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REVIEW ARTICLES

Research Strategies on New Prefabricated Technology for Underground Metro Stations

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Abstract Based on the first successful application of new prefabricated technology in underground metro stations on line 2 of the Changchun Metro in China, a comprehensive analysis and discussion on research strategies for new prefabricated technology for large underground structures is provided. This paper introduces the application status of prefabricated technology in underground engineering worldwide, illustrates the different characteristics of prefabricated technology applied to ground buildings and underground structures, puts forward the key technologies, and compares the major technical, economic, and social benefits achieved. The successful application of prefabricated technology for underground structures in Changchun Metro demonstrates the feasibility and great advantages of the new prefabricated technology for underground engineering.

Keywords Metro station · Prefabricated technology · Monolithic precast concrete structure · Superimposed prefabricated integral structure · Fully prefabricated structure · Rebar splicing by grout-filled coupling sleeve · Grouted mortise–tenon joint · Closed-cavity thin-walled components

1 Introduction

Prefabricated technology represents a significant achievement which can change building construction methods. Prefabricated buildings are being increasingly widely applied in China [1]. Study of prefabricated aboveground buildings has made significant achievements as a result of a tremendous amount of research and applications. Related technology and management systems have been established, and there are increasing applications of such prefabricated aboveground structures in civil engineering. However, there were no studies on prefabricated technology for large underground structures in China until 2012. The first attempt at application of prefabricated technology in China was made in the stations of Changchun Metro line 2 in 2012. To date, five metro stations have been built, and remarkable results have been achieved.

2 Applications of Prefabricated Technology for Underground Engineering

2.1 Applications Worldwide

In the early years, many countries, such as the former Soviet Union, Japan, France, etc., started research on prefabricated technology for underground engineering. Prefabricated linings were first applied in shield tunnels in the late 19th and early 20th century [2]. After more than 100 years, shield tunnels have been applied in many fields such as metro, highway, municipal engineering, etc. Shield tunnels have different types of cross-section, with the circular section being most widely used, with diameter from 3 to 18 m.

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Other applications of prefabricated linings appeared in the 1980s in the former Soviet Union. This prefabricated technology was applied in open-cut metro running tunnels, the principal parts of stations, and auxiliary aisles to overcome the shortcomings of cast-in-place concrete construction in cold weather.

Two approaches can be adopted for the above-mentioned prefabricated open-cut metro tunnels: an integral prefabricated running tunnel in the longitudinal direction with joints between adjacent rings sealed using cement materials (Fig. 1a), or prefabrication of segments with cast-in-place bottom joints (Fig. 1b) [3].

The structures of early prefabricated stations commonly used a complex rectangular system with a prefabricated roof, bottom, side wall, pillar, and beam structure. However, the joints in the bottom are currently formed using cast-in-place reinforced concrete. The holes in the joints are reserved for later connection of the upper component (Fig. 2) [3].

In 1985, Minsk station used a structure with a single arch and one large span [3, 4]. Two joints were set up, in the roof and bottom, respectively. In addition, cast-in-place sections were installed in the side walls. The joints between the components were formed using cast-in-place reinforced concrete (Fig. 3).

Prefabricated technology for metro stations has also been used in Russia and France. Figure 4 shows the Petersburg Stadium prefabricated station [5].

2.2 Applications in China

Except for prefabricated linings used in shield tunnels, other applications of prefabricated underground engineering are confined to open-cut tunnels with small cross-sections, e.g., municipal pipelines. Local prefabricated linings have been used in railway tunnels constructed with mining method, for example, Qinling tunnel, where the inverted arch was prefabricated, whereas the side walls and arch were constructed by in situ casting (Fig. 5) [6].

