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Typical Underwater Tunnels in the Mainland of China and Related Tunneling Technologies

Kairong Hong

State Key Laboratory of Shield Machine and Boring Technology, China Railway Tunnel Group Co., Ltd., Zhengzhou 450001, China

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ABSTRACT

In the past decades, many underwater tunnels have been constructed in the mainland of China, and great progress has been made in related tunneling technologies. This paper presents the history and state of the art of underwater tunnels in the mainland of China in terms of shield-bored tunnels, drill-and-blast tunnels, and immersed tunnels. Typical underwater tunnels of these types in the mainland of China are described, along with innovative technologies regarding comprehensive geological prediction, grouting-based consolidation, the design and construction of large cross-sectional tunnels with shallow cover in weak strata, cutting tool replacement under limited drainage and reduced pressure conditions, the detection and treatment of boulders, the construction of underwater tunnels in areas with high seismic intensity, and the treatment of serious sedimentation in a foundation channel of immersed tunnels. Some suggestions are made regarding the three potential great strait-crossing tunnels—the Qiongzhou Strait-Crossing Tunnel, Bohai Strait-Crossing Tunnel, and Taiwan Strait-Crossing Tunnel—and issues related to these great strait-crossing tunnels that need further study are proposed.

1. Introduction

China has ~18 000 km of land coastline and ~14 000 km of sea island coastline. There are more than 11 000 islands in China, of which 6536 have over 500 m^2 area each and 455 have residents [1]. Due to the restraints caused by the numerous bays and straits, the economic development in local areas is not very balanced and the transportation cost is high. Furthermore, China has many inland rivers, including 28 major rivers. Due to the restraints caused by the rivers, the urbanization on both sides of the rivers has been severely impacted. As China's economy develops, it is highly necessary to build fixed links crossing such rivers, lakes, and seas. Due to the fact that China has a large population and a relatively small per capita land area, tunnels have obvious advantages when such fixed links are built. According to statistics, more than 100 tunnels have been built crossing underneath rivers, lakes, and seas around the world in the 20th century [2].

2. History and the state of the art of underwater tunnels in the mainland of China

2.1. Shield-bored tunnels

In May 1965, the construction of Dapu Road Tunnel crossing Huangpu River began; this was the first river-crossing tunnel in the mainland of China. Dapu Road Tunnel is 2761 m long, with over 600 m of its length passing under Huangpu River. The tunnel was completed and put into operation in June 1971 (Fig. 1). Since then, numerous shield-bored tunnels have been built to cross rivers, lakes, and seas. These tunnels are used for subways, railways, highways, water delivery, oil/gas supply, power supply, and so forth. The diameter of these shield-bored tunnels ranges from 2.4 m to 15.6 m. For example, Shanghai Yangtze River Tunnel, which is used for highways and subways, had the largest diameter in the world at the time of its construction, and Shiziyang Tunnel is used for the Guangzhou–Shenzhen–Hong Kong High-Speed Railway, which operates at a speed of 350 $km \cdot h^{-1}$. Most of these shield-bored tunnels have twin tubes (with one floor or double floors), although some shield-bored tunnels have only one tube with double floors used for highways (such as Shangzhong Road

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E-mail address: ctg_kr@vip.163.com

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Fig. 1. Dapu Road Tunnel in Shanghai.†

Fig. 2. Transportation of an immersed tube by controlling the hauling cable of the winch at the river bank.

Tunnel in Shanghai). These shield-bored tunnels pass through typical ground conditions, such as the soft strata of East China, the boulder strata of Chengdu and Lanzhou, and the composite ground of South China with its extreme strength changes and high strength. Su'ai Tunnel, which is currently under construction, is a sea-crossing shield-bored tunnel with great challenges.

2.2. Immersed tunnels

Yong River Underwater Tunnel in Ningbo was the first immersed tunnel used for traffic in China; it has one tube with six bidirectional lanes. The tunnel is 1019 m long, with an underwater section that is 420 m long and consists of four 85 m immersed tubes and one 80 m immersed tube. The immersed tubes are 11.9 m wide. The construction of Yong River Underwater Tunnel began in June 1987; the tunnel was completed and put into operation at the end of September 1995. The construction of Pearl River Tunnel in Guangzhou began in October 1990 and ended in December 1993. This tunnel is 1380 m long and 33.4 m wide, with an immersed section that consists of five immersed tubes with a total length of 457 m. The tunnel has three tubes; the west two tubes are used for bidirectional four-lane highways and the east tube is used for a double-track subway. The immersed tubes are composed of a reinforced concrete structure. Most of the immersed tubes are transported and sunken by controlling the hauling cable of the winch at the river banks, and are connected using water pressure (Fig. 2). Since then, 11 immersed tunnels have been built (Table 1).

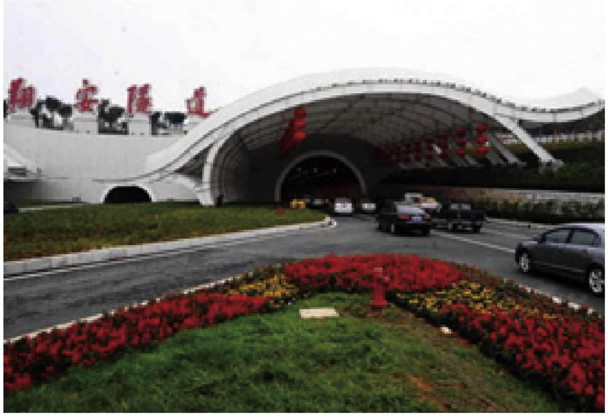

Fig. 3. Xiang'an Tunnel in Xiamen.‡

2.3. Underwater tunnels built by the drill-and-blast method

Xiang'an Tunnel in Xiamen was the first subsea tunnel built by the drill-and-blast method in China. The construction of the tunnel began in September 2005, the tunnel was broken through in November 2009, and the tunnel was put into operation on 26 April 2010 (Fig. 3). Since then, several underwater tunnels have been built by the drill-and-blast method (Table 2).

