Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.jzus.zju.edu.cn; www.springerlink.com
E-mail: jzus@zju.edu.cn

Editorial:

Technical challenges in the construction of bridge-tunnel sea-crossing projects in China

Shen-you SONG[†1], Jian GUO[2], Quan-ke SU[3], Gao LIU[4]
[1]*Shenzhen-Zhongshan Link Administration Center, Zhongshan 528400, China*
[2]*Institute of Bridge Engineering, Zhejiang University of Technology, Hangzhou 310023, China*
[3]*Hong Kong-Zhuhai-Macao Bridge Authority, Zhuhai 519060, China*
[4]*CCCC Highway Bridges National Engineering Research Centre Co., Ltd., Beijing 100088, China*
[†]E-mail: tonysong@163.com

https://doi.org/10.1631/jzus.A20CSBE1

Since the year 2000, China has built a number of bridges crossing rivers and seas, including the Hangzhou Bay Bridge, Jiaozhou Bay Bridge, Zhoushan Bridge, and Hong Kong-Zhuhai-Macao Bridge (HZMB). As the longest sea-crossing bridge in the world, the opening of the HZMB (Fig. 1) was undoubtedly one of the most significant events in 2018 (Jing, 2020). With the rapid development of China's economy, especially in coastal areas, and the concentration of population density, the demand for transportation is increasing. Sea-crossing projects have gradually developed from bridge projects to integrated bridge-island-tunnel projects.

1 Shenzhen-Zhongshan Link under construction

With the completion of the HZMB, more and more large-scale sea-crossing passage projects have been proposed. For example, one of the most significant in the world is the Shenzhen-Zhongshan Link (SZ-Link). It is located in the core strategic area of Guangdong Province, Hong Kong, and Macao, 30 km away from the Humen Bridge to the north and 38 km away from the HZMB to the south (Fig. 2). The SZ-Link is a crucial part of the national high-speed network (Shenzhen to Cenxi, Guangxi Province) crossing the Pearl River estuary (Xu and Huang, 2018). The highway part of the project is a two-way eight-lane expressway with a design speed of 100 km/h. The bridges have a standard deck width of 40.5 m and a clear width of tunnel construction clearance of 2× 18.0 m. The design service life of the project is 120 years. The project started in December 2016, and it is expected that the whole line will be operational in 2024. The entire highway is 24 km long, starting from the Shenzhen Airport Interchange, connecting the Guangzhou-Shenzhen Expressway to the east of the Jihe Expressway, crossing the Pearl River estuary to the west, and passing through the east artificial island, the submerged tube tunnel (total length 6845 m, immersed section length 5035 m, and a total of 32 pipe sections), west artificial island, Lingdingyang Bridge (a suspension bridge with a main span of 1666 m), and the Zhongshan Bridge (a cable-stayed bridge with a main span of 580 m) (Fig. 3) (Wang, 2019).

The SZ-Link is closer to the Pearl River estuary than the HZMB, resulting in more complicated navigation conditions, a stricter air height limit, and more severe sea conditions. Due to the high navigation and traffic capacity, the SZ-Link is more extensive and the bridge span is longer than the HZMB. These factors bring more challenges to the design and construction of the immersed tunnel and main bridge. It can be said that the SZ-Link is one of the most difficult sea-crossing projects in the world. As a sea-crossing project involving bridges, islands, and a tunnel, it faces many difficulties (Song et al., 2020):

1. The Shenzhen China Channel is located in the Pearl River estuary, the core of the Guangdong-Hong Kong-Macao Bay area, and the construction conditions are incredibly complex. The main constraint is the height of aviation. Shenzhen Airport determines the maximum altitude of bridge towers

ORCID: Shen-you SONG, https://orcid.org/0000-0002-9052-0338

and construction equipment. For the navigation situation, the project passes through seven channels. There are two main sea routes with a high navigation level, which determines the height of each bridge and the buried depth of the tunnel: (1) Flood control: the estuaries of the four eastern entrances to the sea of the Pearl River estuary have sensitive flood and tide controls, and strict control of the water blocking ratio. (2) Environmental protection: the site includes the migration area of the China White Dolphin, a first-class protected animal.