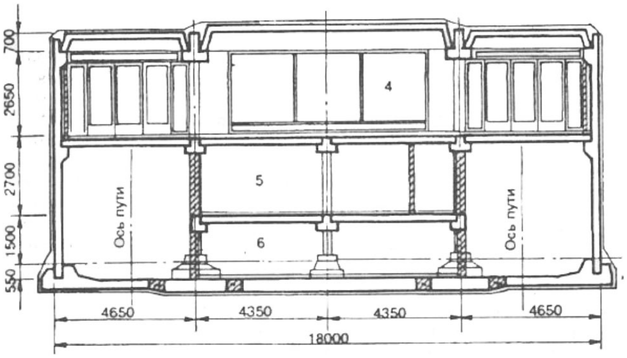

Fig. 2 Open-excavation rectangular prefabricated station

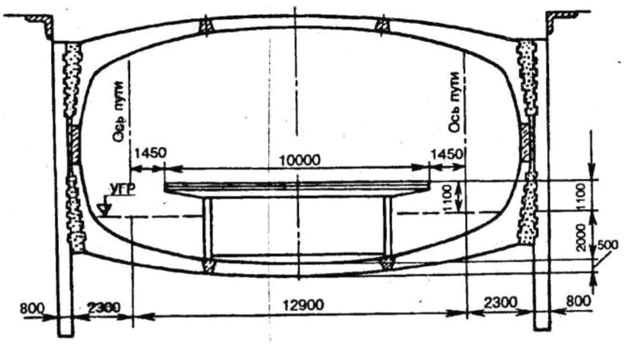

Fig. 3 Open-excavation prefabricated arch metro station in Minsk

3 Analysis of the Characteristics of Prefabricated Aboveground and Underground Structures

3.1 Prefabricated Aboveground Structures

Taking advantage of their high efficiency, high quality, long lifespan, and environmentally friendly nature, prefabricated aboveground structures represent a mature and complete technology system that has been widely applied in the West and Japan [7]. However, research on and applications of prefabricated technology started relatively late in China, although great progress has been made in recent years.

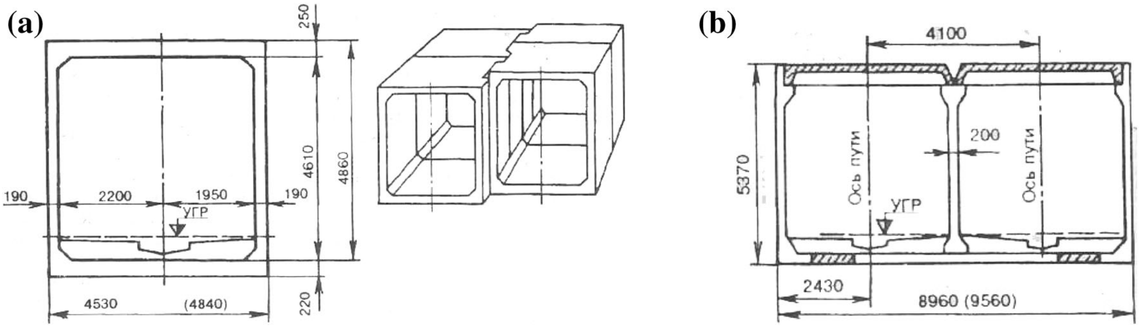

Fig. 1 Prefabricated running tunnel: **a** integral prefabricated running tunnel; **b** partially prefabricated running tunnel with cast-in-place bottom joint

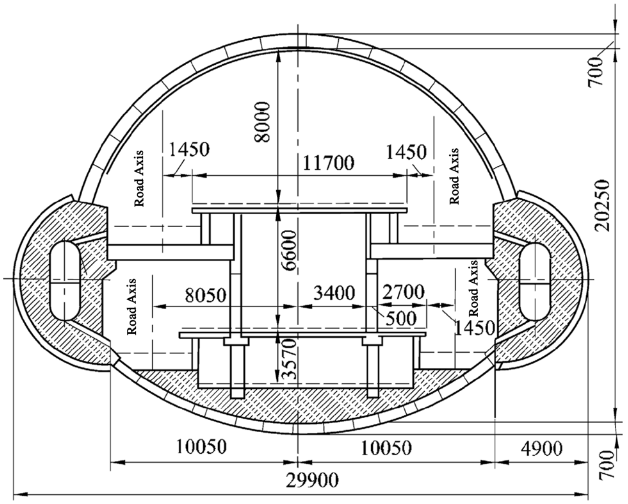

Fig. 4 St. Petersburg Stadium prefabricated station

At present, in China, prefabricated components for aboveground structures are connected using a reliable method to form the whole prefabricated concrete structure, followed by cast-in-place concrete placing and cement grouting, forming what is known as an "integrated prefabricated structure" [8]. Rebar splicing in joints can be achieved by mechanical connection, filling the coupling sleeve with grouting, lapped connection with grouting and anchoring, welding connection, and lapped connection with binding, to realize rigid connections.

