On transfer technology of drilling-blasting construction method and shield construction method at the interface of a subsea tunnel and its application

B. Du, C. Song & W. He  
*China Railway Liuyuan Group Co., Ltd, Tianjin, China*

K. Li  
*China Railway First Group Co., Ltd, Xi’an, China*

**ABSTRACT:** As for the running tunnel section between Wuyuanwan station-Liuwudian station of Xiamen metro line 3, the construction method of “dismantling shield in the subsea first, and continually excavating the rest of section by the drilling-blasting method” is adopted. It is required to overcome such technical difficulties as shield dismantling in a confined space, long-distance single-line transportation, long-distance blind ventilation, protection of formed segments, waterproofing of joint structures, etc. The paper systematically expounds the transfer technology of various construction methods in Wuyuanwan station-Liuwudian station section and mainly introduces the solutions to the above construction difficulties. It has been proved in practice that this technology can greatly improve the construction progress under the premise of guaranteeing construction safety and structural function completeness, having reference significance for the subsea tunnel constructed by multiple combined method.

**1 INTRODUCTION**

At present, the main methods of building subsea tunnels in China are drilling-blasting method, shield method and immersed tube method, which are applicable to different hydrological-geological conditions and have their own representative projects. For example, Qingdao Jiaozhouwan tunnel and Xiamen Xiang’an tunnel were constructed by drilling-blasting method, Shiziyang tunnel of Guangzhou-Shenzhen-Hong Kong high-speed railway and Shantou Suai tunnel were constructed by shield method, and Hong Kong-Zhuhai-Macao Bridge and Shenzhen-Zhongshan Bridge were constructed by immersed tube method. The development of subsea transfer technology for long tunnel with single construction method is relatively mature (Du, 2014; Zhang, 2015). In addition, running tunnel section between Wangjiawan station-Zongguan station of Wuhan Metro Line 3 was constructed by Mining Method + Shield Method (Yang, 2017). The mine expansion cavern was built at the position of complete bedrock and filled with low-strength plain concrete. The underwater reception was realized by tunneling with a shield machine. However, there are few case studies of subsea tunnel in which the drilling-blasting method is used to continually excavate the rest of section after shield dismantling in the subsea. This method has technical difficulties such as shield dismantling in limited space, long-distance single line transportation, long-distance one-end ventilation, formed segment protection, and joint structure waterproof.
2 PROJECT PROFILE

The running tunnel section between Wuyuanwan station-Liuwudian station of Xiamen Metro Line 3 is located 1.3 km to the northwest of Xiang’an tunnel, crossing the east sea of Xiamen and connecting main island and Xiang’an district. The total length is 4.9 km, and the subsea section is about 3.6 km. The tunnel plane is shown in Figure 1.

![Figure 1. Plane position drawing of WuLiu subway tunnel.](image1)

The geological conditions of the strata traversed by the running tunnel section are complex. As shown in Figure 2, the tunnel section in the inland region of island is mainly residual soil and fully-strongly weathered granodiorite strata. Most tunnel sections in the sea area are weakly weathered granodiorite strata and four groups of deep weathered slots. The quartz content of weakly weathered bedrock is high, with an average strength of 110 MPa. The section of Xiang’an side tunnel is mainly composed of medium coarse gravel sand and fully-strongly weathered granodiorite. The strata is highly permeable and hydraulically connected with seawater.