2. For the subsea tunnel, this project is the first two-way eight-lane immersed tunnel in the world, and is also the first application of an immersed steel shell concrete tunnel in China. It is ultra-wide (eight lanes, the widest of which is more than 56 m), deeply buried (the maximum water head is 38 m), and has variable width (the length of variable width section is 615 m) (Chen et al., 2020). The construction of the tunnel foundation and the foundation trench is also challenged by poor geology, including softening of weathered rock, soft and hard strata, liquefied sand, large back-silting of the foundation trench, and seabed evolution (Jin et al., 2019).

3. The Lingdingyang Bridge (Fig. 3) is located in the open sea area of the Pearl River estuary. It is a long-span suspension bridge (main span 1666 m) in a sea exposed to frequent and strong typhoons. Also, the anchorage is located in the sea. The design and construction experience was insufficient, and the structure of the bridge is soft. There is little damping, and the flutter test wind speed reaches up to 83.7 m/s (Zhao et al., 2019). There is also a series of global problems, such as the durability of the main cable of the suspension bridge at high temperatures, high humidity and in a high salt environment, and the fatigue durability of the orthotropic steel deck under the conditions of large traffic volumes and a high proportion of freight cars.

4. The operational safety of the eight-lane immersed tunnel is critical. The airport interchange is the world's first underwater expressway hub, with massive traffic volumes and high trucks. It is challenging to control vehicles carrying dangerous chemicals, and operational safety problems are prominent. The fire prevention standard of the steel shell concrete immersed tube structure with a broad cross-section is lacking, the ventilation and smoke exhaust technology of long and ultra-wide tunnels is not mature, and the traffic flow management and intelligent control technology of submarine interchange tunnels are weak (Song et al., 2019).

5. The excavation and support of the ultra-wide and bottomless foundation pit and the sealing and seepage prevention in the weathered granite stratum in the east artificial island sea area present enormous

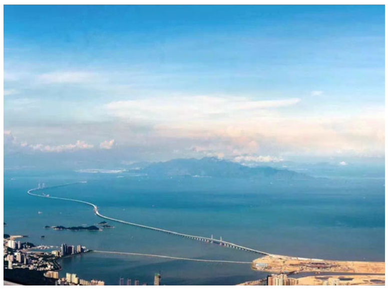

Fig. 1 Hong Kong-Zhuhai-Macao Bridge

Fig. 2 Location of the SZ-Link

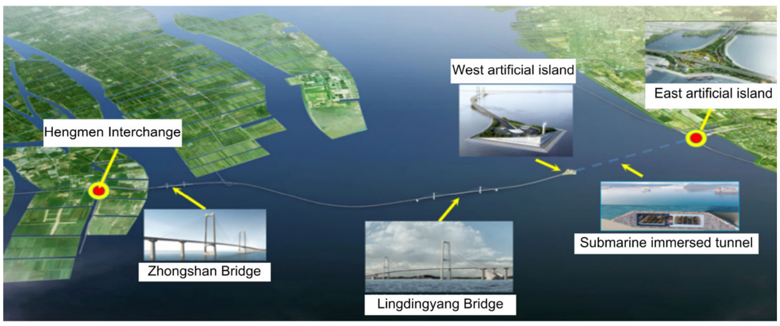

Fig. 3 Schematic diagram of the main structures of the SZ-Link

challenges. The steel cylinder on the west artificial island is located on undulating weathered rock. The vibration settlement of the undulating weathered rock and the precision control technology of the steel cylinder are significant issues. The construction technology, key parameters, soil content, and efficiency of the digital surface model ship's pretreatment of the underwater dense sand layer also need to be considered.

The immersed steel shell tube tunnel of the SZ-Link involves large scale and complex technology. The Lingdingyang Bridge is the world's largest span sea suspension bridge, with the highest wind resistance standard in the world. In summarizing the characteristics and difficulties of the project and the main technical innovation achievements, the SZ-Link has focused on the steel shell concrete immersed tube, offshore suspension bridge, durability of the marine structure, fire prevention and control, intelligent traffic control and other aspects, and has solved the common key technical problems. Based on the above technical characteristics and difficulties, relying on the National Key Research and Development Program of China and the Research and Development Program of Guangdong Province, the SZ-Link has made breakthroughs in new theories, structures, materials, technologies, and equipment.

