Engineering 5 (2019) 15–21

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Engineering Achievements

State-of-the-Art Technology in the Construction of Sea-Crossing Fixed Links with a Bridge, Island, and Tunnel Combination

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1. Introduction

In general, two kinds of structures are used to provide a way across a river, canal, sea, or other obstacle: bridge structures that pass over the obstacle, and tunnel structures that pass below the obstacle. Although the construction of both bridges and tunnels can be traced back over thousands of years, bridge–tunnel combinations that use an island as a sea-crossing fixed link (SCFL) have only been built over the past 82 years. The first such combination was probably the 6.4 km long San Francisco–Oakland Bay Bridge in the United States, which was completed in 1936. The most recently constructed SCFL combining a bridge, tunnel, and island is the Hong Kong–Zhuhai–Macau (HZM) Bridge, which opened for traffic on October 24, 2018 with the longest SCFL combination in the world, at a total length of 29.6 km.

Over the 82-year construction history of SCFL combinations, 10 famous projects have been built around the world [1]. After the San Francisco–Oakland Bay Bridge, the Hampton Roads Bridge–Tunnel, also in the United States, was the second SCFL combination to be constructed. This SCFL combination is 9.72 km long and was completed in 1956; it was the first SCFL to be built with an artificial island between the bridge section and the tunnel section. Next, built in the United States in 1964, the Chesapeake Bay Bridge–Tunnel was the longest SCFL combination until the recent completion of the HZM Bridge. The Chesapeake Bay Bridge–Tunnel project includes 22.2 km of bridge, 3.2 km of tunnel, and four artificial islands. During the 1990s, three bridge–island–tunnel (BIT) combination projects were completed around the world: the Monitor–Merrimac Memorial Bridge–Tunnel in the United States, the Trans-Tokyo Bay Highway in Japan, and the Great Belt Fixed Link in Denmark. In the 21st century, three more BIT combination projects have been constructed thus far, in addition to the HZM Bridge: the Øresund Fixed Link linking Denmark to Sweden, the Shanghai Yangtze River Tunnel and Bridge in China, and the Busan–Geoje Fixed Link in Korea. Table 1 provides basic information on these 10 SCFLs with a BIT combination.

Since an SCFL combination is usually comprised of one or more bridges, tunnels, and natural or artificial islands, along with the connections between these components, the construction technology for an SCFL system must include key techniques for building bridges, tunnels, and artificial islands. In order to make a comparison between the HZM Bridge and other SCFLs with a BIT combination, a state-of-the-art review of the construction technology has been performed on the bridges, tunnels, and artificial islands of eight of the abovementioned projects, in addition to the HZM Bridge, the Monitor–Merrimac Memorial Bridge–Tunnel was left out of the comparison because detailed information on this project was lacking.

2. Sea-crossing bridge construction

Compared with many other bridges, sea-crossing bridges with a BIT combination have several significant characteristics, such as a long length, large span, and deep foundation; they also encounter specific conditions, such as corrosive conditions and a severe construction environment, which may influence their design and construction. Considering these aspects, Table 2 compares the state-of-the-art technologies that were used to construct these sea-crossing bridges, including navigational channel bridges, non-navigational approach bridges, and deep foundations.

2.1. Navigational channel bridges

Although the main navigational channel of a BIT combination lies above the tunnel, bridges with large spans can have one or more other navigational channels positioned under the main channel. The eight combination projects in this comparison involve four kinds of navigational bridges: girder bridges, truss bridges, cable-stayed bridges, and suspension bridges (Table 2).

A girder bridge is the simplest and most widely used type of bridge, with a simply supported and continuous system. The longest girder bridge is the navigational channel bridge of the Trans-Tokyo Bay Highway—a 10 span continuous steel box girder bridge with a maximum span of 240 m. After the completion of the superstructure, a vortex-induced vibration (VIV) with an amplitude of over 0.5 m was observed. In order to suppress this vibration, 16 tuned mass dampers (TMDs), as shown in Fig. 1, were installed. This was one of the earliest applications of TMDs in VIV control [2]. The Shanghai Yangtze River Tunnel and Bridge has

https://doi.org/10.1016/j.eng.2019.01.003

Table 1
Ten SCFLs with a BIT combination.

