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SUPER ENGINEERING

Xiangsheng CHEN, Bo SUN, Wei LI, Yongzhao WU, Wenpeng ZHOU, Meng FENG, Lei WANG, Wensheng YANG, Xiang WU, Weiyi LONG, Dong SU

World’s first implementation of close-fit pipe jacking of twin tunnels for construction of subway station——Innovation in equipment and construction technology

Keywords Subway station, close-fit pipe jacking of twin tunnels, modular rectangular pipe jacking machine, Structural Transformation, equipment, construction

Undertaking Units: Shenzhen Metro Group Co., Ltd.
Design Unit: Shenzhen Municipal Design & Research Co., Ltd.; Construction Contractors: PowerChina Southern Investment Co., Ltd., and Sinohydro Bureau 11 Co., Ltd..; Equipment Manufacturer: China Railway Engineering Equipment Group Co., Ltd.; Technical Support: Shenzhen University

1 Project overview

The Shasan station of Phase II of Shenzhen’s urban rail transit Line 12 is situated in Bao’an District, Shenzhen. It comprises a two-level underground island platform station, measuring 212 m in length, and 22.6 m in width, with an overburden thickness of about 7.0 m. Figure 1 illustrates the presence of a large underground reinforced concrete stormwater culvert, measuring 11.5 m by 3.6 m, traversing the station’s center. The station ends are constructed via the cut-and-cover method, with lengths of 59.6 and 82.4 m, respectively. Meanwhile, the mid-section, which passes under the culvert, employs the pipe jacking method, spanning 70 m. In Fig. 2, the cross-sectional view of the pipe jacking section displays dimensions of 22.6 m in width, 13.53 m in height, and a clear distance of roughly 2.5 m between the station structure’s top and the culvert’s bottom. The primary soil layers at the site, from top to bottom, consist of backfill soil, silty clay, sandy clay, and completely weathered granite. Construction utilized an Earth Pressure Balance (EPB) rectangular pipe jacking machine. Due to the station’s substantial cross-sectional size, a “divide and conquer” construction approach was employed. The station’s cross-section was divided along its central axis into two halves, and rectangular pipe jacking machines were sequentially pushed through to form the left and right tunnels. Subsequently, temporary side walls were eliminated to unify the subway station space. This marks the world’s first subway station constructed using the close-fit pipe jacking of twin tunnels.

2 Technological innovation in the development of large-section rectangular pipe jacking equipment

As illustrated in Fig. 3, the pipe jacking machine employed in constructing Shasan station stands as the world’s largest rectangular pipe jacking machine, boasting dimensions of 11.295 m in width and 13.55 m in height. These measurements surpass the width and height of the

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Xiangsheng CHEN
Shenzhen Univeristy, Shenzhen 518060, China; Shenzhen Metro Group Co., Ltd., Shenzhen 518031, China

Bo SUN, Wei LI
Shenzhen Metro Group Co., Ltd., Shenzhen 518031, China

Yongzhao WU, Wensheng YANG
Shenzhen Municipal Design & Research Co., Ltd., Shenzhen 518000, China

Wenpeng ZHOU, Xiang WU, Weiyi LONG
Sinohydro Bureau 11 Co., Ltd., Zhengzhou 450001, China

Meng FENG
China Railway Engineering Equipment Group Co., LTD. Zhengzhou 450000, China

Lei WANG (✉), Dong SU
Shenzhen University, Shenzhen 518060, China
E-mail: wanglei2020@email.szu.edu.cn

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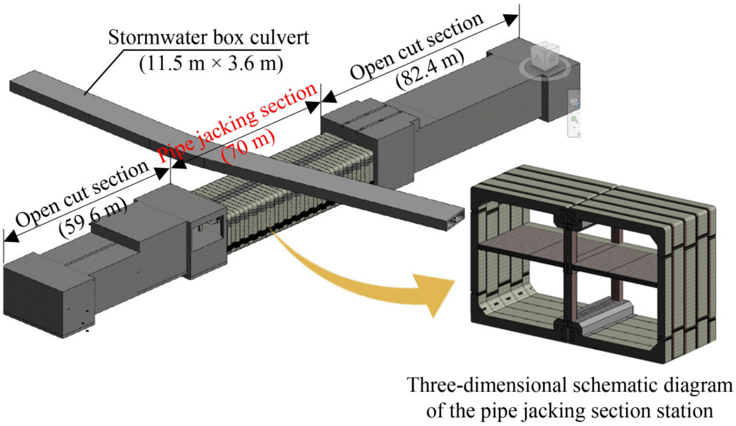


Fig. 1 3D schematic of Shasan station.