2.4. Technologies for underwater tunnels in China

With the development of China's economy and urbanization, the rate of construction of underwater tunnels is increasing. According to statistics, more than 100 underwater tunnels have been built in China, and more than 20 underwater tunnels are currently under construction in China. These underwater tunnels are mainly constructed by the shield method, with 13 underwater tunnels being constructed by the immersed tunnel method and only three being constructed by the drill-and-blast method. Some special underwater tunnels are constructed by the "drill-and-blast plus shield method."

Breakthroughs have been made in the following key technologies [3]:

(1) Regarding underwater tunnels built by the drill-and-blast method, comprehensive advanced geological prediction technology has been developed, and advanced consolidation and radial seepage-reducing and grouting technology have been innovated; these provide solutions that allow underwater tunnels to cross fault and fracture zones and weathered deep troughs, and ensure construction safety. For urban underwater tunnels located in soft surrounding rocks, a method to define the minimum overburden under the prerequisite engineering measures has been established, a deformation control standard based on the construction steps has been determined, and an underwater interchange tunnel with a span of 25 m, a cross-sectional area of 376 m^2, and an overburden/span ratio of 0.46 has been built.

(2) Regarding shield-bored tunnels, breakthroughs have been achieved in the manufacturing and application of shields with greater than 15 m diameter and in the technology of boring large cross-sectional shields in soft/hard heterogeneous ground, ground with weathered sphere-shaped granite, ground with large

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† http://news.yantuchina.com/19764.html.

‡ http://money.163.com/10/0427/07/658QJMM000253B0H.html.

Table 1
Immersed tunnels in the mainland of China.

Number	Tunnel	Main structure	Year of completion
1	Yong River Underwater Tunnel in Ningbo	Bidirectional, six lanes in one tube	1995
2	Pearl River Tunnel in Guangzhou	Bidirectional, four-lane highways and a double-track subway	1993
3	Changhong Tunnel in Ningbo	Bidirectional, four lanes	2002
4	Waihuan Tunnel in Shanghai	Bidirectional, eight lanes in three tubes	2003
5	Luntou–Bio Island Tunnel in Guangzhou	Bidirectional, four lanes	2010
6	Bio Island–University City Tunnel in Guangzhou	Bidirectional, four lanes	2010
7	Hai River Tunnel in Tianjin	Bidirectional, six lanes	2011
8	Zhoutouzui Tunnel in Guangzhou	Bidirectional, six lanes	2015
9	Dongping Tunnel in Foshan	Bidirectional, six lanes and a double-track subway	2017
10	Shenjiamen Port Subsea Tunnel in Zhoushan	Bidirectional passenger way	2014
11	Hong Kong–Zhuhai–Macao Link Tunnel	Bidirectional, six lanes	Under construction
12	Honggu Tunnel in Nanchang	Bidirectional, six lanes	2017
13	Dalian Bay Subsea Tunnel	Bidirectional, six lanes	Under construction

Table 2
Underwater tunnels built by the drill-and-blast method in the mainland of China.

Number	Tunnel	Main structure	Year of completion
1	Xiang'an Tunnel in Xiamen	Twin tubes with six lanes	2010
2	Jiaozhou Bay Subsea Tunnel in Qingdao	Twin tubes with six lanes	2011
3	Liuyang River Tunnel on the Wuhan–Guangzhou High-Speed Railway	Single tube, double-track railway tunnel	2009
4	Liuyang River Tunnel in Changsha	Twin tubes with four lanes	2009
5	Yingpan Road Xiang River-Crossing Tunnel in Changsha	Twin tubes with four lanes	2011
6	Jiaozhou Bay Subway Tunnel in Qingdao	Single tube, double-track subway tunnel	Under construction
7	Haicang Tunnel in Xiamen	Twin tubes with six lanes	Under construction

boulders, ground with high water pressure (0.9 MPa), and so forth [4]. In addition, drainage-limited pressure-reduced cutting tool replacement technology and shield docking technology have been developed, and a technology to replace cutting tools under atmospheric pressure has been innovated.

(3) Regarding immersed tunnels, technologies for pre-casting, transporting, and sinking immersed tubes by means of mobile dry docks have been developed; a technology to construct long immersed tunnels under deep cover in the sea has been innovated; and a large-scale immersed tunnel has been built to cross rivers with high water level fluctuations and high water flow rates [5].

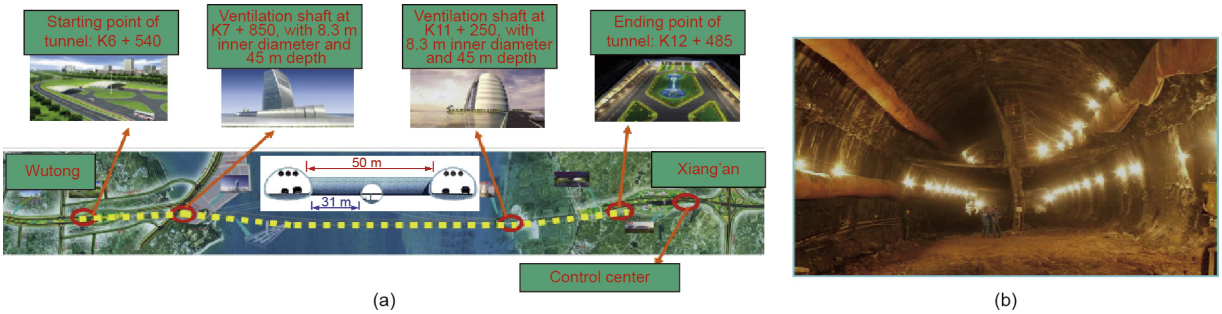
3. Typical underwater tunnels in the mainland of China

3.1. Xiang'an Tunnel in Xiamen

Xiang'an Tunnel in Xiamen is 6.05 km long, of which a 4.2 km long section is located under the sea. The tunnel is bidirectional and has six lanes; its use reduces the driving time from the Xiamen Island to Xiang'an from the original 1.5 h down to 10 min.