	Name	Date of completion	Bridge length (km)	Number of islands	Tunnel length (km)	Total length (km)
1	San Francisco–Oakland Bay Bridge (USA)	1936	3.141 + 3.102 = 6.243	One natural island	0.160	6.403
2	Hampton Roads Bridge–Tunnel (USA)	1957	5.6	One artificial island	2.06 + 2.06 = 4.12	9.72
3	Chesapeake Bay Bridge–Tunnel (USA)	1964	19 + 3.2 = 22.2	Four artificial islands	1.6 + 1.6 = 3.2	25.4
4	Monitor–Merrimac Memorial Bridge–Tunnel (USA)	1992	5.1	Two artificial islands	1.463	6.563
5	Trans-Tokyo Bay Highway (Japan)	1997	4.4	One artificial island	9.6	14.0
6	Great Belt Fixed Link (Denmark)	1997	6.790 + 6.611 = 13.401	One natural island	8.024	21.425
7	Øresund Fixed Link (Denmark to Sweden)	2000	7.845	One artificial island	4.050	11.895
8	Shanghai Yangtze River Tunnel and Bridge (China)	2009	16.6	One natural island	8.9	25.5
9	Busan–Geoje Fixed Link (Korea)	2010	1.87 + 1.65 = 3.52	Two natural islands	3.2	6.72
10	HZM Bridge (China)	2018	22.9	Two artificial islands	6.7	29.6
Summary	Ten projects	1936–2018	3.52–22.9	One to four islands	0.160–9.6	6.403–29.6

Table 2
A comparison of the technologies used to build eight SCFLs with a BIT combination.

	Name	Navigational channel bridge	Non-navigational approach bridge	Deep foundation
1	San Francisco–Oakland Bay Bridge	2 × 704 m suspension bridges 427 m cantilever truss	48 m concrete girder	Piles
2	Hampton Roads Bridge–Tunnel	—	24 m concrete girder	Piles
3	Chesapeake Bay Bridge–Tunnel	140 m steel truss span	23 m concrete girder	PC cylindrical piles
4	Trans-Tokyo Bay Highway	2 × 240 m continuous steel box-box girders	130 m steel box-box girder 80 m steel box girder	Piles
5	Great Belt Fixed Link	1624 m suspension bridge	110 m concrete girder 193 m steel box girder	RC caissons
6	Øresund Fixed Link	490 m cable-stayed bridge	140 m composite girder 120 m composite girder	RC caissons
7	Shanghai Yangtze River Tunnel and Bridge	730 m cable-stayed bridge 220 m PC box girder	105 m composite girder	Piles
8	Busan–Geoje Fixed Link	475 m cable-stayed bridge 2 × 230 m cable-stayed bridge	90 m composite girder	Steel caissons
Summary	Eight projects	Four bridge types	Three materials	Two foundation types

PC: prestressed concrete; RC: reinforced concrete.

the second longest girder bridge—a continuous prestressed concrete (PC) box girder bridge with a central span of 220 m [3].

Steel truss bridges were a common type of bridge construction from the 1870s to the 1930s, and were used as the navigational channel bridges in the San Francisco–Oakland Bay Bridge, which was built in 1936. The original eastern section of the bridge was composed of five through-truss spans, a truss causeway, and a double balanced cantilever span of 427 m (the third longest of its time), all with double decks [4]. The Chesapeake Bay Bridge–Tunnel adopted steel truss girders spanning 140 m for its navigational channel bridge [5]. A steel truss and concrete slab composite girder with a maximum span of 140 m was also used in the Øresund Fixed Link in 2000 [6].

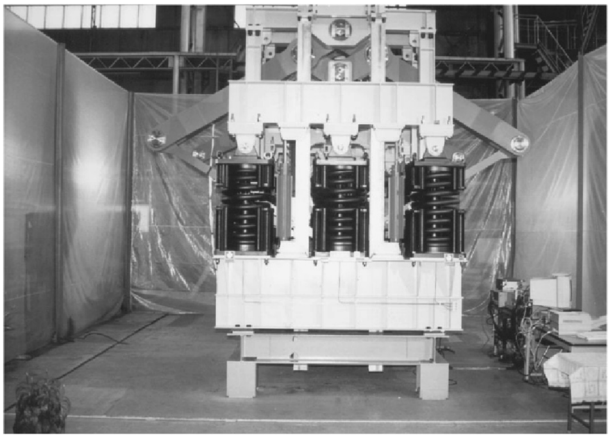


Fig. 1. A tuned mass damper.

