Key Issues in Prefabricated Design and Construction of Shield Tunnel Internal Structure

Cheng Xiaoqing[1,*], Wei Chi[2], Zhang Yazhou[2]
[1]*China First Highway Engineering CO.LTD., Beijing, China*
[2]*CCCC Tunnel Engineering Co. Ltd., Beijing, China*
**Corresponding Author*

Abstract: With the rapid development of large-diameter shield tunnels, the transition of internal structures from traditional cast-in-place to fully prefabricated construction has become an industry consensus. This paper systematically reviews the research achievements on prefabricated design and construction of shield tunnel internal structures in China from 2013 to 2025, covering structural system selection, connection node design and experimental verification, structural mechanical performance analysis, factory-based prefabricated production, on-site rapid assembly processes and intelligent construction equipment, economic benefit evaluation, and operational disease characteristics. The results show that: (1) The "slab-beam-column" structural system has clear force characteristics and is most commonly used in double-layer tunnels; (2) Internal structures can significantly improve tunnel stiffness, with maximum longitudinal displacement reduction of 39.3% and radial convergence reduction of 86.87%; (3) Connection node types should be verified through testing, with grouting sleeve connections and UHPC post-casting materials being important development directions; (4) The prefabrication rate has increased from 50% to over 90%, reducing approximately 70% of labor and 80% of construction time compared to cast-in-place methods; (5) Intelligent assembly equipment has achieved one-click intelligent construction. Research gaps in long-term performance, multi-factor coupling, fire and explosion resistance, and geological adaptability are also discussed.

Keywords: Shield Tunnel; Internal Structure; Structure; Connection Node; Mechanical Performance; Intelligent Construction; Economic Analysis

1. Introduction

Driven by intensive development of urban central districts in China, ground traffic space is growing scarce, making large-diameter shield tunnels a core infrastructure for urban transport. Most internal tunnel structures now adopt a hybrid "prefabrication plus cast-in-place" scheme, which fails to satisfy modern requirements for high efficiency, environmental friendliness and standardized construction. Fully prefabricated assembly has thus emerged as an irreversible development direction for tunnel internal structures, which are generally categorized into single-layer and double-layer forms nationwide.

Chinese researchers have carried out extensive systematic studies covering joint connections, structural fabrication, mechanical performance, economic standardization and intelligent construction. Scholars have proposed novel joint forms including grouting sleeve anchorage, rebar planting, UHPC post-cast lap joints and tie rod connections, with various tests verifying their load-bearing capacity, seismic performance and construction merits. Relying on landmark projects such as Nanjing Weisan Road River-crossing Tunnel and Shanghai Airport Link Line, the industry has developed innovative techniques like precast lane slabs, integrated beam-slab-column fabrication and synchronous tunneling-component installation. The probabilistic limit state theory has also been adopted to realize refined full-lifecycle structural design.

Numerical simulations and field monitoring prove that prefabricated interiors greatly boost tunnel longitudinal rigidity, cut radial convergence and segment deformation, while optimized construction sequences further relieve structural stress. Standardization and economic analyses confirm prefabrication shortens construction schedules and reduces on-site labor, delivering remarkable overall benefits. Intelligent assembly machinery raises installation precision and efficiency, and research on long-term structural defects reveals cracking and damage mechanisms to guide structural optimization.

Domestic research has shifted from empirical summaries to integrated systems combining numerical simulation, model testing and theoretical analysis. Summarizing cutting-edge recent findings, this paper systematically reviews core technical challenges in prefabricated construction of large-diameter shield tunnel internal structures, offering theoretical and technical references for wider adoption of full prefabricated assembly methods.

2. Development History and Application Status of Prefabrication of Internal Structures in Shield Tunnels

As an important component of the main load-bearing system of the tunnel, the internal structure of the shield tunnel mainly undertakes functions such as traffic passage, load transfer, spatial division, ventilation and drainage, and is widely used in various underground transportation tunnel projects such as urban highways, intercity railways, and combined road-rail construction. According to the form of the passage section of the tunnel, it can be divided into two major categories: single-layer shield tunnels and double-layer shield tunnels. The structural forms, spatial scales, and force characteristics of the two types of tunnels are significantly different, and the corresponding technical difficulties, structural schemes, and application modes of prefabricated assembly construction are also different. After more than a decade of technological iteration, the prefabrication of internal structures of domestic shield tunnels has moved from initial exploration to mature application, with the prefabrication rate continuously increasing, the technical system constantly improving, and the engineering application scenarios continuously expanding.