![Figure 2. Geological section drawing of WuLiu subway tunnel.](image2)

The construction method of WuLiu section is adopted according to local conditions. The inland region of island is constructed by earth pressure balance shield method. The inner diameter of tunnel is 5.5 m and the single line length is 869 m. The bedrock surface of the middle sea area is relatively high, and the drilling-basting method is adopted. The horseshoe compound lining structure is selected, and the single line length is 2602 m. Xiang’an side tunnel is constructed by slurry balanced shield method. The inner diameter of tunnel is 6 m, and a 250 mm space is reserved for secondary lining. The single line length is 1451 m. The drilling-blasting tunnel starts from the shaft on the shore of main island, and the slurry shield tunnel starts from the Xiang’an Liuwudian station. The two tunnels are constructed toward each other and transferred in the sea area.
The geological conditions of the cross-sea tunnel are extremely complex, and there are many uncertain factors in the construction process of shield tunnel and drilling-blasting tunnel, so the construction schedule is not stable and it is difficult to ensure that the scheduled docking point is reached at the same time. On the other hand, subject to the strata adaptability of different construction methods, the docking points cannot be changed at will. Reasonable solution of this contradiction is the key to ensure the goal of the construction process.

The construction of slurry shield in WuLiu section reached the scheduled docking point in July 2018. At this time, the drilling-blasting tunnel was affected by the construction progress of weathered slot, and there was still 1.5 km to be completed. Therefore, the scheme of construction method transfer was developed: the shield machine was dismantled in situ, and the tunnel face was excavated by drilling-blasting method continually (this working face is called the receiving side) until the tunnel was transfixed.

The steps of construction method transfer include: (1) Determining a section with relatively complete bedrock as the construction method transfer point, and reviewing the geological conditions of the working face by means of geophysical exploration, advanced drilling, observation in bin; (2) The shield machine and adjacent segments were backside grouting, mechanical tensioning and welding; (3) Dismantling the shield machine in situ, and retain the outer shield shell; (4) Using the formed shield tunnel to build ventilation, drainage, power supply and transportation facilities required by drilling and blasting construction; (5) Under the premise of taking effective protection measures for the formed segments and shield shell, the controlled blasting excavation is carried out; (6) The permanent structure of the construction method transfer section is constructed, and the mining tunnel lining, shield shell and shield segment are connected as a whole. The overall execution steps are shown in Figure 4.

### 4 SCHEME OF SHIELD DISMANTLING IN TUNNEL

#### 4.1 Parameters of shield machine

Herrick air-cushion slurry balanced shield machine (S-1058) is used in the WuLiu section, the total length of the shield machine is 107 m and the total weight is 750 tons. The main shield is 11.3m long and consists of a front shield, a middle shield and a tail shield. The middle shield and the tail shield are connected by passive hinged connection. The cutter head is of spoke-panel composite style, and the diameter is 7020 mm. It is equipped with 133 kinds of cutters,
including 43 hobs. The rear complement is equipped with 6 pallet cars, the total length is about 94m and the weight is about 295 tons.

4.2 Preparation before dismantling

The following preparations should be made before the shield dismantling: (1) empty the excavation bin and slurry pipeline, (2) complete the relevant reinforcement measures, such as grouting behind the segment, segment longitudinal tension. The gap between the tail shield and segment is closed by annular steel plate, and injected with micro expansion cement slurry to make it compact. The hinged pin between the middle shield and the tail shield is fixed by welding, (3) complete the cleaning and labeling of mechanical parts to facilitate reassembly, (4) build temporary facilities of wind, water and electricity for fire work, and pay special attention to ventilation conditions in the tunnel (Li et al., 2015).

4.3 Scheme of dismantling

Shield dismantling generally follows the sequence from back to front and from inside to outside. Firstly, the thrust oil cylinder is removed, and the system of wind, water and electricity is cut off. Then, it is removed according to the sequence of rear complement pallet cars - segment assembling machine and walking beam - H frame - slurry pipeline - person bin and material bin - cutter motor - gravel crusher - cutter and main drive (Fang and Hong, 2012; Zhang and Zhang, 2014).
The rear complement is divided into 1 group every 2 sections, which is separated into 3 times to drag out of the hole. The outer track of the pallet cars is generally only 200 m long, so the rear track needs to be removed to lay the front track, which is used in this cycle.