Except for the underground foundations of such aboveground buildings, the other parts of the structure are above the ground and surrounded by air without any constraints. The structure bears not only vertical load, but also wind load and seismic force. The wind load may produce horizontal displacement and vibration amplitude. Earthquake waves cause ground motion, thus inducing structural vibration. Therefore, aboveground structures will suffer from the whiplash effect under such lateral loads. In this regard, the self-vibration characteristics determined by the shape, quality, and stiffness of the structure play a decisive role.

Therefore, achieving rigid connections between the prefabricated components of the bearing structures and integral orientation of the integrated prefabricated parts are key ways to achieve prefabrication of aboveground structures. Accordingly, Chinese national industry standard *Technical specification for fabricated concrete structures*: *JGJ1-2014* states that "integrated prefabricated structure can use the same structural analysis method of cast-in-place concrete structure under various design conditions." Indeed, this integrated prefabricated technology conforms to the mechanical and environmental characteristics of aboveground structures. Furthermore, it is economic, reasonable, and safe.

However, investigation has revealed that, when applying the most widely used method of rebar splicing by grout-filled coupling sleeve, deviation of the embedded rebar and the coupling sleeve of the prefabricated components can be easily produced (Fig. 6). Many connection problems also occur with existing technology, including difficulties with positioning or insertion, reproduction of components, and serious grout leakage of late-poured band [9, 10]. Therefore, there is still room for improvement regarding the type of rigid joint and construction technology applied for such integrated prefabricated structures.

Some aboveground engineering projects have also introduced the technology of slab concrete shear walls. This method uses inner and outer prefabricated components as the later-pouring concrete lattice formwork in the core area. Accordingly, permanent monolithic concrete structures are formed using the former prefabricated

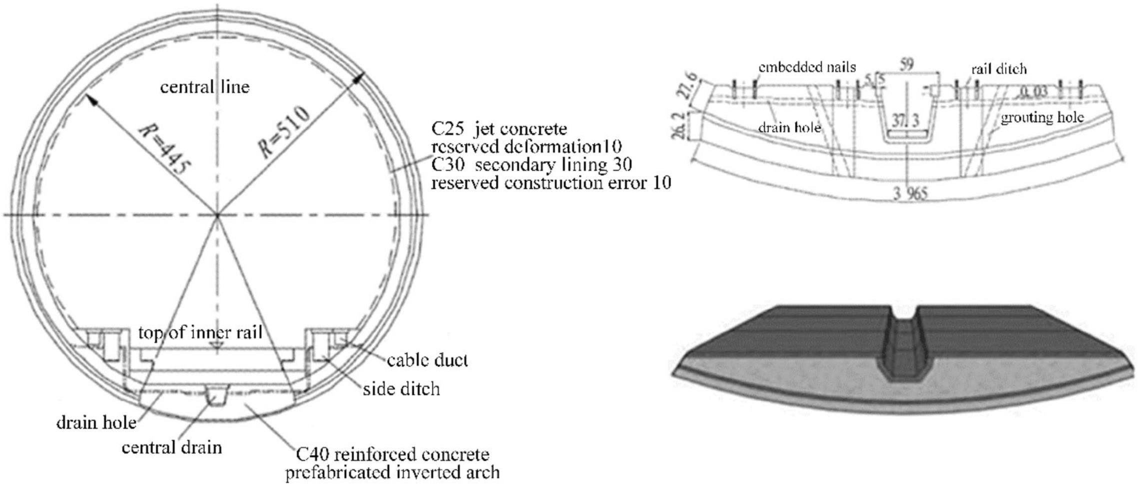

Fig. 5 Prefabricated inverted arch structure of Qinling tunnel

Fig. 6 Rebar splicing by grout-filled coupling sleeve and typical deviation

concrete and later cast-in-place concrete. Nevertheless, such structures suffer from shortcomings such as the huge amount of concrete that must be placed. In addition, the construction of such structures is difficult. Moreover, this method is unfavorable in terms of post detection and inadequate seismic design [11–13]. Therefore, from the perspective of prefabrication, such "superimposed prefabricated integral structures" offer no obvious advantages because of the large amount of site work required.