2.1 Application Forms of Prefabricated Structures for Single-Layer and Double-Layer Tunnels

The internal structure of single-layer shield tunnels is relatively simple in function, mainly including vehicle lane slabs, prefabricated profile pieces, flue slabs, anti-collision side walls, evacuation and rescue facilities, etc. The prefabrication construction difficulty is relatively low, and it is the earliest tunnel type in China to attempt prefabrication assembly. At present, single-layer shield tunnels in China mainly adopt two types of semi-prefabricated and fully prefabricated modes. The first type is the semi-prefabricated mode, where the lower structure uses prefabricated opening pieces combined with cast-in-place construction on both sides, and the upper flue system uses prefabricated flue slabs combined with cast-in-place corbels formed. This mode is widely used in key projects such as the Nanjing Heyan Road Cross-river Passage and the Beijing East Sixth Ring Road Renovation project; The second type is the improved prefabrication mode, which uses prefabricated opening parts at the bottom and prefabricated lane slabs at the top, and supports the corbels through rebar planting in segments, significantly reducing the amount of cast-in-place work. The Yan 'an East Road Tunnel in Shanghai is a typical example. With technological upgrades, the new Tsinghua Garden Tunnel on the Beijing-Zhangjiakou Railway has achieved full prefabrication of single-story tunnels, using a combination system of prefabricated middle box culverts and prefabricated side box culverts at the bottom, completely eliminating large-scale on-site cast-in-place operations, significantly improving construction quality and efficiency, and improving the working environment in the confined space of tunnel construction.

The double-layer shield tunnel has a complex spatial structure, with the upper and lower layers respectively undertaking the passage function, and contains a large number of load-bearing components such as columns, longitudinal beams, lane slabs, partition walls, and bases inside. The prefabrication and assembly are difficult and have high precision requirements, making it a key scenario for current prefabrication technology research and application. There are obvious differences in the prefabrication forms of the internal structure of typical double-layer large-diameter shield tunnels built in China. Different projects adapt different prefabrication schemes according to the tunnel diameter, passage function and geological conditions. The prefabrication situation of the internal structure of domestic double-layer shield tunnels is shown in Table 1.

Table 1. Prefabrication of the Internal Structure of Domestic Double-Layer Shield Tunnels

Tunnel Names	Diameter /m	Upper lane structure	Lower lane structure
Fuxing Road Tunnel	Outer diameter: 11 Inner diameter: 10	① Prefabricated corbels ② Prefabricate upper lane slabs	Cast-in-place
Military Industrial Road Tunnel	Outer diameter: 14.5 Inner diameter: 13.3	Cast-in-place	Prefabricated π -shaped parts
Yangzhou Slender West Lake Tunnel	Outer diameter: 14.5 Inner diameter: 13.3	Cast-in-place	Cast-in-place
Nanjing Weisan Road Tunnel	Outer diameter: 14.5 Inner diameter: 13.3	① Cast-in-place columns and longitudinal beams ② Prefabricated upper lane slabs	Prefabricate the beveled components
Upper Middle Road Tunnel	Outer diameter: 14.5 Inner diameter: 13.3	Cast-in-place	Prefabricated π -shaped parts
Zhuguanglu Tunnel	Outer diameter: 14.5 Inner diameter: 13.3	① Prefabricated columns and longitudinal beams ② Prefabricate the upper lane slabs	Prefabricate π -shaped pieces
Zhoujiazui Road Tunnel	Outer diameter: 14.5 Inner diameter: 13.3	① Prefabricated columns and longitudinal beams ② Prefabricate the upper lane slabs	Prefabricate π -shaped pieces

In recent years, a breakthrough has been made in the fully prefabricated technology of double-deck tunnels. The Shanghai Intercity Railway Airport Link project innovatively adopted a fully prefabricated assembly structure of prefabricated arc-shaped parts + prefabricated partition walls, with the size of the lower prefabricated components reaching 9.5m×2m×2.85m, addressing the assembly problem of large-sized components in the narrow tunnel space. The development of supporting assembly positioning technology and dedicated transport assembly equipment completely eliminates the large number of wet joints in the traditional "prefabrication + cast-in-place" mode, which not only significantly improves construction efficiency but also significantly enhances the overall structural rigidity of the tunnel, providing a benchmark case for the fully prefabricated construction of super-large diameter double-deck tunnels. In addition, the Wuhan Sanyang Road Yangtze River Tunnel, the world's first combined road-rail shield tunnel, adopts a three-layer cross-sectional layout, taking into account both road and rail traffic functions, providing an important reference for the prefabrication design of the internal structure of multi-functional composite large-diameter shield tunnels.

