Increased work efficiency: These equipment solutions allow for prompt and efficient sealing of the rock face, supporting the completion of tunnel lining. This process effectively controls the loosening and deformation of the surrounding rock, ensuring construction safety.

(3) Lower labor intensity and improved work environment: Mechanized equipment helps decrease the physical strain on workers and enhances the overall work environment. This reduces the risks

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associated with high-intensity labor in adverse conditions.

(4) Enhanced construction quality: The use of complete mechanized equipment contributes to higher construction quality, resulting in increased safety of the tunnel structure.

By addressing these key aspects, complete mechanized tunnel construction equipment plays a vital role in maintaining a safe and efficient tunnel construction process.

VI. PROBLEMS IN MECHANIZED CONSTRUCTION

6.1 Overall low level of mechanization

In highway tunnel construction, the level of mechanization primarily focuses on excavation and support processes, utilizing equipment such as rock drilling jumbos, self-propelled invert arch bridges, concrete wet spraying manipulators, and arch frame installation vehicles. However, most tunnels use only one or two of these methods, with very few tunnels employing a complete set of mechanized construction methods. Other specialized equipment like intelligent lining vehicles, waterproof board installation vehicles, cable duct trench vehicles, temperature-controlled spray curing vehicles, intelligent grouting machines, and tunnel cooling and dust removal equipment are relatively less common. Overall, the mechanization level in China is not very high, and the application of intelligent equipment is limited.

6.2 High construction costs

The upfront costs of purchasing mechanical equipment can be substantial, often exceeding tens of millions of RMB. The tunnel construction industry lacks specific itemized rates for mechanized construction, and budget estimates do not account for the associated costs of mechanization. This results in discrepancies between the actual costs of mechanization and the budgeted amounts. Moreover, there is a lack of comprehensive planning for mechanized construction within the industry, leading to equipment being underutilized after the completion of a project, as well as higher maintenance and spare parts expenses during the mechanized construction process.

6.3 Limited adaptability

Mechanized construction exhibits limited adaptability to geological changes compared to manual construction. It is generally suitable for tunnels with relatively uniform rock characteristics but struggles with complex geological conditions. Additionally, in terms of excavation methods, mechanized equipment occupies significant space and is less flexible, making it suitable primarily for full-face excavation and less so for methods involving multiple excavation steps, such as CD (Conventional Drilling), CRD (Conventional/Reaming/Drilling), and twin sidewall pilot tunnels.

6.4 Shortage of skilled technical workers

(1) Lack of skilled operators for mechanical equipment: For equipment like fully computerized rock drilling jumbos, concrete wet spraying machines, and gantry-type arch frame installation vehicles, there are no specialized training institutions for the operators, leading to a lack of skilled personnel.
(2) Shortage of on-site maintenance personnel for mechanical equipment: Relying solely on manufacturers for maintenance cannot meet on-site requirements. The market lacks a large-scale industry chain for equipment maintenance technicians, resulting in potential work stoppages waiting for repairs.
(3) Need for improved competency of on-site management and technical staff: On-site management and technical staff typically follow traditional construction methods for site arrangement, management, and control. They often do not consider the characteristics of mechanized construction, leading to issues with poor coordination between construction phases and the failure to fully leverage the benefits of mechanization.

6.5 Lack of matching standards, regulations, and design

Existing standards and regulations for highway tunnels are primarily based on traditional construction methods. Mechanized construction, due to the variety of equipment types, differing process requirements, and large space requirements, may not align with existing acceptance standards, design criteria, and construction specifications. Additionally, during the design phase, there is often insufficient consideration of the technical specifics of mechanized construction, which can make certain construction processes challenging to implement.

VII. PROSPECTS FOR MECHANIZED CONSTRUCTION

7.1 Informatization

Due to limitations related to geology, topography, technology, and costs, preliminary

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survey and design data may not accurately reflect the actual geological conditions at the construction site. Although the basic concept in highway tunnel construction is "information-based design and construction," in reality, information-based construction in highway tunnels has not been fully realized due to limited data collection and accuracy. In the future, it is crucial to take advantage of rapid advancements in sensing technology, information technology, and communication technology. This includes establishing an "information-based design and construction" platform that integrates data collection, analysis, and decision-making. Information technology should be introduced into various aspects, including safety and quality control, on-site personnel management, emergency response, enabling comprehensive information-based construction throughout all phases and processes.

7.2 Intelligence

With the continuous development of new technologies such as the Internet of Things (IoT), artificial intelligence, and big data, the tunnel equipment industry is also moving towards digitization and intelligence. In the future, the focus should be on the complete process of tunnel construction. It is essential to research and develop intelligent equipment systems for key processes in the drilling and blasting method in tunnels. By studying the test data between equipment and equipment, equipment and the environment, and equipment and the surrounding rock, digitalization and intelligence of tunnel equipment can be realized.

7.3 Systemization

Promote the mechanization technology of the New Austrian Method for highway tunnels vigorously. This should involve advanced mechanized equipment for key processes in tunnel excavation, initial support, and extend to mechanized construction in secondary lining, maintenance, drainage prevention, and auxiliary works within tunnels. It is necessary to adapt the mechanization level according to specific geological conditions on a case-by-case basis. Additionally, design and construction methods should match the level of mechanization to maximize the efficiency of mechanized systems.

7.4 Modularization

Prefabrication and modularization technology offer advantages such as high-quality control, rapid construction, and minimal environmental impact. This technology has seen significant success in the application of shield tunneling and cut-and-cover subway platform projects internationally. In China, prefabrication technology is relatively mature in tunneling projects using tunnel boring machines (TBM) and immersed tube methods but less so in highway tunnel construction using drilling and blasting methods. To promote the use of prefabrication technology in highway tunnel construction, comprehensive research should be conducted in theoretical calculations, system development, standardized design of prefabricated components, and construction machinery. This research should lead to a complete set of prefabrication and modular construction techniques tailored to the needs of highway tunnel projects.

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