3.2 Prefabricated Underground Structures

3.2.1 Mechanical Characteristics

As they are surrounded by strata, the environmental and mechanical characteristics of underground structures are fundamentally different from those of aboveground structures. Apart from self-weight, pedestrian load, equipment load, and other vertical loads, the most important loads come from water–soil pressure. Meanwhile, underground structures also suffer all-around constraints from the surrounding strata. In other words, the strata act as both load and carrier. Figure 7 indicates the equilibrium relationship between the structure and strata. Even in the event of an earthquake, underground structures carried by surrounding strata exhibit synchronous vibration and codeformation with the strata. For underground structures, the motion characteristics of the soil play a principal role in the earthquake response rather than their self-vibration characteristics. Furthermore, the shape, quality, and stiffness of the structures cannot change the vibration characteristics of the structure or strata.

The good bearing capacity and seismic performance of underground engineering structures, such as Loess cave dwellings without linings, rock tunnels with simple shotcrete-bolt support, prefabricated shield tunnels in various soft and hard strata, and all kinds of cast-in-place reinforced concrete structures, fully reflect the mechanical characteristics of such underground structures.

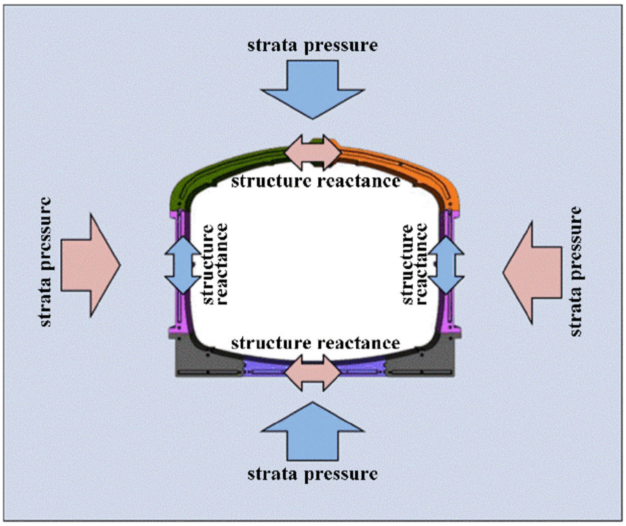

Fig. 7 Equilibrium relationship between structure and strata

For prefabricated underground structures, a stable structural system, suitable joint type, appropriate stiffness and bearing capacity of the joints, reasonable distribution of the joints, and effective mechanical behavior of the structural system are the key technologies.

3.2.2 Waterproofness

Groundwater load is inevitable for underground structures. Aboveground structures change water flow paths, retaining and draining water like "umbrellas and raincoats." Unlike aboveground structures, the waterproofness of underground structures is similar to a "submarine," carrying high groundwater load.

In terms of waterproofing and its effects, a large number of construction practices have shown that leakage sometimes occurs in underground structures, even cast-in-place reinforced concrete structures with full waterproofing layers between the structure and strata. However, many shield tunnels show favorable waterproofing without any outer waterproofing layers or cast-in-place linings, especially shield tunnels crossing rivers or the seabed, which must bear head pressures of more than 60 m.

Given the discussion above, the key to achieving perfect waterproofness of prefabricated underground structures is self-waterproofing of the concrete and the performance of the joint waterproofing. To achieve this, a reasonable waterproofing system, material properties, structural measures, construction technology, and detection methods must be determined.

3.2.3 Construction Environment

The construction of underground structures is closely related to the method used for soil excavation. Soil excavation methods mainly include the open-cut method using foundation pit excavation, undercutting methods such as mining excavation, and the shield method using mechanical tunneling, all of which have a narrow working space. Prefabricated components for aboveground structures are small with less reinforcement and have free space for hoisting and assembly. However, for prefabricated underground structures with large components and high reinforcement ratio, the assembly is similar to building blocks in a box. Therefore, the construction environmental conditions should be fully considered at each stage from structural selection, joint type, and waterproofing measures to hoisting, and positioning and assembly of components.