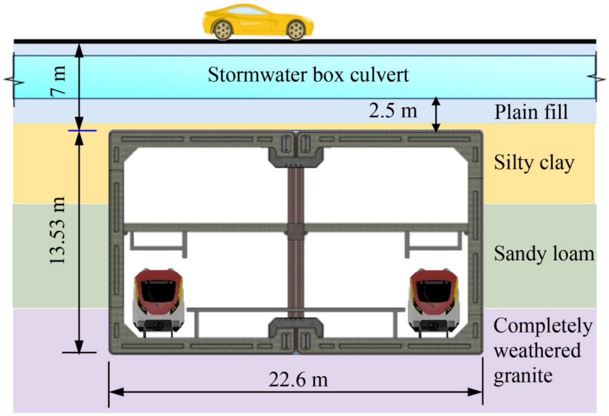


Fig. 2 Cross-sectional view of the pipe jacking section at Shasan station.

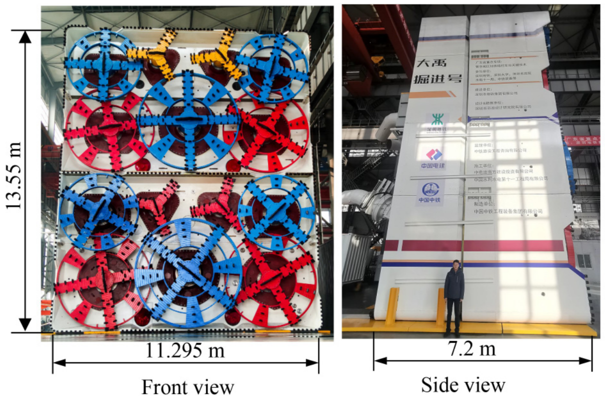


Fig. 3 “Dayu”—The large cross-section modular rectangular pipe jacking machine.

left (right) tunnel sub-structures by 2 cm, respectively. Weighing 950 tons and spanning 7.2 m in length, the pipe jacking machine is longitudinally divided into a front shield and a rear shield. A hinged hydraulic cylinder is positioned between these shields, facilitating adjustments to the pipe jacking machine’s head attitude during the pushing process. The hydraulic cylinder system can exert a maximum pushing force of 103200 kN, while the machine achieves a maximum advance speed of 60 mm/min.

The design of the large-section rectangular pipe jacking machine follows a modular concept, comprising upper and lower sub-machines, each with a height of 6.775 m, as depicted in Fig. 4. Both segments are outfitted with seven cutter heads, featuring diameters that range from 4.8, 4.2, 3.6 to 2.8 m. Each cutter head is independently controlled by motors, and the operational cutting rate of the pipe jacking machine is 88.7%. Employing micro-step excavation technology, the spoil chamber of the pipe jacking machine utilizes a partition plate to segregate the spoil chamber between the upper and lower sub-machines. Each sub-machine incorporates two spiral spoil removal holes, enabling autonomous spoil removal. Additionally, the pipe jacking machine can be disassembled into two independent rectangular pipe jacking machines for utilization in similar sectional underground projects. This strategy enhances the pipe jacking machine’s utilization rate and diminishes the amortization cost of construction machinery.