The tunnel has three tubes: two main tunnel tubes and one service tunnel tube in between. The excavation cross-sectional area of the main tunnel tube reaches 170 m^2; the service tunnel has a repairing passage and an escape passage in its upper part and a municipal utility gallery in its lower part. Two ventilation shafts, as shown in Fig. 4, are installed at positions close to the sea, in order to cope with the operation ventilation. A total of 12 connection passages are installed for the tunnel in order to facilitate evacuation. Along the tunnel route, the maximum sea water depth is 26.2 m, the minimum overburden in the sea is 28.4 m, and the lowest point of the tunnel is located about 65 m below the sea surface.

The tunnel is mainly located in slightly weathered rocks; however, the completely weathered or heavily weathered ground on both banks, the permeable sand strata through which the tunnel section below the shallow beach on the Xiang'an side passes, and the completely weathered or heavily weathered deep troughs (bags) in the sea section (as shown in Fig. 5) had a severe impact on the construction of the tunnel. Therefore, for the tunnel section below the beach, dewatering was performed both from outside the tunnel and from inside the tunnel. For the tunnel section below the sea, technical measures such as advanced geological prediction (as shown in Fig. 6), advanced grouting for water stoppage, and consolidation along the perimeter of the tunnel were performed; instead of full-face curtain grouting, perimetrical curtain grouting and top heading grouting [6] were performed to dramatically reduce the grouting and consolidation scope; and modified equipment was used to dramatically improve the tunneling efficiency [7].



(a) (b)

Fig. 4. (a) Plane sketch, ventilation shafts, and excavation method for Xiang'an Tunnel in Xiamen; (b) photograph of the construction site of Xiang'an Tunnel.

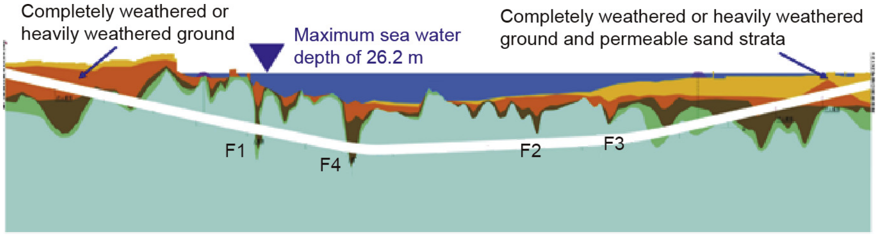
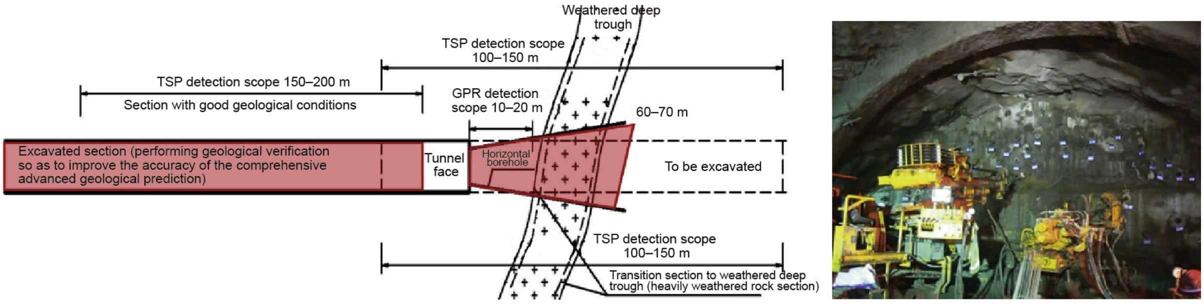


Fig. 5. Geological profile of Xiang'an Tunnel in Xiamen. F1, F2, and F3 are the completely weathered or heavily weathered deep troughs; F4 is the completely weathered or heavily weathered deep bag.



(a) (b)

Fig. 6. (a) Advanced geological prediction and advanced grouting; (b) photograph of the construction site. TSP: tunnel seismic prediction; GPR: ground-penetrating radar.

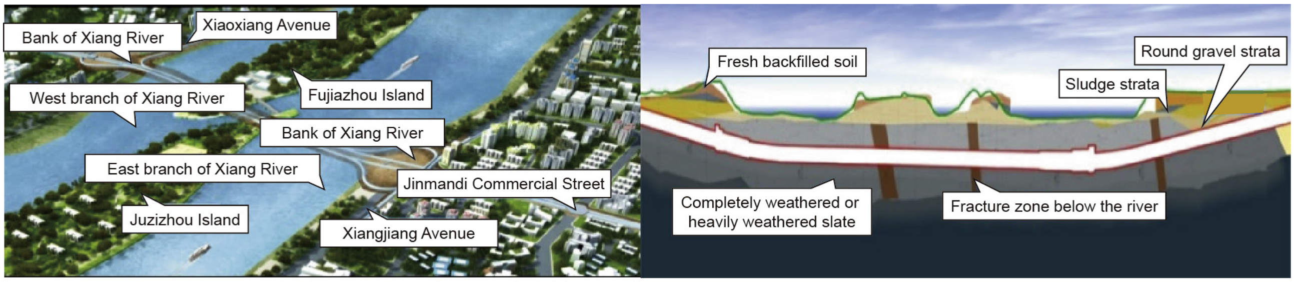
3.2. Yingpan Road Xiang River-Crossing Tunnel in Changsha