2 Development of the bridge-tunnel sea-crossing project

The opening of the HZMB and the construction of the SZ-Link provide valuable experience for the preparation of sea-crossing projects. For example, the Ningbo-Zhoushan Highway and Railway Combined Project (Fig. 4), will build tunnels and bridges to connect the four natural islands with the mainland. Among them, the construction between Jintang Island and Ningbo has the highest requirements for navigation and the most difficult natural conditions in the whole project. An integrated bridge-tunnel connection is planned for this project. The Xihoumen Channel is located between Cezi Island and Jintang Island, with a maximum water depth greater than 90 m. After the project line passes through Cezi Island, it needs to cross the Taoyaomen Channel before entering Zhoushan Island. To cross the two channels, two long-span bridges are expected to be built. During the course of the project, to reduce the difficulty of sea-crossing engineering, construction will start on Fuchi Island, cross the Xiangjiaomen Waterway, and then move onto Zhoushan Island.

As shown in Table 1, comparing the HZMB, SZ-Link, and Ningbo-Zhoushan Highway and Railway Combined Project, the construction of each sea-crossing project has its own technical difficulties and challenges. However, China has made a breakthrough from crossing rivers to crossing the sea. There is still an urgent need to build mega sea-crossing projects to improve the traffic network (Guo, 2010). The

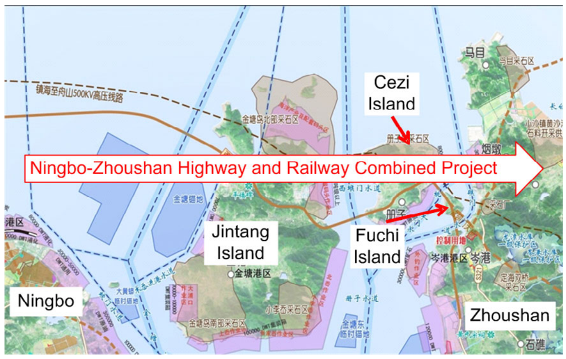

Fig. 4 Sketch map of the Ningbo-Zhoushan Highway and Railway Combined Project

Table 1 Main features of three sea-crossing projects

Feature	HZMB (2018)	SZ-Link (under construction)	Ningbo-Zhoushan Highway and Railway Combined Project (to be built)
Length	55 km	24 km	About 77 km
Structure type	Bridge-island-tunnel	Bridge-island-tunnel	Bridge-island-tunnel
Traffic situation	Two-way six-lane expressway	Two-way eight-lane expressway	Two-way two-lane railway; two-way six-lane expressway
Main bridge	Three cable-stayed bridge: Jiuzhou Channel Bridge (main span: 693 m), Jianghai Channel Bridge (main span: 994 m), Qingzhou Channel Bridge (main span: 1150 m)	Lingdingyang Bridge (main span: 1666 m, suspension bridge), Zhongshan Bridge (main span: 580 m, cable-stayed bridge)	Xihoumen Highway and Railway Bridge (main span: 1488 m, suspension bridge), Taoyaomen Highway and Railway Bridge (main span: 666 m, cable-stayed bridge), Fuchimen Highway and Railway Bridge (main span: 388 m, cable-stayed bridge)
Tunnel	6.7 km immersed tunnel, width: 2×14.25 m	6.8 km immersed tunnel, width: 2×18 m	10.87 km shield tunnel

completion of these projects will significantly promote the further development of the economy, and of course, will also face great challenges. Sea-crossing engineering will develop in the direction of high durability, deep water areas, tunnel-island-bridge combinations, and intelligent traffic control.