3 Technological innovations for constructing a subway station by close-fit pipe jacking of twin tunnels

3.1 Segmental technology for large cross-section prefabricated ring segments

For Shasan station, a single ring of rectangular pipe jacking segments boasts dimensions of 11.275 m in width and 13.53 m in height, weighing a total of 212.7 t. These substantial dimensions and weights pose significant challenges for both road transport and lifting operations. Consequently, in the structural design, each single ring segment is divided into four components. These components are prefabricated in the factory, transported to the site, and subsequently assembled through joints

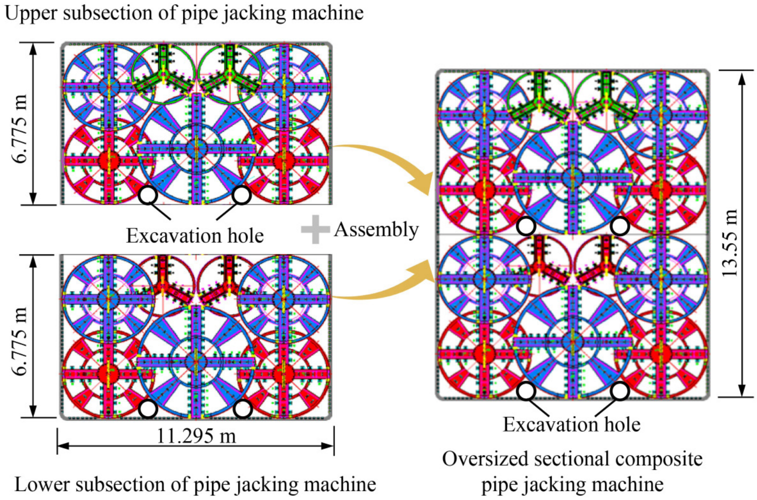


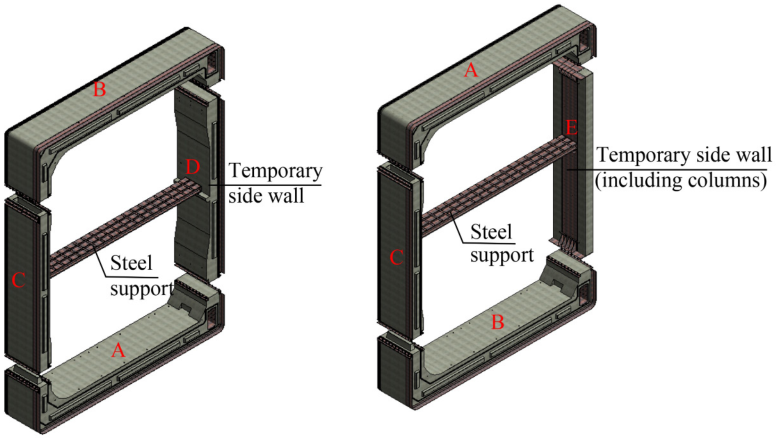
Fig. 4 Assembly scheme for the large cross-section modular rectangular pipe jacking machine.

strategically positioned near the inflection points of the side walls, as depicted in Fig. 5. Structural steel supports are installed in the middle of the side walls to facilitate this assembly process.

The segments are classified into two types: standard rings and column rings. A standard ring comprises components A, B, C, and D, whereas a column ring consists of components A, B, C, and E. The primary distinction between them lies in the temporary side walls of the column rings, which feature structural steel-reinforced concrete columns.

3.2 Connection technology for large cross-section assembled ring segment

As depicted in Fig. 6, the segment joints primarily feature C-shaped steel channels, high-strength bolts, concrete tenons, and mortises. Both the inner and outer sides of the joint are connected by two C-shaped steel channels with high-strength bolts, utilizing ten bolts on each side spaced 200 mm apart. The design of the C-shaped steel channels and high-strength bolts maximizes the strength and ductility of steel, thereby enhancing the bending load-bearing capacity of the joints. Moreover, the bolts can exert pre-tensioning force, bolstering deformation resistance and consequently improving the waterproofing capability of the joints. In the middle of the joint, a reinforced concrete tenon and mortise are positioned. The concrete mortise reinforces the shear resistance of the joint and serves as an aid for assembly positioning, enhancing joint assembly precision. To augment the joint's waterproofing performance, elastic sealing gaskets are situated on both sides of the tenon and mortise. Under axial pressure, the gasket compresses to establish a dual waterproofing system. Additionally, post-assembly, the gap between the tenon and mortise is sealed with grout through grouting pipes, creating a third waterproofing system.