Starting at Xianjiahu Road in the west and ending at Yingpan Road in the east, the main route of Yingpan Road Xiang River-Crossing Tunnel in Changsha has a total length of 2850 m. The main tunnel is bidirectional and has four lanes and a design speed of 50 km·h^{-1}. Ramp A and Ramp B are on the west bank of the tunnel and Ramp C and Ramp D are on the east bank. The ramps have only one lane, with a 40 km·h^{-1} design speed; the total length of the ramps is 2752.4 m. The tunnel was constructed by the drill-and-blast method. Fig. 7 illustrates the layout of the tunnel. The tunnel mainly passes through round gravel strata, completely weathered or heavily weathered slate, and fresh backfilled soil. The ground has strong permeability and poor self-support capability and was subject to collapse and water inflow during excavation. The tunnel crosses three fracture zones below the river (Fig. 7).

Because the overburden of the tunnel consists of sludge strata, round gravel strata, and completely weathered or heavily weathered slate, a minimum overburden design method based on engineering measures was established, a deformation control standard based on the construction steps was defined, and technical measures such as forepoling, pipe roofs, sequential excavation, and coordinated double-support layers were taken in order to ensure the overall stability of the tunnel. In the end, an underwater tunnel with a super-shallow overburden was successfully built; the largest span of the tunnel is 25 m, the largest excavation cross-sectional area is 376 m^2, and the overburden/span ratio is only 0.46. At the interchange point in the round gravel strata, the four tunnel tubes have close spacing, with the strata between the upper tunnel tube and the lower tunnel tube being less than 0.5 m thick and the horizontal spacing between the tunnel tubes being 2.8 m. To address this situation, measures were taken such as excavating the lower tunnel tube before the upper tunnel tube, performing construction activities alternately, performing advance support, performing construction activities step by step, and installing the lining in a timely manner. To enable the underground interchange, the tunnel is smoothly connected to the urban roads on both banks of the Xiang River.

3.3. Shiziyang Tunnel on the Guangzhou–Shenzhen–Hong Kong Express Rail Link

Shiziyang Tunnel is located between Dongchong Station and Humen Station on the Guangzhou–Shenzhen–Hong Kong Express Rail Link. The tunnel is 10.8 km long, of which the shield-bored



(a) (b)

Fig. 7. (a) The plan layout and (b) the profile of Yingpan Road Xiang River-Crossing Tunnel in Changsha.

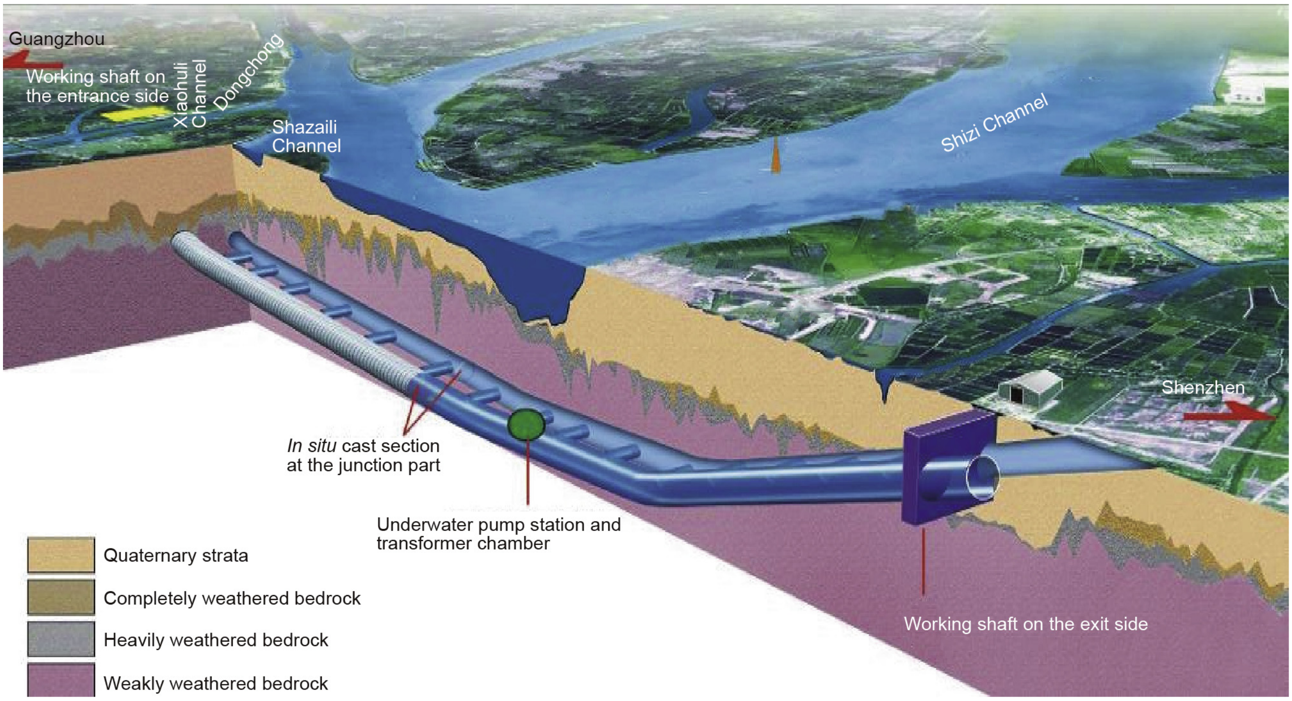


Fig. 8. Geological profile of Shiziyang Tunnel.

section is 9340 m long. The inner diameter of the tunnel is 9.8 m and the outer diameter is 10.8 m. The twin tubes of the tunnel have 23 connection passages. Shiziyang Tunnel is the first underwater high-speed railway tunnel with a design speed of 350 km·h^{-1} in the world, and is also the first super-long underwater tunnel in China. The shield-bored section of Shiziyang Tunnel crosses underneath the Xiaohuli Channel, the Shazaili Channel, and the Shizi Channel; the Shizi Channel is 26 m deep at its maximum and is the main channel of Pearl River. The maximum cover of the tunnel is 52.3 m and the minimum cover is 7.8 m. The minimum underwater cover of the tunnel is 8.7 m deep, and the design water pressure reaches 0.67 MPa.