2.2 Division of the Development Stages of Prefabrication Technology

Reviewing the relevant research and engineering practices in China from 2013 to 2025, the development of prefabricated assembly technology for the internal structure of shield tunnels can be clearly divided into three stages, with the technical maturity, prefabrication rate, and research depth all showing stepwise improvement characteristics.

The first stage was the partial prefabrication exploration period from 2013 to 2017. During this period, the internal structure of the tunnel was still mainly constructed by cast-in-place construction. The industry initially attempted a semi-prefabricated combination model of "cast-in-place + prefabrication", with only factory prefabrication of simple accessory components such as lane slabs and flue slabs, while the core load-bearing components were still formed by cast-in-place on site. The overall prefabrication rate was maintained at around 50%. This stage of research is mainly based on the summary of engineering experience, lacking systematic theoretical analysis and experimental verification. The connection process of prefabricated components is simple and the assembly accuracy is low, and a standardized technical system has not yet been formed.

The second stage is the period of key technological breakthroughs from 2018 to 2021. The concept of fully prefabricated construction was first proposed in shield tunnel engineering, and the industry focused on tackling core technologies such as prefabricated component node connection, high-precision assembly, and structural force matching. The load-bearing performance and seismic performance of various nodes were verified through full-scale model tests and numerical simulation analysis. The compatibility of prefabricated components was significantly improved, and the overall prefabrication rate increased to 70% to 85%. The Shanghai Zhuguanglu Passage, as a typical example, has an internal structure prefabrication rate of 93%, basically achieving prefabrication and assembly of the main structure, marking a phased breakthrough in China's shield tunnel prefabrication technology.

The third stage is the full-scale promotion and deepening period from 2022 to the present. Full prefabrication and assembly have become the mainstream technical route for the construction of the internal structure of large-diameter shield tunnels, with the industry's prefabrication rate generally exceeding 90%. New technologies such as intelligent assembly equipment, BIM full life cycle control, and probabilistic limit state design have been fully implemented, and the concept of integrated force design for structures has been gradually established. At the same time, the industry has carried out large-scale engineering statistics and standardization research. Based on data from 36 super-large diameter shield tunnel projects, scholars such as Guangming have proposed standardized classification suggestions for segment ring width, thickness, and connection methods, promoting the transformation of the internal structure design of tunnels from the traditional "one tunnel, one design" customized model to a standardized and modular model. Further solidifying the foundation for the promotion of prefabricated assembly technology.

3. Key Technologies for the Design of Prefabricated Internal Structures of Shield Tunnels

3.1 Selection of Structural Force System

The structural force-bearing system is the core of the internal structural design of prefabricated tunnels, directly determining the form of component disassembly, assembly process, force-bearing transmission path and overall structural stability. Combining the spatial characteristics and functional requirements of single-story and double-story tunnels, a number of mature prefabricated structural stress systems have been developed in China to adapt to different engineering scenarios.

3.1.1 Single-layer Shield Tunnel Structure System

The internal structure of a single-layer shield tunnel is mainly responsible for one-way passage, ventilation and smoke exhaust, and emergency evacuation. The overall structure can be divided into two major modules: the flue system and the lane system. Among them, the flue system mostly adopts the combination form of "prefabricated flue slabs + cast-in-place corbels", taking into account the requirements of ventilation and smoke exhaust as well as structural load-bearing; The core of the lane system is a combination of prefabricated couplers and prefabricated lane slabs, which is the main load-bearing system for vehicle loads. At present, two types of structural forms are mainly applied in large-section single-layer shield vehicle tunnels in China, each with obvious technical shortcomings. The first type is a structure with prefabricated openings in the middle and cast-in-place lane slabs on both sides. This model requires formwork erection and removal operations in the narrow arc space of the tunnel, has a long construction period, consumes a large amount of formwork materials, and has low construction efficiency. The second type is a simply supported structure with prefabricated openings in the middle and prefabricated lane slabs on both sides. Although it significantly reduces the cast-in-place operation, it has problems such as a large number of lane slab joints, difficulty in joint treatment, poor structural integrity, insufficient longitudinal connection stiffness, and prone to pavement cracking diseases during long-term operation.