As the youngest bridge type created in 1955, cable-stayed bridges have been widely used as sea-crossing navigational channel bridges in recent projects. The Øresund Fixed Link adopted a double-deck cable-stayed bridge with a span of 490 m and very heavy loads for both highway and railway; this project was the longest railway cable-stayed bridge at that time [6]. About 10 years later, the Shanghai Yangtze River Tunnel and Bridge was built with a 730 m twin box girder cable-stayed bridge [7], and the Busan–Geoje Fixed Link was built with two cable-stayed bridges, including a 475 m main-span bridge and a bridge with two main spans of 230 m [8].

Although these eight BIT combination projects include only two suspension bridges, major contributions have been made to bridge construction technology by the development of sea-crossing suspension bridges with long spans. The western section of the San Francisco–Oakland Bay Bridge contains two single main-span suspension bridge units with 701 m spans—the second longest at that time. These units were built and then connected by means of a central shared anchor block, as shown in Fig. 2(a), which was an excellent method at that time of maintaining the balance in terms of mechanics while reducing the costs [4]. Further progress in suspension bridges led to the development of a multiple main-span suspension bridge, which is a suspension bridge with two side spans, several main spans, and only two anchors on both ends; there is no additional anchor anywhere,

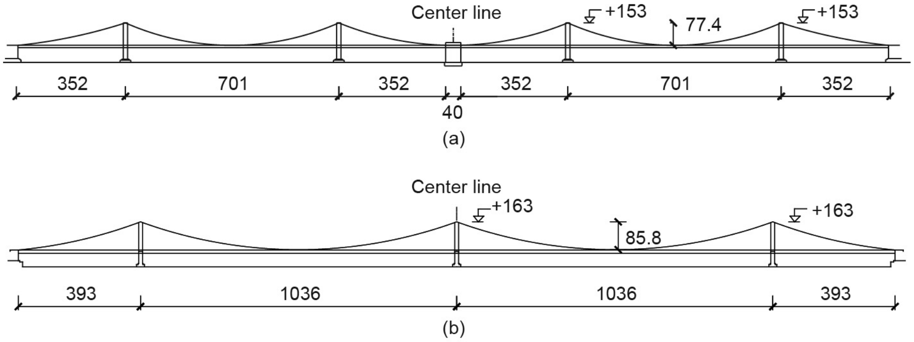


Fig. 2. Single or double main-span suspension bridges. (a) Two single main-span suspension bridges; (b) one double main-span suspension bridge. Unit: m.

as shown in Fig. 2(b) [9]. The other contribution of suspension bridge technology is the creation of a new world record in span length: The box girder suspension bridge in the Great Belt Fixed Link is 1624 m in length, and is further characterized by wind-resistance technology for flutter and VIV control with corner deflectors [10].

2.2. Non-navigational approach bridges

Due to their long length, as well as for engineering economy and construction convenience, non-navigational approach bridges are almost all girder-type bridges with steel, concrete, and steel–concrete composite structures. Since a sea-crossing bridge is built under severe conditions and with a deep-water foundation, it must be designed with a long span, and built on a span-by-span basis.

A non-navigational approach bridge usually requires a shorter span than a navigational channel bridge; therefore, concrete box girders are the first choice for reasons of economy. The first three sea-crossing combination bridges, which were built between 1936 and 1964, used reinforced concrete (RC) and PC girders; their longest spans ranged from 23 to 48 m.