Most of Shiziyang Tunnel is located in slightly weathered sandstone, sandy conglomerate, and sandy mudstone. The maximum uniaxial compressive strength reaches 82.8 MPa, the content of the quartz in the rock reaches 55.2%, and the maximum permeability coefficient of the ground reaches 6.4×10^{-4} m·s^{-1}. The geological profile of Shiziyang Tunnel is shown in Fig. 8 [8].

Fig. 9. The docking effect used in the construction of Shiziyang Tunnel.

A cutting tool replacement technology for use under conditions with reduced pressure and limited drainage was created during the construction of the tunnel. In fractured ground with high permeability, the water in the chamber is drained and the pressure in the chamber is reduced—based on fluid–structure interaction theory—to stabilize the tunnel face by low air pressure in order to enable workers to enter the chamber and perform operations [8]. The new technology had a significant effect on the construction of Shiziyang Tunnel, for which the pressure-reducing ratio reached 34.4%. A technology in which shield boring is performed from opposite directions, with docking in the ground and shield disassembling in the tunnel, was applied in the construction of the tunnel; the docking accuracy reached 28.5 mm deviation in the horizontal direction and 19.6 mm in the vertical direction. The docking effect is shown in Fig. 9 [9].

3.4. Water-delivery tunnel for the Taishan Nuclear Power Station

The water-delivery tunnel for the Taishan Nuclear Power Station is located under the sea, between Yaoguzui (on land) and Dajin Island. The tunnel is 4330.6 m long; its excavation diameter is 9.03 m, the cover of the tunnel ranges from 10 m to 29 m, and the distance between the twin tubes of the tunnel is 29.2 m. The tunnel was constructed by means of slurry shields with air cushions, and it is provided with secondary lining on the inner side of the segment lining. The water outlet section of the water-delivery tunnel passes through Yanshanian ($\gamma5$) granite, the water-intake section of the water-delivery tunnel passes through silty sandstone of the Laohutou Formation of the Devonian System (D2-31), and the other sections of the water-delivery tunnel pass through coarse gravelly sand and gravelly sandy clay. The most difficult challenge of the project was related to the slightly weathered granite, which had a maximum strength of 197 MPa, and to the spherical weathered granite boulders that occurred locally, as shown in Fig. 10.

A real-time kinematic (RTK) system, a high-frequency high-density seismic wave technology, and a common-depth-point (CDP) stacking technology were used for geophysical detection.

(a) (b)

Fig. 10. (a) A sketch of the water-delivery tunnel for the Taishan Nuclear Power Station; (b) locally encountered spherical granite boulders.

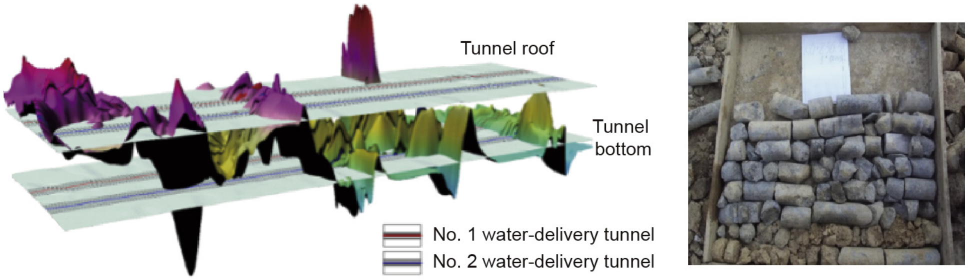
In addition, a technology that permits accurate detection of abrupt bedrock protrusion and boulders under the sea was developed [10,11]; this technology accurately determines the top surface of the bedrock and the boulders. A fragmentation blasting technology to determine the layer location and the operation depth below the seabed was also developed [10,11]. Underwater ground blasting was performed on the high-strength bedrock during the tunnel construction [12,13]. After bedrock blasting, the diameter of the cores was mostly below 30 cm, and only a few cores had a diameter between 30 cm and 55 cm. With the assistance of these technologies, the shield machines successfully passed through the 200 m long bedrock section, as shown in Fig. 11.

4. Typical underwater tunnels under construction in China

4.1. Shiziyang Tunnel on the Foshan–Dongguan Intercity railway

Shiziyang Tunnel on the Foshan–Dongguan Intercity Railway is an important control works on the east–west axis of the Pearl River Delta Intercity Railway; this is the second underwater shield-bored tunnel that crosses the Shizi Channel. The tunnel is 6.15 km long and has an underwater tunnel section that is 1.8 km long. This tunnel was built by means of the shield method. As shown in Fig. 12, the shield machine bored for a length of 4.9 km in a single direction.