In conclusion, prefabricated technology for underground structures must comprehensively consider the bearing characteristics, construction method, and environmental conditions. In addition, to take full advantage of such prefabricated technology, key technologies such as rational structural style, connection joints, waterproofing measures, prefabrication, and assembly should be determined appropriately according to the application experience of underground and aboveground practical engineering. Only when implementation of all the above-mentioned key technologies is ensured will prefabricated underground structures be technologically advanced, safe and reliable, environmentally friendly, economical, and reasonable.

4 Key Technologies for Prefabricated Underground Stations on Changchun Metro Line 2

4.1 Research Background

Changchun City is located in the northeast of China, where a winter break of 4–5 months is required during metro construction due to extreme cold weather. To alleviate such schedule pressures in construction engineering in cold regions, Yuanjiadian station on Changchun Metro line 2 was selected as a test section to carry out research on and apply prefabricated technology for underground engineering in 2012. Thereafter, the proposed new prefabricated technology for metro stations was applied in another four stations on Changchun Metro line 2. To date, five prefabricated metro stations have been completed, as displayed in Fig. 8.

The five cut-and-cover stations are all supported by anchor-pile systems. Each of these horseshoe-shaped two-storey stations is 20.5 m wide and 17.45 m high. The station structures are built by assembling seven 2-m-wide prefabricated components into the section geometry without any concrete wet spraying (Fig. 9). The grouted mortise–tenon joint was invented and used between the circular and longitudinal components. Moreover, multiple waterproofing measures are applied in the joints. Except for the arch crown, there are no other outer waterproofing layers. To date, no water leakage has occurred in the completed stations after back filling and recharging of groundwater during 1.5 years with two rainy seasons. In addition, long-term monitoring of structural deformation revealed good performance in terms of stability. Figure 10 shows different assembly stages of the station structures.

4.2 Key Technical Research

A complete technological system for prefabricated metro stations was developed, covering design, construction, and component manufacturing. The prefabricated metro station project included six main areas of study, viz. structural selection and mechanical behavior, connection joint technology, key technology for structural waterproofing, construction technology and equipment development, manufacturing technology for large prefabricated components, and multispecialty integration design of prefabricated stations, each of which is discussed in detail below.

4.2.1 Research on Connection Joints between Prefabricated Components

Connection joints between prefabricated components, which affect the comprehensive stress state and load-bearing characteristics of the structure, the manufacturing technique of components, construction assembly process, and waterproofing performance, are a core issue for prefabricated structures. A review of work on joint technology, such as rebar splicing by grout-filled coupling sleeve and composite assembly technology for aboveground structures, prefabricated joint technology for shield tunnels, and cast-in-place and opening inserting joint technology in the former Soviet Union, is presented in Sect. 2. Based on the advantages and disadvantages and adaptability of these previous joint technologies and the characteristics of prefabricated underground structures, the grouted mortise–tenon joint (Fig. 11) was developed to apply as as a simple process offering accurate positioning and rapid assembly for prefabricated structures.

The typical characteristic of the grouted mortise–tenon joint is its variable stiffness under different loading conditions. This increases the complexity of prefabricated underground structures, but makes a significant contribution to effective regulation and optimization of the amplitude of the inner force on the structure (especially bending