Future sea-crossing engineering construction will face many technical challenges. Design concepts, disaster prevention capability, application of new materials, long-term service performance, maintenance, and other key technologies need further study. In this special issue, for example, Xie et al. (2020) adopted the up-to-date Bayesian fast Fourier transform method to investigate the modal properties when the sea-crossing bridges are in their operation conditions. Guo and He (2020) evaluated the dynamic response of the sample bridge and local damages of the fragile components under impact force. Zhao et al. (2020) proposed a framework to identify a comprehensive set of aerodynamic admittance functions for bridge decks, including the effects of the contributions of the cross-spectra between wind velocity and turbulence components. We are confident that this special issue will provide researchers with a unique opportunity to present and discuss recent progress in sea-crossing engineering construction control. High-quality technical publications and scientific standards will promote interaction between basic science and engineering applications. We sincerely hope that this special issue can extend the research frontiers of sea-crossing engineering.

Contributors

Shen-you SONG and Jian GUO wrote the manuscript. Quan-ke SU and Gao LIU provided the suggestions.

Conflict of interest

Shen-you SONG, Jian GUO, Quan-ke SU, and Gao LIU declare that they have no conflict of interest.

References

Chen WL, Guo C, He X, et al., 2020. Experimental study on the mechanical behavior and deformation characteristics of gravel cushion in an immersed tube tunnel. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(7):514-524. https://doi.org/10.1631/jzus.A1900408

Guo J, 2010. Current principal technique status and challenges to be confronted in construction of sea-crossing bridges. *Bridge Construction*, (6):66-69 (in Chinese).

Guo J, He JX, 2020. Dynamic response analysis of ship-bridge collisions experiment. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(7): 525-534. https://doi.org/10.1631/jzus.A1900382

Jin WL, Han ZY, Li HY, et al., 2019. Research on hydrodynamic and sedimentary characteristics along the immersed tunnel of Shenzhen-Zhongshan Link. *Journal of Waterway and Harbor*, 40(5):497-503 (in Chinese).

Jing Q, 2020. Continuous steel box girders and reinforced concrete structures in the Main Bridge Project of Hong Kong-Zhuhai-Macao Bridge. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(4):249-254. https://doi.org/10.1631/jzus.A1900645

Song SY, Nie JG, Xu GP, et al., 2019. Development and application of steel-concrete-steel composite structures in immersed tunnels. *China Civil Engineering Journal*, 52(4):109-120 (in Chinese). https://doi.org/10.15951/j.tmgcxb.2019.04.010

Song SY, Chen WL, Jin WL, et al., 2020. Key technologies and challenges of Shen-Zhong Link. *Tunnel Construction*, 40(1):143-152 (in Chinese). https://doi.org/10.3973/j.issn.2096-4498.2020.01.019

Wang X, 2019. Overall design of Zhongshan Bridge in Shenzhen-Zhongshan Link. *Bridge Construction*, 49(1): 83-88 (in Chinese). https://doi.org/10.3969/j.issn.1003-4722.2019.01.015

Xie YL, Li BB, Guo J, 2020. Bayesian operational modal analysis of a long-span cable-stayed sea-crossing bridge. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(7):553-564. https://doi.org/10.1631/jzus.A1900511

Xu GP, Huang FQ, 2018. General design of Shenzhen-Zhongshan river-crossing Link Project. *Tunnel Construction*, (4):627-637 (in Chinese). http://doi.org/10. 3973 /j. issn.2096-4498.2018.04.014

Zhao L, Wang Q, Song SY, et al., 2019. Investigation of wind-resistance performance of Lingdingyang Bridge with main-span 1666 m in Shen-Zhong Link. *China Journal of Highway and Transport*, 32(10):57-66 (in Chinese). https://doi.org/10.19721/j.cnki.1001-7372.2019.10.005

Zhao L, Xie X, Wu T, et al., 2020. Revisiting aerodynamic admittance function of bridge decks. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 21(7):535-552. https://doi.org/10.1631/jzus.A1900353