The main shield and cutter of the shield are dismantled in the tunnel, and the vertical movement is completed by using the inverted chain. The rail flat car is used to transport main shield and cutter out of the tunnel, as shown in Figures 5. The cutter is segmented into 13 pieces. Firstly, pieces No. 4, No. 8 and No. 12 are welded and fixed with the shield body. Then, pieces No. 5, No. 6 and No. 7 are segmented, and the lower space is used as a sliding rail and fixed bracket. The cutter is segmented in symmetrical blocks from top to bottom, and finally pieces No. 4, No. 8 and No. 12 are segmented in sequence, and the center piece (piece No. 0) is transported out, as shown in Figure 6.

5 SCHEME OF DRILLING-BLASTING METHOD TRANSFER

5.1 Construction transportation

To save project cost and avoid duplicate construction, the track-bed backfill is used as trackless transportation pavement after the retesting of shield tunnel alignment. According to the requirements of building limits and vehicle limits, the backfill height does not exceed 600 mm, which can form a traffic space with a width of 3.6 m and a height of 4.2 m, as shown in Figure 7. After the civil construction is completed, only the road surface needs to be chiseled and cleaned before the roadbed structure can be constructed.

As shown in Figure 8, there is a cross passage at 15 m behind the tunnel face of the receiving side in the WuLiu section. Taking this as the dividing point, the construction transportation at the receiving side is divided into 2 stages: Before the construction of the cross passage, the tunnel solo shall be excavated for 15 m. The vehicle reverses to the tunnel face, and drives out of tunnel in the forward direction after loading muck. After the construction of the cross passage, the vehicle can be turned around through the passage to achieve normal driving. At the same time, the left line working face (back row hole) is opened to facilitate the reception of shield machine in the left line, and the dismantling efficiency can be greatly improved.

5.2 Construction ventilation

According to the ventilation method, the ventilation at the receiving side is divided into 2 stages: the air is supplied by wind pipe before shield dismantling in the left line. After the shield arrived and dismantled in the left line, the cross passage is used for alleyway type ventilation (Liu, 2001). Two axial fans with 1.2 m diameter wind pipes are used in the right line to press the air to the excavation face. There is a jet fan behind the cross passage in the right line. The jet boost is used to force the dirty air to enter the left line through the cross passage, forming an air flow circulation system, as shown in Figure 8.
5.3 Construction drainage

The sources of wastewater are mainly construction water at the tunnel face, structure leakage water (mainly the extension seepage of the drilling-blasting method) and water from the advanced exploration holes at the tunnel face. The water volume of the first two changes little, which can be predicted and controlled. While, once the advanced exploration hole penetrates the water layer or the fissure zone, it is difficult to control the sudden water bursting. At the drilling-blasting tunnel in WuLiu section, under the same geological conditions, the water yield from the drilling hole once reached 120 L/min, and the water pressure was 0.6 MPa, which basically reached the hydrostatic head pressure of the sea surface. Therefore, the temporary drainage must take account of the condition of the sudden water in the drilling hole.

The wastewater of the receiving section adopts 2 stage improvement, and sedimentation tank and transfer tank are set in the cross passage, and the construction wastewater is reused or discharged after reaching the standard through the tunnel face water collection pit - transfer tank - wastewater treatment station. The pump flow at the tunnel face and transfer point is not less than the predicted water volume, and all of them are one for use and one for standby. The effective volume of the transfer pumping station is not less than the pumping capacity of one pump for 10 min.

5.4 Protection measures for blasting construction

The working face of continually drilling-blasting method is about 1.5 m from the shield shell cutting ring (cutter height + expansion) and about 10.5 m from the tail shield segment. Blasting vibrations and flying rocks may cause damage to existing structures. Thus, vibration damping and protection measures must be taken.