(a) Standard ring (b) Column ring

Fig. 5 Segmental scheme for pipe jacking ring segments.

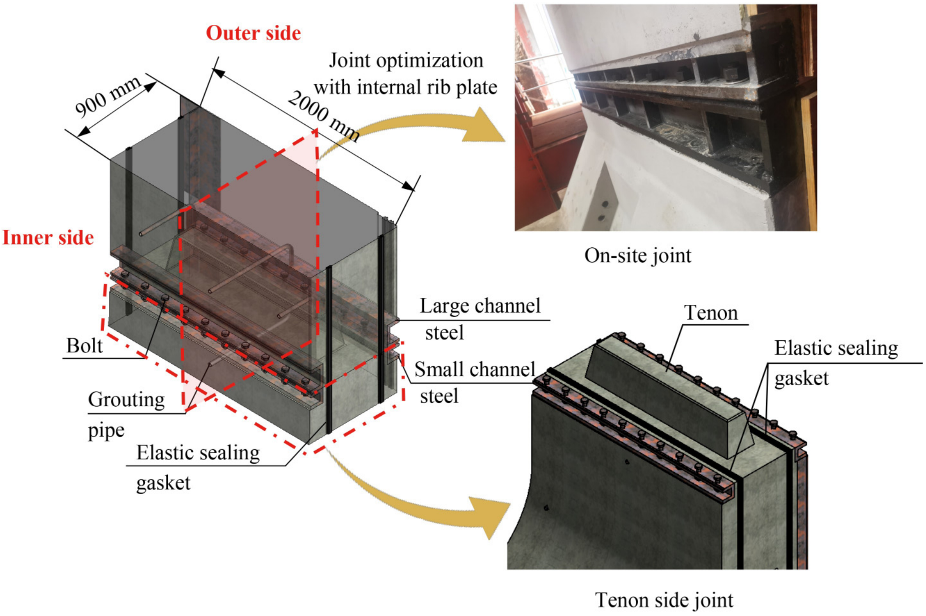


Fig. 6 Structure of the channel steel-bolt joint.

3.3 Assembly technology for large cross-section prefabricated ring segments

Rectangular pipe jacking ring segments are assembled onsite using components prefabricated in the factory. These prefabricated components are relatively small, with the largest single piece weighing up to 72.8 t, facilitating transportation and lifting operations. Illustrated in Fig. 7, on-site assembly involves employing a gantry crane to lift and transport the components to an assembly frame within the launching shaft. During the advancement of the left line tunnel, the right line tunnel's launching shaft area is utilized for assembly, with the assembly area occupying approximately half of the launching shaft's surface area. Assembly frames are positioned on both sides of the segment to ensure stability and also function as platforms for joint assembly operations. Upon assembly completion, the segment is transferred to the jacking area using a rolling platform located at the segment's bottom. It is then propelled forward under the influence of the hydraulic cylinders and U-shaped jacking irons.

3.4 Advanced control technologies for large cross-section rectangular pipe jacking

3.4.1 Advancement and spoil removal

The close-fit pipe jacking of twin tunnels in Shasan station unfolded in two stages: commencing with the advancement of the left line tunnel, followed by the right line tunnel. As illustrated in Fig. 8, during the jacking construction of the left line tunnel, the hydraulic cylinders