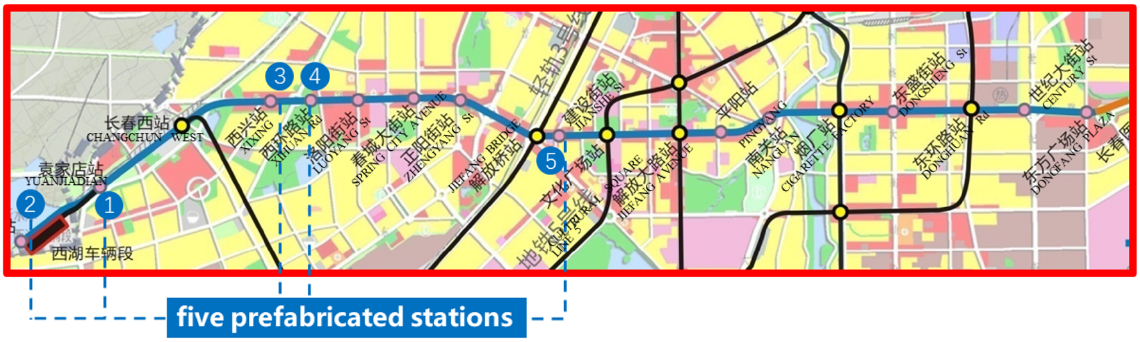

Fig. 8 Five prefabricated stations on Changchun Metro line 2

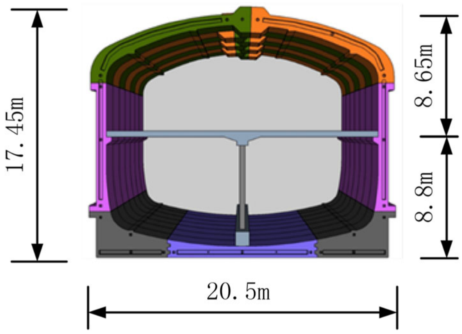

Fig. 9 Sectional diagram of prefabricated station on Changchun Metro line 2

moment). A series of studies including theoretical analysis and 1:1 prototype testing were carried out to discuss the mechanical behavior, stiffness, bearing capacity, reasonable geometric type, grouting mechanism, and waterproofing properties of the grouted mortise–tenon joint, thus obtaining constitutive relations and a design method for the bearing capacity of the joints, thereby providing the theoretical basis for prefabricated technology for metro stations.

4.2.2 Research on Structural System and Mechanical Behavior

The prefabrication aspect as well as the use of nonrigid joints are the key differences in terms of the structural system and mechanical behavior of fully prefabricated underground structures compared with cast-in-place underground structures. Therefore, this research focused on the structural stability and mechanical behavior of the structural system with variable stiffness.

There are many aspects of the stability of structural systems. Firstly, stable mechanical equilibrium should be achieved between the structure and surrounding soil, while additional necessary capacity for the structure should be reserved. Secondly, structures surrounded by soil should retain their statically determinate nature and ensure that components such as baseboards, side walls, arch crown, and floor slab form a statically determinate or indeterminate system. Moreover, local instability problems related to the bearing capacity of single components or the load and deformation capacity of joints must be avoided.

The mechanical behavior of a structural system with variable stiffness is relatively complex. Firstly, the use of nonrigid joints effectively increases the deformability of the structural system. Secondly, the stiffness and bearing capacity of the joints are related not only to the geometric type, but also to the acting axial force. Furthermore, the diversity of geometric types and acting forces can lead to different stiffness in every joint, with a nonlinear constitutive relationship with the acting bending moment and axial force. Therefore, analysis of the mechanical behavior of the structural system should consider all stages from assembly construction to normal service under normal working conditions as well as seismic cases. The behavioral characteristics of the joints and the mechanical behavior of the whole structure during the loading evolution process were thus investigated with multiple iterations according to the properties of the joints.

4.2.3 Research on Seismic Resistance

The seismic behavior of underground structures is better than that of aboveground structures because of the stratigraphic constraints. The dominant factor affecting the response of a structure to an earthquake is the nature of the movement of the soil. The vibration characteristics of the soil were the main concerns of previous studies, whereas research on the seismic behavior of underground structures, particularly prefabricated underground structures, remains at a preliminary stage.

Increasing the ductility of a structure is an important approach to improve the seismic behavior of underground structures. In the event of an earthquake, the nonrigid joints of prefabricated structures increase the deformability of the whole structure, which can decrease the bending moment of joints and adapt to stratum deformation. Moreover, the

Fig. 10 Photos of different assembly stages and decoration rendering of the station floor

(a) Bottom assembly **(b)** Top arch assembly.

(c) Completion of structure **(d)** Construction of floor slab

(e) Decoration rendering of station hall.

structural ductility of prefabricated structures is better than that of traditional cast-in-place structures. In addition, use of a rational structural system can avoid formation of plastic hinges.

Based on these concepts, three key points in the study of the seismic performance of prefabricated underground structures can be identified:

(a) Analysis of the seismic behavior of a structural system under multiple conditions: Extensive numerical simulations of the station structures must be conducted considering different geological conditions, joint properties, and earthquake magnitudes. Investigations of the performance, internal force, and deformation law of the structural system are required. Parallel simulations using different computing software packages should be validated when necessary.