Vibration control standards refer to “Safety Regulations for Blasting” (GB6722-2014). The vibration control value of the existing traffic tunnel is 12~15 cm/s for underground deep hole blasting, but the shield tunnel at the receiving side is not yet sealed. The vibration speed shall be reduced as much as possible on the basis of meeting the construction requirements. Blasting vibration control measures (Yang and Zhang, 2010) mainly include: (1) Shortening the excavation footage: it is estimated that the single section of the trenching hole in the first cycle is 0.9 kg, the footage is 0.6 m, and the vibration velocity of adjacent segments is about 5 cm/s. (2) Control the interval of blasting segment: electronic detonators are used for cutting holes, and 1~19 segments of high-precision detonators are used for auxiliary holes, and the detonators are detonated by jumping sections. (3) Optimize the arrangement of shell holes: according to the field monitoring results, the peripheral damping holes are added.

Anti-flying stone measures (Li, 1999) mainly include: (1) Before each blasting construction, two layers of protection shall be hung between the cutting ring and the tunnel face. The first layer is wire rope net with aperture of 90 mm × 90 mm. The 8 evenly distributed points around are fixed with auxiliary steel hooks welded on the shield shell. In addition, the wire rope net is covered with waste tires, as shown in Figure 9.
This protection layer can block large pieces of debris and some small diameter flying stones. The second layer is the blasting cover, which can be used as waste quilt or tire woven fabric, and this protection layer can block the remaining smaller particles flying out. (2) The blasting cover is used to cover the inside of the shield shell and the adjacent 20 segments, and the blasting cover on the side wall and vault is fixed by using the bolt hand hole.

Under the above measures, the site blasting construction progresses smoothly, and no damage or cracks are found in the existing structure. The displacement monitoring results are normal, and the protection means receive good results.

6 JOINT STRUCTURE AND WATERPROOF

As shown in Figure 10, the structure of construction method transfer is divided into three sections: (1) Horseshoe lining reinforced section: the initial support of the drilling-blasting tunnel within 10 m of the shield shell is added with grille arch frame on the basis of shotcrete concrete. (2) Shield shell + mold build lining: the tunnel section structure from outside to inside is: outer grouting filling layer of shield shell, shield shell, 100mm shotcrete concrete screed-coat, waterproof layer, reinforced concrete lining. The inner diameter of the forming tunnel is 5.5 m. (3) Segment + mold build lining: within the range of 6~7 ring pipe pieces at the tail shield, 250 mm space is reserved for reinforced concrete lining by using the clearance in the shield tunnel. The inner diameter of the forming tunnel is 5.5 m.

Figure 9. Flying stone protection facilities.

Figure 10. Elevation drawing of construction method transfer structure.

The last ring of tail shield adopts a special segment with steel plate pre-embedded in the side, so as to make a boot-shaped ring beam at the lock position later, and solve the fixing and waterproofing problem of the tail end of shield tunnel. The ring beam reinforcement and embedded
steel plate are welded and connected with the shield shell in situ, and two rubber water stop belts and repeatable grouting pipes are embedded in the joint position, as shown in Figure 11.

The construction method transfer section is the key of the construction process transformation and structural section change of the tunnel, and also the weak of the force and waterproof of the whole tunnel structure, especially the shield shell section. The grouting compactness behind the shield shell section has a great influence on the structural stability. The longitudinal stiffness and the waterproof performance of the tunnel can be increased by constructing the whole cast-in-situ lining in the whole construction method transfer and the extension section on both sides.

7 CONCLUSION

For tunnel engineering, especially the cross-sea tunnel, it is not uncommon to see great difference in site range and strata. It is a recommended solution to combine two or more construction methods. Based on the engineering case of WuLiu section of Xiamen Metro Line 3, this study introduces a construction method transfer technology which adopts drilling-blasting method to continually excavate after the shield dismantling, and discusses the key links and special schemes of the process respectively. The tunnel was successfully completed in September 2020. After applying transfer technology, the connecting side extended into the sea for nearly 500 m, greatly alleviating the construction period pressure and achieving the expected goal of the scheme.

The technical experience of engineering can not only provide reference for similar tunnel construction of multi-method combination, but also the shield dismantling technology, auxiliary ventilation and transportation technology can be applied to the temporary inclined shaft of shield method construction, and the shield docking in the ground.

REFERENCES