The prominent characteristics of this project included high water pressure and long-distance boring in soft/hard heterogeneous ground. The design water pressure reached 0.9 MPa, and the difference between the hard ground and the soft ground in the same cross-section of the tunnel reached 84.6 MPa. Such characteristics caused major challenges for the shield boring machine and for replacement of the cutting tool. A technology of full-face disc cutter replacement under atmospheric conditions was adopted for this project. As there is no opening within a scope of 4.8 m around the center of the cutterhead, clogging easily occurs during shield boring. Therefore, a correlation between the boring speed, ground characteristics, and cutterhead center flushing was established. When the cutterhead was under atmospheric conditions, muck could only enter the slurry port after passing a distance of 3.97 m; as a result, clogging and delayed discharging easily occurred. Therefore, a complete set of shield boring control technologies was developed, which laid a technological foundation for the construction of underwater shield-bored tunnels with super-deep cover in China.



(a) (b)

Fig. 11. (a) Top surface of bedrock with three-dimensional graph showing accurate boulder location determination; (b) cores from the bedrock after blasting.

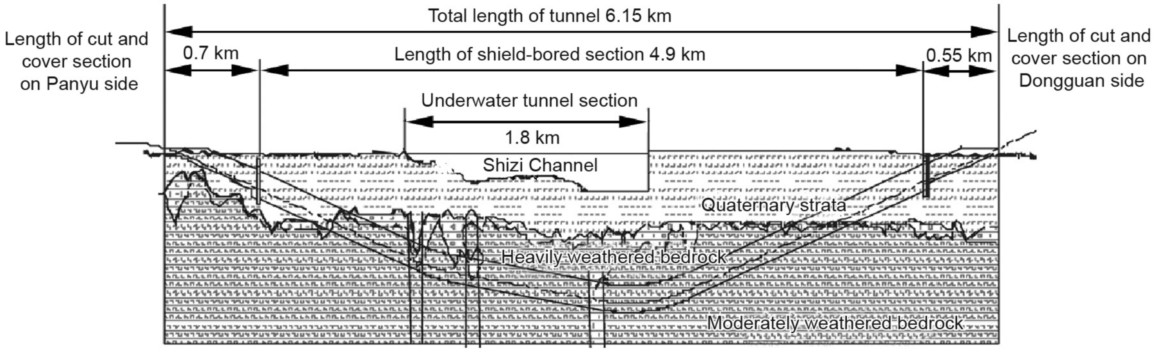


Fig. 12. A longitudinal profile of Shiziyang Tunnel on the Foshan–Dongguan Intercity Railway.

4.2. Su'ai Tunnel in Shantou

Su'ai Tunnel in Shantou is located on the second line of National Highway G324. The tunnel is bidirectional and has six lanes and functions as part of an urban highway. The main line of the tunnel has a design driving speed of 60 km·h^{-1}; the total length of the project is 6.68 km, of which the tunnel is 5.3 km. The length of the shield-bored tunnel is 3047.5 m, and the diameter of the shield-bored tunnel is 14.5 m. Fig. 13 shows the plan layout of the tunnel.

Su'ai Tunnel is the first subsea tunnel in China to be located in an area with eight degrees of seismic intensity. The tunnel passes through challenging ground, such as very soft soil, boulders, and soft/hard heterogeneous ground in the same cross-section as marine muddy soil (in the upper part of the excavation) and granite with a strength of more than 216 MPa (in the lower part). Seismic-resistant measures, seismic-reducing measures, and seismic-isolating measures were innovatively used in the design of this tunnel (as shown in Fig. 14). For example, a node structure that can be adapted to serious deformation was used to dissipate seismic-induced energy, and simultaneous grouting materials with a strong compressive deformation capacity were used to achieve a seismic-isolation effect. Protruding bedrock exists in local positions, and there is very soft sandy clay in the upper part of the tunnel cross-section. Therefore, abnormal damage could occur to the cutting tools due to overloading during shield boring. To address this issue, a technology was developed to trace the force undertaking and operation of the cutting tools [14].

Su'ai Tunnel had complex geological conditions, great construction difficulties, and high risks, so its construction involved the use of innovative technologies. The construction of Su'ai Tunnel provides a reference for the construction of other large-diameter subsea shield-bored tunnels in China in the future.

4.3. Immersed tunnel on the Hong Kong–Zhuhai–Macao Bridge

The main project of the Hong Kong–Zhuhai–Macao Bridge is 29.6 km long, including a 22.9 km long bridge and a 6.7 km long immersed tunnel. The immersed tunnel has six lanes and crosses the west navigation channel of Lingding Channel and the Tonggu navigation channel. An artificial island was established on each end of the immersed tunnel. This immersed tunnel is the first immersed tunnel built in the sea in China, and is also the longest and deepest immersed tunnel in the world. The immersed tubes were installed 45 m below the seabed. Fig. 15 shows the plan layout, island cofferdam, and immersed tube transportation for the immersed tunnel of the Hong Kong–Zhuhai–Macao Bridge.

During the construction of the immersed tunnel, the following innovative technologies were developed: a technology to build large artificial islands in the sea, a technology to control and deal with sedimentation in the immersed tube trenches located at the sea entrance, a technology to fabricate the 180 m long reinforced concrete immersed tubes, and a technology to transport the immersed tubes, which weighed 80 000 t each. Furthermore, heavy-duty equipment was developed for the construction of immersed tunnels in the sea. These new technologies boosted the technological progress of immersed tunnel construction in China. On 25 May 2017, the immersed tunnel of the Hong Kong–Zhuhai–Macao Bridge achieved breakthrough.