中文概要

题　目：中国桥隧一体化跨海工程建设的技术挑战

概　要：近年来，跨海大桥的建设越来越受到重视。杭州湾跨海大桥、舟山跨海大桥和港珠澳大桥等跨海

工程已在中国成功建成；作为目前世界上难度最大的桥隧一体化跨海工程，深中通道工程正在施工。中国已经在跨海大桥设计和施工领域取得了显著成绩，特别是在桥隧一体化跨海工程技术创新中实现了高水平的技术跨越。本专辑收集了相关科研人员和工程管理人员在设计理论、施工工艺、新材料应用、养护管理技术等方面取得的一批核心技术成果，包括大跨度跨海桥梁抗风抗震性能、大型沉管隧道结构体系的受力机理及防灾设计、船舶碰撞跨海桥梁的致灾风险识别及安全防护等突出问题。这些宝贵经验对未来的甬舟铁路、渤海海峡通道和琼州海峡跨海通道等大型跨海工程具有重要的参考价值。

关键词： 跨海工程；桥隧一体化；深中通道；港珠澳大桥；舟山跨海大桥；技术创新

Introducing Guest Editors-in-Chief and Guest Editors:

Guest Editors-in-Chief

Shen-you SONG is deputy director and chief engineer of Shenzhen-Zhongshan Link Management Center, Professorate Senior Engineer. He has successively presided over the survey and design of many large cable-stayed bridges, long-span girder bridges, and expressways.

In the past ten years, he has presided over the engineering technology and scientific research management of Shenzhen-Zhongshan Link Management Center. He advocates the idea of deep integration of architectural design and structural design, actively promotes the intelligent construction of cross-sea transportation cluster project, and promotes the high-quality development of transportation infrastructure industry. He has been responsible for many provincial and ministerial scientific research projects. He has won one special prize for Science and Technology Progress of China Highway Society, three third prizes for science and technology progress of provincial and ministerial level, and one special prize for Building Information Modeling Engineering Innovation of China Highway Society.

Prof. Jian GUO holds a PhD in Civil Engineering from Zhejiang University, China in 2004. Prior to joining Zhejiang University of Technology, he worked as a Postdoctoral Scholar at Zhejiang University and Dalian University of Technology, and he put in charge of research & development of key technologies as deputy director at the Crossing-sea Bridge Headquarters of Zhoushan, China and as vice chief at the Administration of Major Bridge Construction of Zhoushan. He is a short-term Visiting Professor of University of Illinois at Urbana-Champaign, USA.

His research interests include structural health monitoring and intelligent transportation infrastructure. He received the National Excellent Science and Technology Researcher of China in 2014 and Mao Yisheng Science and Technology Award–Bridge Youth Award in 2016. He has won the Science and Technology Progress Award of Zhejiang Province for three times. He won endowment from Leading Talents of Scientific and Technological Innovation under the Ten-thousand Plan in Zhejiang Province.

Guest Editors

Dr. Gao LIU serves as deputy general manager and chief expert of CCCC Highway Bridge National Engineering Research Centre Co. Ltd. He obtained his PhD degree from Southwest Jiaotong University in 2000. He worked as a post-doctoral scholar at Dalian University of Technology between 2000 and 2003, visiting scholar at Hong Kong Polytechnic University in 2003, and doctoral researcher at Tongji University between 2003 and 2004. Dr. LIU is an executive director of Bridge and Structural Engineering Branch of China Highway and Transportation Society. As project leader, he has completed more than thirty research projects. He has published more than 100 academic papers and six books, participated in the compilation of 10 technical standards, obtained 35 national invention patents, and won 15 provincial and ministerial science and technology progress awards.

Dr. Lin ZHAO works in School of Civil Engineering of Tongji University as a professor and PhD supervisor, deputy director of Bridge Engineering Department, and Secretary General in Wind Engineering Specialized Committee of Chinese Civil Engineering Society. He has been vice Director of Chinese Wind Engineering and Industrial Aerodynamic Specialized Committee since 2012. His main majors are structural wind engineering and bridge engineering. He won endowment from China Scholarship Council for academic visit and studied in University of Notre Dame, USA from 2013 to 2014. He won endowment from the Outstanding Young Science Fund of National Natural Science Foundation of China in 2012, and support from the New Century Excellent Talent Fund Program of Ministry of Education in 2013.