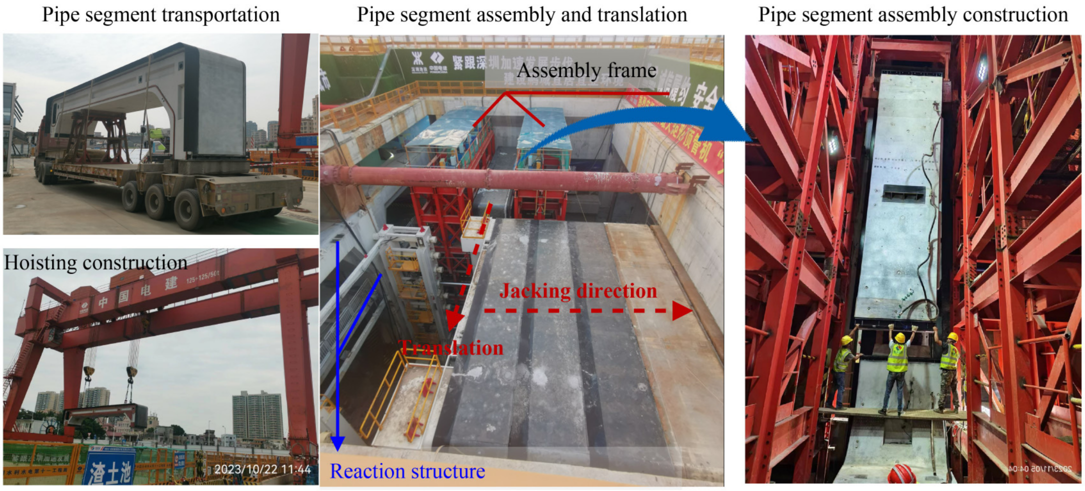


Fig. 7 Assembly technology for prefabricated pipe jacking ring segments.

initially propel the machine toward the excavation face. Subsequently, the cylinders retract, shifting the assembled ring segment to the area ahead of the cylinders, before extending to push the segment forward. The spoil generated by the cutter head during advancement is conveyed to a muck bucket via four screw conveyors. Once the muck bucket reaches capacity, it is transported to the launching shaft area by rail and subsequently hoisted, transported, and discharged into a spoil disposal area using a gantry crane.

3.4.2 Attitude control of machine head

Due to its high width-to-height ratio, the rectangular pipe jacking machine utilized at Shasan station is susceptible to rolling owing to uneven ground pressure on either side of the machine head during advancement. Weighing approximately three times that of the segments, the machine head is prone to "nose diving," a phenomenon exacerbated by its slender shape, which creates significant pressure differentials between the top and bottom of the excavation face. Moreover, during the close-fit advancement construction of the right line, the clear distance between the two tunnels must be meticulously controlled within 5 to 10 cm. Consequently, a series of measures are required to precisely manage the machine head's attitude.

To accurately monitor the machine head's attitude, a visual linear guidance system is employed. A laser theodolite installed on the station's middle plate emits a laser parallel to the design centerline from the open-cut section behind the launching shaft. A dual-screen laser target at the main machine's location captures the angle between the target and the laser in real-time. This data, along with horizontal and vertical deviations at the machine's cutting face and tail, and the machine's pitch angle, is displayed in real-time on the control system interface. A high-precision inclinometer on the front shield continuously monitors the equipment's rolling posture. For close-fit construction of left and right line tunnels, four sets of close-fit construction spacing measurement devices are arranged on both the front and rear shields, as illustrated in Fig. 9. When the machine is stationary, distance detectors measure the gap between the two tunnels.

In terms of controlling the machine head's attitude, aside from conventional measures such as adjusting the thrust of the machine head's hinged hydraulic cylinders and the jacking hydraulic cylinders in the launching shaft, additional corrective measures are employed. The machine is equipped with four sets of independently controllable screw conveyor spoil removal systems, two sets each for the upper and lower sub-machines. By regulating the direction and speed of different screw conveyors, the distribution of soil pressure in the spoil chamber is adjusted, aiding in corrective adjustments of the machine head's direction. The machine features 14 cutter heads symmetrically arranged about its central axis, with each head's rotation direction independently controllable. During normal advancement, the cutter heads on either side rotate in opposite directions to balance soil reactive forces. For corrective adjustments, the cutter heads can rotate in the same direction to generate torque, aiding in correction. Additionally, correction grouting holes are preinstalled on both sides of the machine. In case of rolling deviation or centerline deviation, the grouting pressure difference between upper and lower grouting holes can be adjusted to correct the machine's attitude.