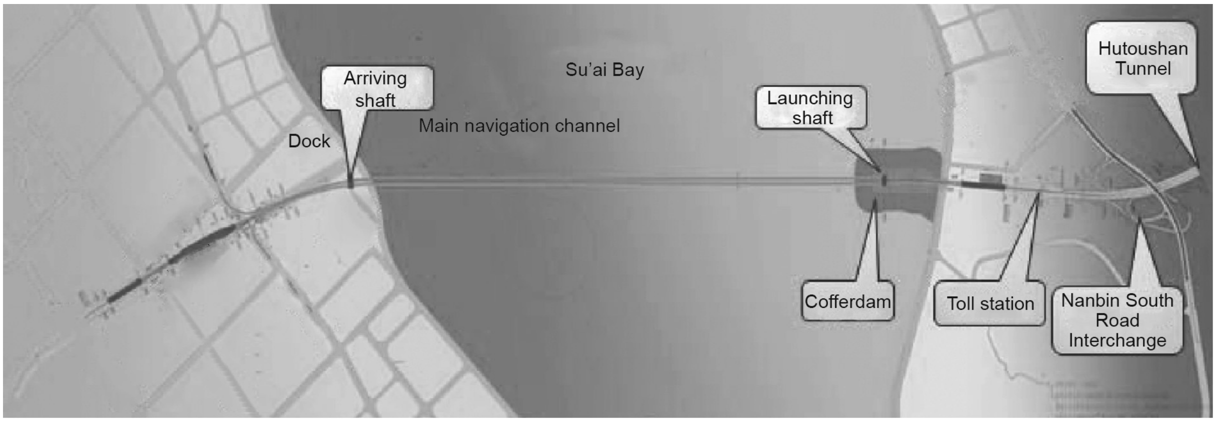


Fig. 13. Plan layout of Su'ai Tunnel in Shantou.

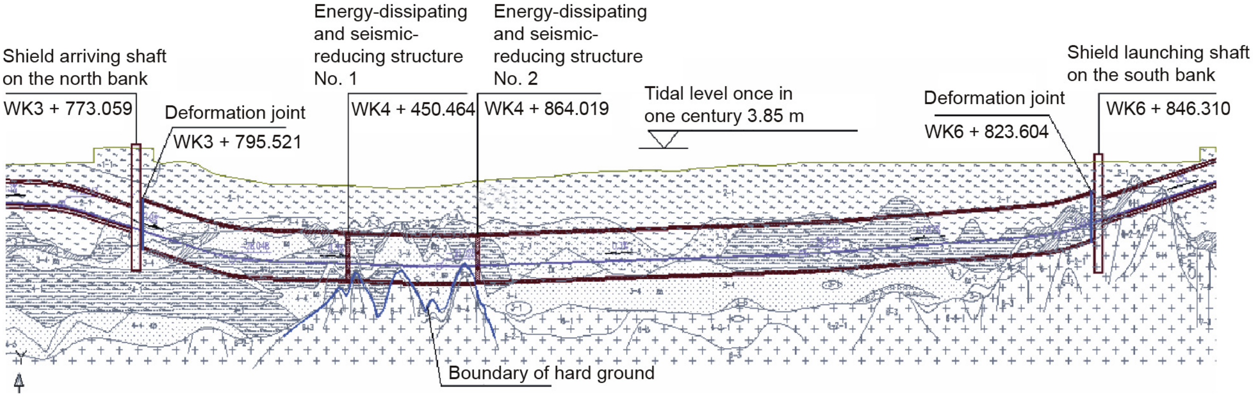


Fig. 14. A longitudinal profile of Su'ai Tunnel with a layout of the energy-dissipating and seismic-reducing nodes.


(a) (b) (c)

Fig. 15. (a) Plan layout for the immersed tunnel of the Hong Kong–Zhuhai–Macao Bridge; (b) island cofferdam; (c) immersed tube transportation.

5. Suggestions regarding three great strait-crossing tunnels in China

The Qiongzhou Strait-Crossing Tunnel and Bohai Strait-Crossing Tunnel are critical projects on the Heilongjiang–Hainan railway and highway corridor, and the Taiwan Strait-Crossing Tunnel is an important link between the mainland and Taiwan of China. The construction of these three great strait-crossing tunnels has great significance for China [3].

5.1. Qiongzhou Strait-Crossing Tunnel

The minimum width of the Qiongzhou Strait is 18.3 km, the water depth ranges from 20 m to 117 m, and the ground within the scope of 200 m below the seabed mainly consists of clay and silt of the Tertiary and Quaternary Periods, as well as sand strata and sandy gravel strata. According to studies that were performed on three possible routes—the east route, central route, and west route—the central route is believed to be the most preferable route; this route can be constructed by means of shield machine [15].

Due to the ecological environmental protection situation in Hainan Province, it is not suitable for numerous cars to come to Hainan Province through a strait-crossing tunnel. Rather, the strait-crossing tunnel should take the form of a railway tunnel for passenger and freight transportation, with cars being transported by train just as they are through the Channel Tunnel. Based on operational experience of tunnels with lengths over 20 km, both in China and abroad, the railway tunnel may take the form of twin tubes, as shown in Fig. 16. The tunnel will have characteristics such as deep cover and high water pressure, so shield machines with the capability to replace cutting tools under atmospheric pressure should be used. Given the performance and lifetime of shield machines, four shield machines may be used to bore the twin tunnel tubes from opposite directions; these can be docked in the ground. The freezing of the ground at the docking points will be a technological challenge and critical issue for this project.

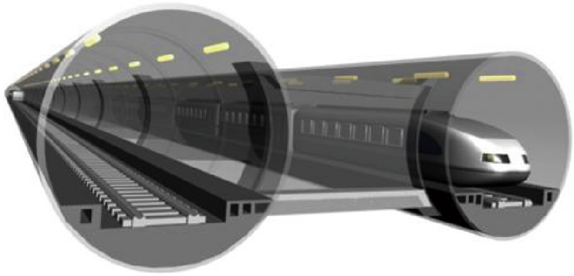


Fig. 16. A possible conformation for the Qiongzhou Strait-Crossing Tunnel: a railway tunnel consisting of twin single-track tubes.