In response to the shortcomings of traditional single-layer prefabricated structures, new key projects have completed technical optimization. The Tsinghua Garden Tunnel of the Beijing-Zhangjiakou Railway and the Shanghai Intercity Airport Link Tunnel adopt a fully prefabricated substructure system. All core components are prefabricated in factories in a standardized manner. After completing modular assembly on site, the integral formation is achieved by filling mortar or concrete in the gap between the components and the shield segments. This scheme completely avoids the drawbacks of cast-in-place construction in confined Spaces, reduces on-site operation procedures, and at the same time solves the problems of poor integrity and easy cracking in the assembly of prefabricated slabs, significantly improving construction efficiency while ensuring structural safety and construction quality. In addition, the current research on the design of flue slabs focuses on fire resistance, drainage capacity, control of structural self-weight deflection, and optimization of overall sealing performance, further enhancing the service durability of single-story tunnel prefabricated structures.

3.1.2 Double-layer Shield Tunnel Structure System

The upper and lower layers of double-layer shield tunnels pass independently, and the structural forces are complex. Currently, three types of prefabricated force systems are mainly applied in China, namely the "corbel + prefabricated simply supported slab" system, the "slab - beam - column" system and the "slab - wall" system, and the force characteristics and applicable scenarios of each type of system are significantly different.

The "corbels + prefabricated simply supported slabs" structure system is a common form for early double-deck tunnels, represented by the Shanghai Fuxing Road Tunnel and the French A86 working Tunnel. It supports the prefabricated upper lane slabs through tunnel segment corbels, with a simple structure and easy component disassembly. However, the system has poor integrity, with the lane slabs in a simply supported state, weak seismic performance and single load transfer, and is only suitable for low-load, low-standard urban ordinary highway tunnels.

The "slab - beam - column" structure system is currently the most widely used core system for double-layer large-diameter shield tunnels in China, and most key projects such as the Shanghai Shangzhong Road Tunnel, Gongjun Road Tunnel, Zhoujiazui Road Tunnel, and Nanjing Weisan Road Tunnel have adopted this form. The system consists of prefabricated lane slabs, longitudinal beams, columns and bases to form a complete force-bearing frame. Loads can be transferred in an orderly manner step by step through slabs, beams and columns. The force transmission path is clear and the force mechanism is definite. At the same time, the components have small disassembly dimensions, low self-weight of individual components, low requirements for on-site hoisting and assembly equipment, and are suitable for the narrow construction space of tunnels. However, the longitudinal beams of this system are subjected to combined bending, shear and torsional loads for a long time, and the stress state of the components is complex, which is a key weak point in structural design and operation and maintenance monitoring.

The "plate-wall" structural system has relatively few application cases, represented by the SR99 highway tunnel in Seattle, USA, and the North Cross Passage in Shanghai, which mainly consists of prefabricated lane slabs, integral side walls, and bases as the force-bearing system. The load is transferred from the lane slab to the side wall, and then through the base to the shield segment. The overall rigidity is large, the structural integrity is good, and the anti-deformation ability is excellent. It is suitable for key traffic tunnel projects with large loads and high seismic requirements.

3.2 Design and Test Verification of Key Connection Nodes

Prefabricated connection nodes are the core weak links in prefabricated tunnel structures. The bearing capacity, stiffness characteristics, seismic performance and durability of the nodes directly determine the safety and stability of the overall structure. The core nodes inside shield tunnels mainly include lane slab and segment connection, column and base connection, base and segment connection, beam-plate-column junction nodes, etc. Domestic scholars have carried out a large amount of design optimization and test verification work for various node forms.

3.2.1 Core Node Connection Forms

The connection between the lane slab and the segment is mostly in the form of a corbel-shaped support with rebar planting. The corbel-shaped support with rebar planting on the inner side of the shield segment provides support for the prefabricated lane slab. Before construction, the surface of the segment needs to be mechanically roughened to enhance the bonding performance of the joint surface. The design of the rebar planting should take into account the most unfavorable load combination, precisely control the planting depth and the performance of the rebar planting adhesive, and minimize the damage to the main structure of the segment while ensuring the safety of the cantilever structure.

The connection between the column and the segment is divided into two modes: direct connection and indirect connection at the base. The column direct rebar planting connection segment is simple in structure and clear in force application, and is widely used in projects such as the Bund Passage in Shanghai and the Weisan Road Tunnel in Nanjing. However, in soft soil areas, the segment deformation is large, the rebar planting drilling is prone to touch the main rebar of the segment, and the positioning accuracy is difficult to guarantee, which cannot meet the requirements of high-precision prefabrication and assembly. The connection of the column to the segment through the cast-in-place base can effectively solve the above problems. By fixing the segment through the base with rebar planting, the prefabricated column is anchored inside the base and can use the base to correct the shield construction error and adapt to the complex construction conditions in soft soil areas.