3.4.3 Friction reduction technology for advancement

Reducing friction is paramount for advancing large cross-section rectangular pipe jacking, addressing both circumferential friction around the pipe and friction on the machine's surface. To alleviate circumferential friction, each ring segment features 24 friction-reducing slurry injection holes distributed around its perimeter, as depicted in Fig. 10. These holes inject friction-reducing

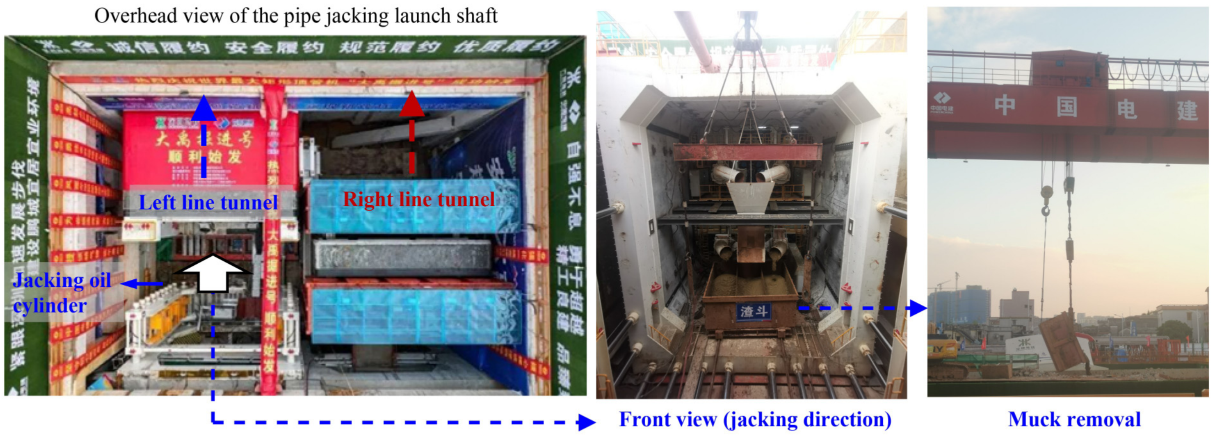


Fig. 8 Advancement pipe jacking ring segments and spoil removal.

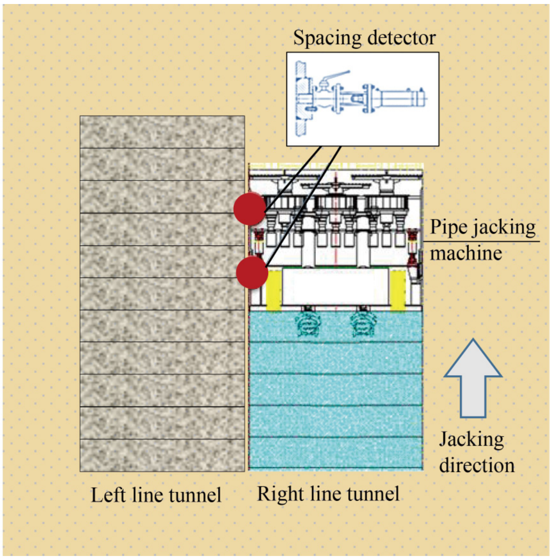


Fig. 9 Spacing detection device for close-fit construction of twin rectangular pipe jacking tunnels.

slurry during segment advancement, forming a lubricating slurry sleeve around the pipe. This alteration shifts the frictional contact from pipe-soil to pipe-slurry-soil, markedly diminishing resistance to advancement. Moreover, the substantial surface frictional resistance between the rectangular pipe jacking machine and the ground is a significant consideration. At shallow depths, this friction can induce the soil above to move forward, resulting in a "carrying-soil effect" that triggers soil heave in front of the excavation face and settlement behind the machine head. To counteract this effect, 34 friction-reducing slurry injection holes are strategically positioned around the front and rear shields. Before segment assembly and machine reactivation, an appropriate amount of friction-reducing slurry is injected around the machine head to diminish soil-machine friction.