(b) Analysis of the seismic behavior and structure of the joints: The seismic behavior of the joints has two aspects—bearing capacity and deformability (angle

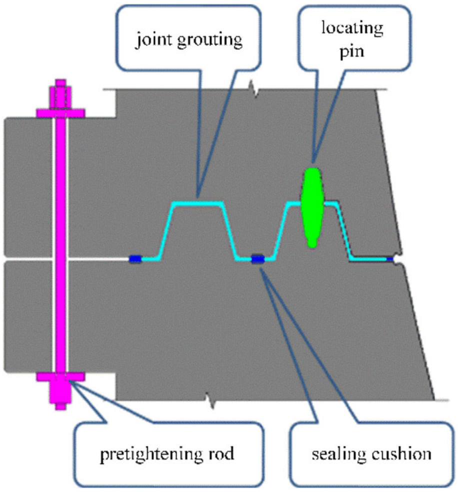

Fig. 11 Schematic diagram of grouted mortise–tenon joint

of rotation). Prototype tests were carried out to study these two aspects. Moreover, the characteristics of a joint depend on its structure, and its geometric type and additional structural measures directly affect the deformability and failure mode of the joint.

(c) Comparative analysis between the prefabricated structures and cast-in-place structures of the same type under static and dynamic conditions: Different characteristics of prefabricated and cast-in-place structures are studied and discussed to validate the technical advantages and characteristics of prefabricated structures.

Research on the main behavioral characteristics and relative technical index of the prefabricated metro station structures on Changchun Metro line 2 fully verified that the seismic behavior of the prefabricated structures meets the performance requirements under earthquakes and the prefabricated structures offer an advantage in terms of reducing the amplitude of the internal force (bending moment). This research also demonstrated the safety and stability of the structural system in the event of an earthquake.

4.2.4 *Research on Waterproofing Technology*

According to the characteristics of the prefabricated technology, the following waterproofing targets were established for the prefabricated metro station structures on Changchun Metro line 2: removing the traditional outer waterproofing layer and meeting or exceeding standard waterproofing specifications for metro stations.

The use of prefabricated components itself solves the problem of structural self-waterproofing. Therefore, the waterproofing of joints is the key aspect to be considered. Many crisscross joints are distributed throughout such structures. Initially, a reliable waterproofing system should be built after rational planning and design of an integral sealing and waterproofing system. Next, the path setting of such a system requires rational planning, especially for parts such as sides, corners, mortise and groove, cross and reserved holes, to ensure that no leakage occurs at the joints and avoid disordered water string in the longitudinal direction.

Joint waterproofing with a high-standard configuration is essential. Our design philosophy is to use a multichannel waterproofing line and active sealing. The specific measures are two cushions, one grout, and one caulking (Fig. 11), viz. two hydroexpansive rubber sealing cushions set up in the joint face, tight filling of the gap between two joint faces with grout, and caulking for drainage in the grooves of the joint surface.

A series of waterproofing tests on joints for the prefabricated metro stations on Changchun Metro line 2 were carried out. The results indicated that one hydroexpansive rubber sealing cushion can bear 80 m head pressure without any leakage when in the worst location (10 mm joint opening and 5 mm dislocation of the other sealing cushion). Moreover, filling the grouting section with a developed modified epoxy resin left no possibility of leakage in theory. In addition, caulking the inner face of the joints has the function of both drainage and surface sealing.

4.2.5 *Research on Lightweight Design of Prefabricated Components*

Generally, underground structures bear huge water–soil pressures, so their components must be large and have high reinforcement ratio, in contrast to aboveground structures. Even when a prefabricated underground structure is divided into multiple components, each of them is still large and heavy, increasing the assembly difficulty and hoisting device requirements. Therefore, lightweight design of components is an important measure to improve the constructability of prefabricated structures.

Using light materials instead of concrete in the interior is an effective way to reduce the weight of concrete components. A closed cavity filled with light materials in the interior (eight dark-yellow blocks in Fig. 12) is proposed according to the mechanical characteristics of the concrete cross-section. Figure 12 shows an axonometric drawing of one such closed-cavity thin-walled component.