The mainstream connection forms between the base and the prefabricated column include four types: open grouting connection, cup mouth joint, socket joint and grouting sleeve connection. The open connection achieves a rigid connection by inserting the exposed reinforcing bars of the column into the reserved openings of the component through high-pressure grouting; The cup-mouth joint casts the base into a cup-shaped structure, and after the prefabricated column is inserted, it is filled with grouting. The construction is simple and does not require welding. The socket-type joint relies on the tenons of the column to bear the construction load and is formed by welding the reinforcing bars and pouring the concrete, saving steel; Grouting sleeve connection is the preferred technology for current tunnel engineering, which achieves effective connection of reinforcing bars through pre-embedded sleeves, insertion of reinforcing bars, and high-pressure grouting, with high precision and stable performance.

3.2.2 Test Study on Node Performance

Domestic scholars have systematically verified the engineering applicability of various nodes through full-scale pseudo-static tests, pure bending tests, static and dynamic numerical simulations, and other methods. Jiang Haixi [1] conducted quasi-static tests on grouting sleeve connection and rebar planting connection nodes, and the results showed that the bearing capacity and seismic performance of this connection method met the design requirements, and the base rebar planting did not reach the yield strain, and the engineering cost could be reduced by optimizing the number of rebar planting. Wen Zhuyin et al. [3] compared and analyzed the static and dynamic performance of the four forms of fixed connection, unconnected connection, hinged connection and chain bar connection, and found that under static load, the stronger the constraint of the node, the greater the force on the segment and the smaller the force on the internal structure; Under seismic action, the stronger the node constraint, the better the overall seismic performance of the tunnel. Finally, the chain-rod connection is recommended as the comprehensive optimal scheme, which has the advantages of reasonable force application, convenient construction, and good seismic performance.

Wang Wendong [2] compared the joint performance of three types of post-poured materials, namely C60 ordinary concrete, C80 high strength concrete, and UHPC ultra-high performance concrete, through pure bending tests. The tests confirmed that UHPC post-poured material can achieve only lap joint of reinforcing bars without welding, and the bearing capacity and stiffness of the nodes are on par with the traditional welding +C60 concrete system, greatly simplifying the construction process and improving the construction efficiency. The bearing capacity of the C80 concrete lap scheme was only 50% of the specification requirement, failing to meet the engineering application standards, verifying the core application value of UHPC materials in the post-pouring construction of prefabricated nodes and providing a new path for the lightweight and efficient construction of nodes.

3.3 Research on Overall Mechanical Properties of Prefabricated Structures

With the deepening of research, the industry has completely broken the traditional perception that "the internal structure is only a filling component and does not participate in the overall force", and established the design concept of "segment - internal structure integrated load-bearing". A large number of studies have confirmed that the prefabricated internal structure can significantly enhance the overall stiffness of the tunnel, reduce structural deformation, and optimize the force state.

In terms of longitudinal stiffness improvement, Wang et al. [8] found through ABAQUS three-dimensional refined numerical model analysis that after the application of prefabricated internal structures, the maximum longitudinal displacement of combined road-rail tunnels decreased by 39.3%, the displacement of double-deck highway tunnels decreased by 28.4%, and the stiffness improvement effect was more significant for through-joint assembled tunnels. In terms of lateral resistance to deformation and seismic performance, He Yingdao et al. [9] conducted dynamic time-history analysis based on the Jinan Yellow River Tunnel. The results showed that the internal structure could reduce the radial convergence of the tunnel by up to 86.87%, the minimum principal stress by up to 50.75%, the structural bending moment significantly reduced, and significantly improved the lateral stability and seismic performance of the tunnel.

In terms of construction timing optimization, Hu Zhenyu et al. [10] studied the influence of the timing of internal structure construction on the force-induced deformation of segments. The results showed that by advancing the timing of construction from the 5‰ ellipticity deformation stage of segments to the 3‰ stage, the deformation of segments could be reduced by 28.47%, the internal structure uplift could be reduced by 32.83%, and the stress levels of segment bolts and reinforcing bars were significantly reduced It is demonstrated that early construction of the internal structure can effectively constrain segment deformation and optimize the overall stress state, providing data support for the optimization of prefabrication construction timing. Overall, prefabricated internal structures have become an indispensable core component of the overall load-bearing system of shield tunnels, and integrated force design is the core direction of future structural design.