By implementing these innovative technologies, the close-fit advancement construction of the large cross-section left and right line rectangular pipe jacking at Shasan station was accomplished successfully. The distance between the left and right tunnels was meticulously controlled within 10 cm, fulfilling the project's objectives of constructing a subway station using the twin tunnel close-fit pipe jacking method. This achievement is depicted in Figs. 11 and 12.

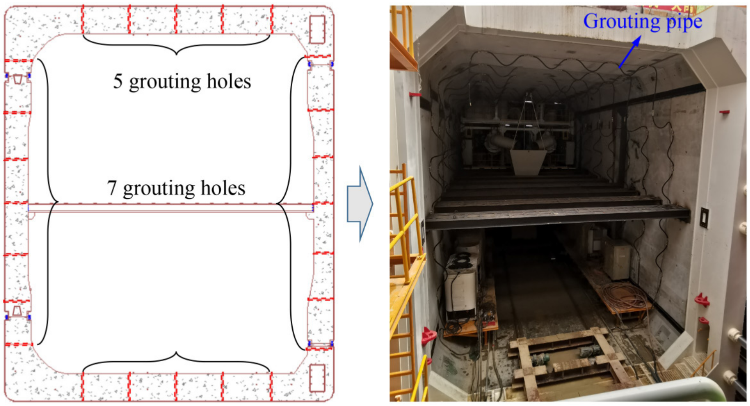


Fig. 10 Layout of friction-reducing slurry injection holes around the ring segments.

(a) Receiving of the left line rectangular pipe jacking machine

(b) Receiving of the right line rectangular pipe jacking machine

Fig. 11 Receiving of rectangular pipe jacking machines for the twin tunnels at Shasan station

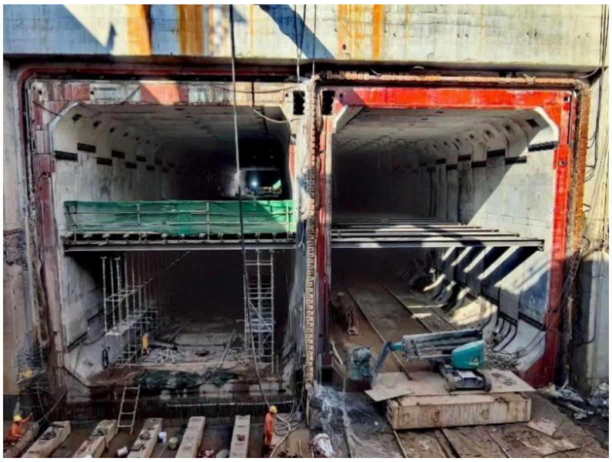


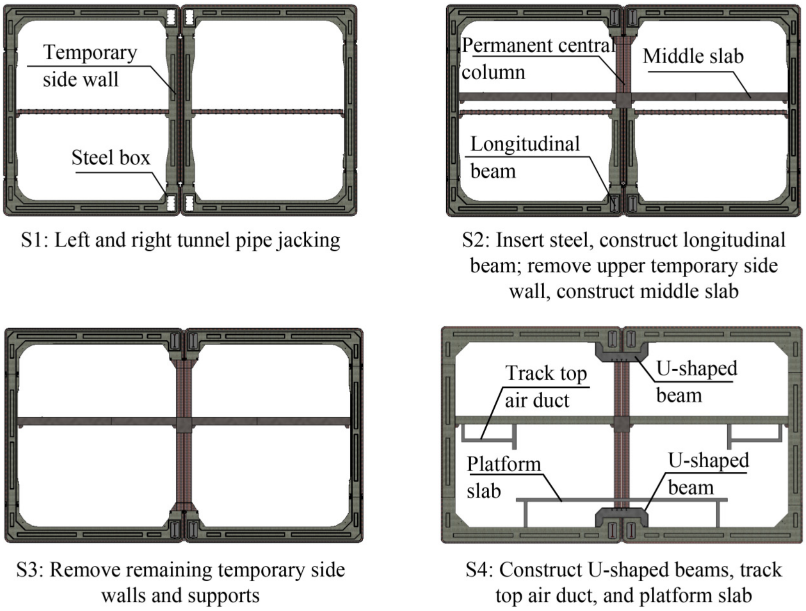
Fig. 12 Breakthrough of the twin tunnels at Shasan station.