The Trans–Tokyo Bay Highway, built in 1997, was the first sea-crossing combination bridge to use continuous steel box girders with span lengths ranging from 80 to 240 m [2]. Around the same time, the Great Belt Fixed Link adopted both steel box girders with a span of 193 m and PC box girders with a span of 110 m, so that each girder type would have the same weight for the span-by-span hoisting construction [10]. The three most recent BIT combination bridges built in the 21th century were all constructed using steel truss and concrete slab composite girders with spans of 90 to 140 m in order to maintain a balance between material strength and weight. It is interesting to conclude that the development of sea-crossing approach bridges has transitioned from concrete, to steel, and then to steel–concrete composite structures.

Almost all non-navigational approach bridges have been built using span-by-span techniques, which require the creation of large-scale ships or floating cranes for whole-span girder construction. The largest floating crane for bridge construction is the Dutch-built HLV Swanen Crane, made in 1991, which has a lifting capacity of 8700 t and a hoisting height of 76 m (Fig. 3(a)). The second largest is the Japanese-made FC Crane, made in 1995, which has a lifting force of 3000 t. In order to construct sea-crossing bridges in China, two large floating cranes were made, including the small Swanen Crane, with a lifting force of 2500 t, which was used for the east sea bridge construction in 2003 (Fig. 3(b)), and the Tianyi Crane, with a lifting force of 3000 t, which was used for the construction of the Hangzhou Bay Bridge in 2005. Both of these cranes, along with two more recently built cranes—the Changda Haisheng Crane, with a lifting force of 3200 t, and the Yihang Jintai Crane, with a lifting force of 4000 t—were used in the hoisting construction of the HZM Bridge (Fig. 4.).

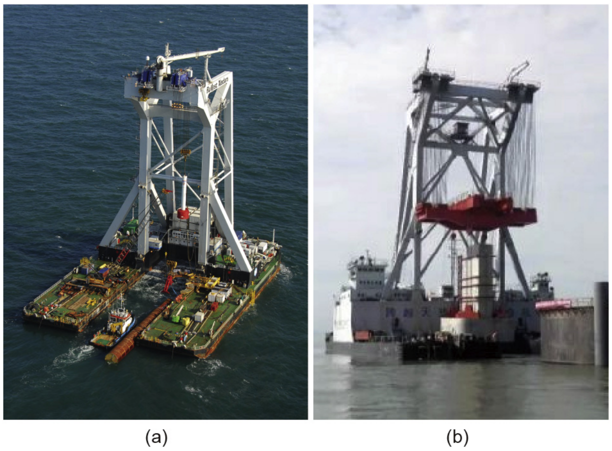

(a) (b)

Fig. 3. Giant floating cranes. (a) The Swanen Crane; (b) the small Swanen Crane.

2.3. Deep foundations

A deep foundation is a type of foundation that transfers the load of the bridge into the earth further below the surface than a shallow foundation. There are two main types of deep foundation: pile foundations and caisson foundations.

Pile foundations can be made using two different kinds of piles: driven piles made of steel, or drilled piles cast with RC. The first four BIT combination bridges in Table 2 and the Shanghai Yangtze River Tunnel and Bridge used driven or drilled pile foundations. Of these, the San Francisco–Oakland Bay Bridge holds the record for the deepest underwater foundation, at 74 m under water [4], and the Chesapeake Bay Bridge–Tunnel is the first bridge foundation to have been applied with hollow, precast, and prestressed cylindrical concrete piles [5].

A caisson foundation is a watertight retaining structure made of RC or steel, which is sunk into the ground to a desired depth and then filled with concrete to form a foundation. The remaining three BIT combination bridges in Table 2 adopted caisson foundations, which were prefabricated on the bank, shipped from the bank to the site, and then sunk onsite. The largest RC caissons were used for the Great Belt East Bridge, with the caisson for the pylon foundation being 78 m long, 35 m wide, and 20 m deep and having a weight of 30 000 t, and the caisson for the anchor foundation having an area of 6100 m^2 area and a mass of 50 000 t [10]. The largest steel caisson was used for the pylon foundation of the 475 m spanned cable-stayed bridge in the Busan–Geoje Fixed Link;