4. Key Technologies for Construction of Prefabricated Internal Structures

4.1 Factory High-Precision Prefabrication Production Process

Standardized factory prefabrication of components is the foundation of full prefabrication assembly construction, and the precision of component production directly determines the quality of on-site assembly and the integrity of the structure. The current industry has formed a mature high-precision prefabrication production process, covering the entire standardized process of steel bar processing, steel bar cage insertion, concrete pouring, curing and demolding, and finished product protection.

During the steel bar processing stage, the longitudinal coupler bars are fixed by special limit devices, and the verticality is precisely corrected by using a horizontal straightedge to ensure accurate welding positioning of the main bars and stirrups and eliminate the problem of coupler offset and tilt. After the steel cage is formed, first fix the end plates to the bottom mold, then close the side mold to lock and position, and precisely fix the position of the coupler through mold bolts to ensure the embedded accuracy of the component. The concrete pouring uses a dedicated hopper for layer-based feeding. The vibrator follows the principle of quick insertion and slow extraction, inserting 10cm into the lower layer of concrete to avoid the position of the embedded parts, and uses a defoamer to fully expel the internal air bubbles to ensure the density of the concrete and the flatness of the component surface.

Demolding of components strictly follows the strength standard. Demolding can only be carried out when the concrete strength reaches 75% of the designed strength. After demolding, the steel bar couplings are sealed and protected. Components are stacked layer by layer and set with sleepers and spacers to avoid collision damage. Before leaving the factory, special lifting gear is used for hoisting and transportation, foam protection is applied to the corners of the components, and a dedicated person is assigned for quality inspection and record-keeping to ensure the dimensional accuracy of the prefabricated components and the quality of the finished products, laying the foundation for high-precision assembly on site.

4.2 On-Site Modular High-Precision Assembly Process

The assembly of the internal structure of the large-diameter double-layer shield tunnel follows the core principle of "bottom-up, layer-based construction, and section formation". The overall construction process is as follows: assembly and filling of the lower π -shaped components → base construction and positioning of the reinforcing bars → hoisting and installation of the prefabricated columns and grouting → assembly of the upper lane slabs → post-pouring of the wet joints → installation of the prefabricated cover plates and anti-collision sidestones → pavement construction.

The assembly of the lower π -shaped prefabricated components is based on the tunnel centerline as the control reference, precisely adjusting the component posture in combination with the designed slope, periodically rechecking the axis and slope, and filling the assembly gap through the base plate padding and local concrete filling to ensure smooth joints without misalignment. Before assembly, thoroughly clear the debris at the bottom of the segments, seal the handholes, precisely position the layout, and strictly control the levelness and flatness of the components.

The base construction is the core link of assembly accuracy control. The position of the base is determined by precise layout, and the reliable connection between the base and the main body of the tunnel is achieved by using the segment rebar planting process. To ensure the accuracy of the reserved bar insertion for the column, a special positioning device was developed. Through the combination limit of the grouting disk and the positioning disk, the positioning error of the bar insertion was strictly controlled within ±2mm, avoiding the installation deviation of the column from the source.

The prefabricated columns are installed using a single-point turning and hoisting process. Special hoisting joints are used to connect the column couplers, and a flexible cushion layer buffers the turning impact force to prevent component damage. After the posts are hoisted into position, the plane position and verticality are precisely corrected by infrared rangefinders and plumb lines, and fine-tuning fixation is completed with diagonal braces to ensure the installation accuracy of the posts.

The upper lane slab is assembled by first hoisting longitudinally and then turning and positioning. The lateral deviation is controlled by the limit device at the top of the column, and the assembly error is kept within ±5mm. After the components are in place, the post-pouring construction of beam-plate-column joints, plate-plate joints, and plate-segment joints is carried out simultaneously. Special quick-assembly brackets are used as the working platform and bottom formwork, and various types of wet joint concrete are poured simultaneously to ensure the overall rigidity and integrity of the structure.

4.3 Application of Intelligent Construction Equipment and Technology

Traditional manual assembly has low precision, poor efficiency and high labor intensity, making it difficult to meet the demands of fully prefabricated large-scale construction. The development and application of intelligent equipment have pushed tunnel prefabrication construction into the stage of digitalization, precision and efficiency. Based on the Shanghai Airport Link project, Lin et al. [14] developed an intelligent installation machine for traveling arc-shaped parts, with a hydraulic control system assembly accuracy of up to 0.5mm, on-site actual assembly deviation controlled within ±5mm, achieving one-click fully automatic assembly, single-section assembly only takes 32min, construction efficiency increased by more than 30%, labor input reduced by 50%.