3.5 Temporary to permanent structure conversion technology

Following the twin tunnel pipe jacking breakthrough, a structural conversion is imperative to transition the closely fitted twin tunnel rectangular pipe jacking (temporary) structure into a unified subway station (permanent) structure. This conversion includes both vertical and horizontal structural coversions, detailed in the construction procedure depicted in Fig. 13. Vertical structural conversion entails shifting the support of the tunnel's top and bottom plates from temporary side walls to longitudinal beams and columns. I-beams are inserted into pre-embedded steel boxes in the top and bottom plates, followed by concrete pouring to create steel-reinforced concrete longitudinal beams. Removal of the temporary side walls, while retaining the steel-reinforced concrete core columns of the column rings, finalizes the vertical structural component conversion. Horizontal component conversion involves transitioning the temporary horizontal steel supports in the tunnel sidewalls to the station's middle plate supports. The temporary steel supports, slightly lower than the station's middle plate, provide space for plate construction during the conversion. Initially, the temporary side walls above the supports are removed, utilizing the temporary steel supports as formwork supports for pouring the station's middle plate. Upon meeting the design requirements for plate strength, the temporary steel supports and remaining temporary side walls are removed, completing the conversion of the station's horizontal load-bearing components. Utilizing temporary supports as formwork for middle plate pouring obviates the need for extensive scaffolding, facilitating time and cost savings in construction. Figure 14 presents a 3D schematic of the permanent station structure, featuring staggered joint heights in both horizontal and vertical directions to prevent the formation of shear weak planes.

4 Conclusions

The completion of the Shasan station within Phase II of Shenzhen's urban rail transit Line 12 marks a historic milestone as the world's inaugural subway station constructed using the twin tunnel close-fit pipe jacking method, employing the largest cross-section rectangular pipe jacking machine ever utilized. This project's execution has been instrumental in propelling advancements in equipment for large cross-section rectangular pipe jacking



S1: Left and right tunnel pipe jacking

S2: Insert steel, construct longitudinal beam; remove upper temporary side wall, construct middle slab

S3: Remove remaining temporary side walls and supports

S4: Construct U-shaped beams, track top air duct, and platform slab

Fig. 13 Construction procedure for the Shasan station.

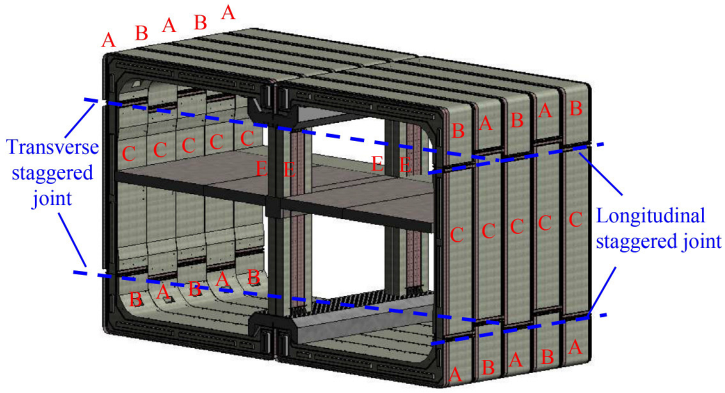


Fig. 14 3D schematic of the station structure after structural conversion.

and innovations in control technologies for large cross-section rectangular pipe jacking advancement, notably the twin tunnel close-fit advancement technology, and underground structure system conversion technologies. As a transformative methodology for subway station construction, the twin tunnel close-fit pipe jacking method addresses the challenges inherent in traditional open-cut methods, such as extensive demolition work, public disturbance, and traffic disruption. It notably elevates the engineering technical proficiency and equipment developing and manufacturing capabilities within the realm of underground construction, thereby catalyzing the expansion and technological progression of related industrial chains.