5.2. Bohai Strait-Crossing Tunnel

The Bohai Strait-Crossing Tunnel will be located on the shortest corridor from Northeast China to East China and South China. Laotieshan Channel is an important sea navigation channel, so a bridge cannot be built across it. The width of Laotieshan Channel reaches 50 km, so a highway tunnel cannot be built because the problems of ventilation, disaster prevention, and emergency rescue cannot be solved at present. Therefore, a fixed railway link may be preferentially considered in the short term, although the route of the fixed highway link should be preserved. Fig. 17 shows the geographical location of the Bohai Strait-Crossing Tunnel.

The route of the Bohai Strait-Crossing Tunnel crosses many islands; this allows the long tunnel to be divided into several sections, is favorable for ventilation during construction and operation, and is favorable for emergency rescue. Considering the requirements of emergency rescue and emergency evacuation, the tunnel may consist of three parallel tubes, with the central tube serving as an emergency rescue passage (as shown in Fig. 18). Due to the thick cover of the tunnel, the tunnel will be mostly located in bedrock. The surrounding rock of the tunnel will mostly be granite. The tunnel may be constructed by tunnel-boring machines (TBMs) with about 10 m diameter, assisted by drill and blast [15]. However, the 25 km long single-direction boring of a TBM under marine water is a major challenge.

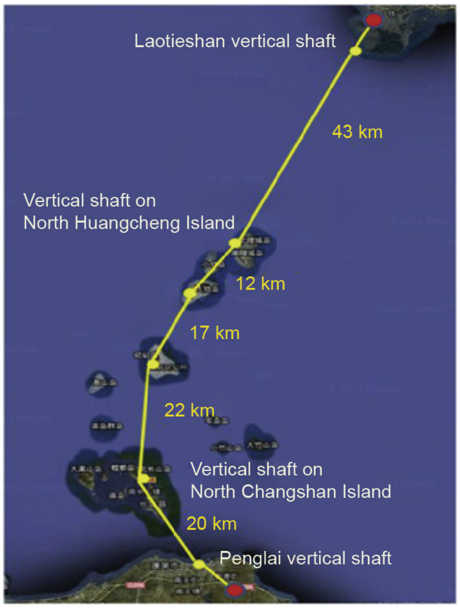


Fig. 17. Geographical location of the Bohai Strait-Crossing Tunnel.

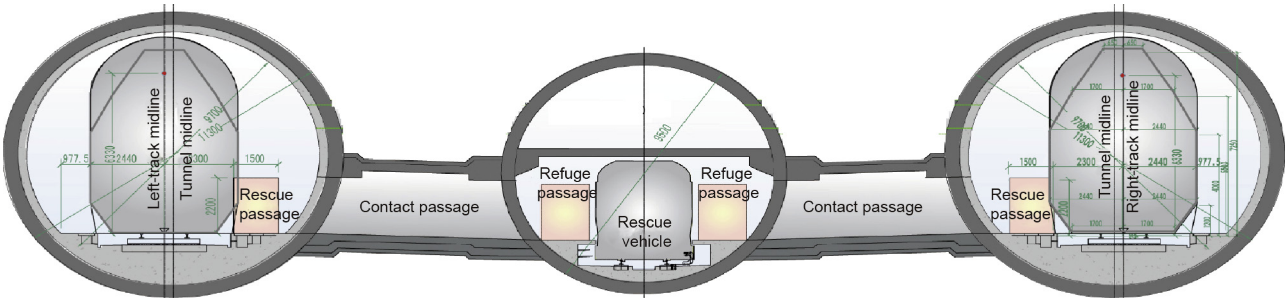


Fig. 18. A possible conformation for the Bohai Strait-Crossing Tunnel, consisting of three parallel tubes.

5.3. Taiwan Strait-Crossing Tunnel

The Taiwan Strait-Crossing Tunnel needs to cross the Taiwan Strait over a width of more than 100 km. The water of the Taiwan Strait is about 85 m deep, and the ground below the water is mainly composed of interbed consisting of Tertiary sandstone and shale of different thicknesses. The thickness of the subhorizontal sandstone and shale ranges from 200 m to 300 m. At present, the optimal option may be to build a railway tunnel, which may be constructed by open TBM assisted by the drill-and-blast method [2].

According to the long-term prospective, and considering the foresight and feasibility of the project, the Taiwan Strait-Crossing Tunnel may consist of four railway tracks (of which two tracks are used for trains carrying cars) to separate the freight transportation from the passenger transportation.

As noted earlier, many natural islands are present along the route of the Bohai Strait-Crossing Tunnel, which can be used for tunnel construction. However, there is no natural island along the route of the Taiwan Strait-Crossing Tunnel; as a result, this project presents significantly greater difficulties. The difficulties of the Taiwan Strait-Crossing Tunnel include the following issues: ① How to build a working platform in the deep sea, so as to divide the long tunnel into several sections; and ② how to guarantee operational safety, protection, and emergency rescue in a subsea tunnel that is more than 100 km long.

6. Conclusions and suggestions

In the past three decades, Chinese engineers have accumulated a considerable amount of underwater tunnel construction experience, mastered a complete set of long underwater tunnel construction technologies, and established a strong technological basis and great innovative capability. We now have the technological capability to build underwater tunnels for almost any purpose under complex geological conditions and complex environmental conditions.

In order to further control the construction risks and project investment of underwater tunnels, and to ensure the operational safety of underwater tunnels, we propose that an offshore deep-water operation shaft platform be studied, that the study of the geological investigation technology for underwater tunnels be strengthened, that the study of the rapid and safe long-distance driving of underwater tunnels from a single portal be intensified, and that the operational risk-control technology, ventilation, and energy-saving technology of underwater tunnels be enhanced.

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