The intelligent assembly machine for the middle partition wall developed by Zhao Xu uses a track-type side grasping structure and relies on a PLC multi-sensor fusion positioning system to achieve one-click intelligent assembly. It only takes 40 minutes for a single operation, with a posture deviation of less than 5mm, and can be completed by a single person, significantly reducing labor costs. Meanwhile, by optimizing the movement path of component assembly, the industry has reduced the traditional 20mm installation error to 1mm, significantly improving the construction accuracy. In addition, the full application of BIM technology has enabled digital management of the entire process, including modeling of prefabricated components, construction simulation, process optimization, and resource control, and identified core construction influencing factors through the AHP method, effectively avoiding construction risks and improving the overall construction quality of prefabricated assembly.

4.4 Comparative Analysis of the Economic Aspects of Prefabrication and Cast-in-Place Construction

A large amount of engineering data and quantitative research confirm that fully prefabricated assembly construction has significant comprehensive economic and social benefits compared to traditional cast-in-place construction. Zhu Xuanyin [12] research shows that the prefabricated assembly process can reduce on-site workers by more than 70%, shorten the construction period by about 80%, the installation accuracy of components is comprehensively better than that of cast-in-place construction, and the quality stability is significantly improved. Based on a quantitative analysis of the Zhoujiazui Road Tunnel in Shanghai, Jiang Haixi [13] found that the fully prefabricated construction mode with a prefabrication rate of over 90% has increased work efficiency by more than 70%, with a daily installation capacity of up to 50 columns and 25 lane slabs, and only 5 to 10 people on site are needed to complete the core construction. Compared with the operation configuration of more than 50 people for cast-in-place construction, the labor cost is significantly reduced.

Although the single production cost of standardized production in prefabricated component factories is slightly higher than that of on-site cast-in-place, from the perspective of the entire life cycle, the significant shortening of the prefabricated construction period can significantly reduce indirect costs such as equipment leasing, on-site management, and safety protection. At the same time, construction dust and noise pollution are greatly reduced, with prominent green construction benefits. Moreover, prefabricated structures have better durability and lower later operation and maintenance costs. The combined economic and social benefits are far superior to the traditional cast-in-place process, and it has an economic basis for large-scale promotion.

4.5 Disease Characteristics and Existing Problems during the Operation Period

At present, domestic research on the operational performance of prefabricated tunnels is relatively weak. Existing disease research indicates that segment joint deformation is the core inducement for internal structural cracking. Dong et al. [16] conducted disease statistics on the Nanjing large-diameter cross-river tunnel and found that 87.4% of the segment circumferential joint missets were associated with corbel crack diseases, and the middle partition wall cracks showed a distribution characteristic of "dense in the middle of the tunnel and sparse at both ends". The critical missets of the segment circumferential joint and longitudinal joint were 5mm and 3mm respectively. Beyond the critical values, the risk of water seepage and structural cracking in the tunnel increased significantly.

Overall, there are still many shortcomings in the current research on prefabricated tunnels in China: First, there is a lack of study on the evolution law of long-term service performance, and there is no systematic performance prediction model for design life of 50 to 100 years; There is insufficient research on the mechanism of multi-factor coupling, and the coupling effects of vehicle vibration, temperature and humidity cycling, and groundwater erosion are still unclear; Third, there is a lack of research on performance under extreme conditions, and the fire, explosion and shock protection system is incomplete; Fourth, there is a lack of research on geological compatibility, and the theory of optimal design for prefabricated structures under complex conditions such as high water pressure and composite strata is incomplete, which is a key area that needs to be broken through in future research.

5. Conclusions

In order to make full use of the interior space of highway tunnels, shield tunnels are currently developing towards larger diameters and double layers, with increasingly complex internal structures. The narrow tunnel space brings many inconveniences to the construction of the internal structure. To address this issue, research on the prefabrication and assembly design and construction of the internal structure of the tunnel was carried out, and the following conclusions were reached:

This paper provides a systematic review of the key issues in the prefabrication design and construction of the internal structure of shield tunnels. The study shows that in terms of structural force-bearing systems, single-layer shield tunnels commonly use flue systems (prefabricated flue slabs + cast-in-place corbels) and lane systems (prefabricated lane slabs + prefabricated couplers), while double-layer tunnels mainly adopt the "plate-beam-column" structural system, which has clear force transmission paths, small component sizes, and is convenient for prefabrication and assembly; In terms of connection nodes, grouting sleeve connections and UHPC post-cast materials are important development directions, and the type of node needs to be determined through test verification; In terms of construction technology and equipment, prefabricated assembly can reduce the number of workers by about 70% and shorten the construction period by about 80% compared with cast-in-place. The prefabrication rate has increased from 50% in the early stage to over 90%, and intelligent assembly equipment has achieved a leap from manual operation to one-click intelligent construction, with assembly accuracy controlled within ±5mm. In terms of mechanical properties, the internal structure can significantly increase the overall stiffness of the tunnel, with longitudinal displacement reduced by up to 39.3% and radial convergence reduced by up to 86.87%, marking the transformation of the internal structure from "non-load-bearing filling" to "integrated load-bearing" design concept.

References

[1] Jiang Haixi. Research on Key Connection Technologies of Double-layer Prefabricated Structures inside Shield Tunnels [J]. Urban Road and Bridge & Flood Control,2018(10):190-194+23-24.

[2] Wang Wendong. Research on Beam-column Joint Connection Technology of Double-layer Prefabricated Structure inside Shield tunnels [J]. Urban Road, Bridge and Flood Control,2020(10):101-105+19.

[3] Wen Zhuyin, Liu Nian, Yan Xiao. Research on Double-lane Structure and Different connection forms of segments in shield tunnels [J]. Modern Tunnel Technology,2020,57(S2):464-471.

[4] Huang Jun. Design Technology of Double-layer Prefabricated lane Structure inside Shield tunnels [A]. Proceedings on Construction and Management Technology of Underwater Tunnels [C]. China Highway Magazine,2013:8.

[5] Wang Shang-gao, Shi Shi-bo, Shu Heng, Gao Fan-ding, Li Dong-sheng. Prefabrication technology for Internal structure of Single-tube Double-layer Extra-long Shield Tunnel: A Case Study of the Nanjing Weisan Road Cross-river Shield Tunnel Project [J]. Tunnel Construction,2016,36(04):451-457.

[6] Zhao Liansan. Synchronous Construction Technology for Internal Structures of Large-diameter single-bore double-track Shield tunnels [J]. Mechanization of Construction,2022,43(09):56-60.

[7] Jiang Wenxing, Dong Song, Wei Wen. Research on Design and construction Technology of Prefabricated components for the Internal structure of large shield tunnels [J]. Modern Urban Rail Transit,2022(08):61-65.

[8] Wang Junyong, Feng Kun, Sun Wenhao, et al. The influence of different internal structure types on longitudinal mechanical properties of shield tunnels [J]. Railway Standard Design,2022,66(10):87-93.

[9] He Yingdao, Xiao Mingqing, Feng Kun, et al. A Study on the lateral seismic performance of the composite system of segments and internal structures in combined road-rail shield tunnels: A Case Study of the Jinan Yellow River Tunnel [J]. Tunnel Construction (Chinese and English),2022,42(11):1987-1996.

[10] Hu Zhenyu, Feng Kun, Guo Wenqi, et al. Study on the Influence of Different Construction Timing of Internal Structures on the Force of segment Linings in extra-large section shield tunnels [J]. Modern Tunnel Technology,2023,60(02):41-50.

[11] You Guangming, Liu Nian. Research on Standardized Design of super-large Diameter Shield Tunnels [J]. Urban Road, Bridge and Flood Control,2020(07):65-68+10.

[12] Zhu Xueyin. A Comparative study of cast-in-place and Prefabricated assembly techniques for double-layer Structure of shield tunneling [J]. Anhui Architecture,2019,26(10):120-122.

[13] Jiang Haixi. [J]. China Municipal Engineering,2025(01):56-60+108-109.

[14] Lin Chun-gang, Ma Zhao-lin, Chen Yong-liang, et al. Prefabrication and assembly technology of arc-shaped components for large diameter shield tunnels and application of intelligent installation machines [J]. Tunnel Construction (Chinese and English),2023,43(S1):456-462.

[15] Zhao Xu. Research and application of intelligent Assembly Equipment for Prefabricated structures of Large diameter tunnels [J]. Mechanization of Construction,2023,44(06):43-46.

[16] Dong Fei, Li Ao, Yang Kui, et al. Research on Typical Diseases of large-diameter cross-river shield tunnels for metro [J]. Modern Transportation Technology, 24,21(03):29-34.