Such use of a closed cavity with light materials has a remarkable effect on light weighting the components; For example, before lightweight design, every 2-m segment ring weighs 360 t, with the heaviest and lightest component weighing 65 t and 35.35 t, respectively. After lightweight design, one 2-m segment ring weighs 300 t, achieving an average weight reduction of 16.67%. The lightweight

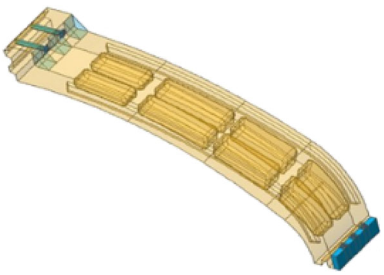

Fig. 12 Axonometric drawing of closed-cavity thin-walled component

components are not only convenient for construction, but also save concrete and rebar consumption. Furthermore, another unexpected benefit has been found in the component manufacturing stage; viz. the hydration heating and cooling downtime of closed-cavity thin-walled component is greatly reduced. Use of lightweight components also avoids cracking when cooling and improves productivity.

However, lightweight design of components certainly increases the difficulty in research, design, and manufacturing. The internal force and stress transfer mechanism and process in the endings, crossbeam, longitudinal ribs, and cavity of such components become more complicated because of the internal closed cavity. Therefore, the mechanical behavior of closed-cavity thin-walled components and the interactions among the internal force, stress–structural scale–component performance must be studied and discussed comprehensively, and the component design method based thereon. In addition, various studies on light materials, molding methods, prevention of water absorbency, and economical efficiency of the core mold in the closed cavity have also been conducted. Evidently, the expected outcomes have been achieved in the applications on Changchun Metro line 2 after such research into and optimization of lightweight components.

4.2.6 Construction Technology and Equipment Development

As a new construction method for prefabricated metro stations, all the processes and steps for the assembly technology should also be taken into account in a scientific and rational way. Key construction stages include scientific and rational process arrangement of assembly construction, hoisting of large prefabricated components, locating approach, assembly line of joints, tensioning, and joint width control.

It is also very important to develop special construction equipment and aided assembly accessories, which include special assembly stair vehicles, support screw jacks, locating rods for components, auxiliary tensioning equipment, special grouting equipment for joints, measuring and positioning systems for components, automatic assembly control systems, etc.

5 Conclusions

The prefabricated underground structures applied in five prefabricated stations on Changchun Metro line 2 demonstrate the feasibility and many advantages of application of such technology for underground metro stations, in particular:

(a) Significantly improved engineering quality
(b) Substantially increased construction efficiency
(c) Enhanced security of engineering construction, as it is well known that the construction risk of underground engineering is high, whereas prefabricated technology can achieve greater security by greatly reducing construction operation steps
(d) Decreased effect on the environment, as site construction steps are prominently reduced or even avoided when using prefabricated technology, while construction noise and dust are remarkably decreased
(e) Labor saving, as at present, a shortage of site construction workers is becoming more prominent with the gradual decrease of China's demographic dividend and continuous rise of the cost of labor, whereas prefabricated technology used in underground engineering can reduce the demand for labor
(f) Overcoming the problems of winter construction delays in cold weather regions

A preliminary analysis of the technical and economic benefits has been carried out based on the prefabricated metro stations on Changchun Metro line 2. Compared with an open-cut double-deck cast-in-place standard metro station of rectangular type with two spans on the same scale, the prefabricated metro station offers the following benefits:

- Saving 4–6 months on the construction period (20–30%)
- Reducing site construction workers from 130–150 to 30 at peak times
- Saving steel consumption of 800 t, wood consumption of 800 m^3, and reducing construction waste by 50%
- Reducing construction space by 1000 m^2.

The above mentioned advantages of using prefabricated technology for underground structures indicate that it has great potential for development and will play an important role in the field of construction industrialization in the future. Moreover, much research work on prefabricated technology systems for underground structures remains to be carried out. The research and application of new prefabricated technology for metro stations in Changchun provides a practical demonstration on the applying prefabricated technology in underground engineering.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no conflicts of interest.

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