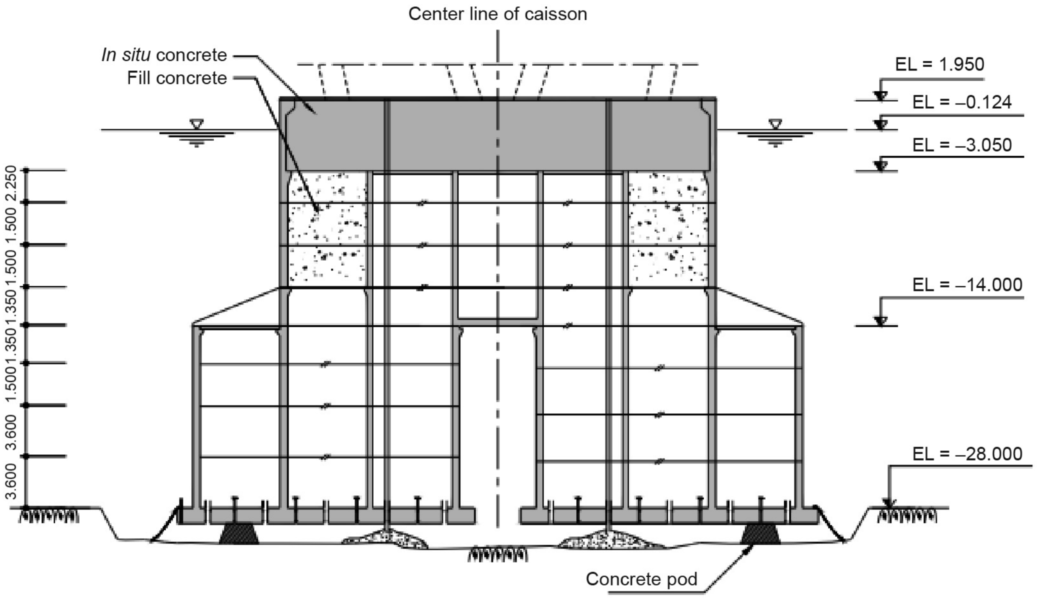


Fig. 4. A pylon steel caisson in the Busan–Geoje Fixed Link. EL: elevation. Unit: m.

this caisson had an area of 38 m × 20.5 m, a depth of 14 m, and a mass of 2600 t [8].

3. Artificial island construction

An island, whether natural or artificial, can be used to provide a connection between a bridge and a tunnel, or can constitute the transition from a bridge to a tunnel. If no natural island is available in area of the planned project, an artificial island must be constructed.

Human-made islands or islets vary in size and function, and have a long history. In modern times, artificial islands for land transportation have been constructed as pier foundations of bridges, ventilation towers of tunnels, and transit passages between a bridge and a tunnel. Land can be reclaimed from water to form an artificial island in two main ways: by filling in an existing islet or reef, and by reclaiming land from water.

3.1. First fill in an existing islet or reef and then protect the bank

The conventional way to reclaim land from water is to locate an islet or reef in shallow water, and then enlarge it using stones and other materials. Once the required land has been shaped, it is necessary to construct protective structures for the bank. Examples of artificial islands that were constructed by infilling the sea include Kisarazu Island of the Trans-Tokyo Bay Highway [11] and Peberholm of the Øresund Fixed Link [12]. These islands act as a transition from undersea tunnel to bridge.

3.2. First reclaim the sea, and then fill it in

The other way is to reclaim the water field using a cofferdam. In the past, cofferdams were built by dumping loose materials into the water in order to form a bank enclosing a region of water. Sheet-piling is one way to enclose a region of water; this method is usually adopted for shoal parts of water. If the land required is not large, the sinking of a prefabricated caisson is a possible alternative; this method was used for the construction of Kawasaki Island of the Trans-Tokyo Bay Highway [11] (Fig. 5). The caisson first serves as a starting shaft for the shielding machines, and then becomes a ventilation tower during operation.

Long-term settlement of an artificial island in soft ground occasionally happens. This is detrimental not only to the function of the protective structure of the island, but also to the connections to the bridge and tunnel. Improvement of the soft ground is important. Frequently used approaches include replacing the soft soil with sand (i.e., sand compaction piles or SCPs) or cement (i.e., deep cement mixed piles or DCMs). Another method involves the application of a pile foundation; however, this method is more expensive.

4. Sea-crossing tunnel construction

The San Francisco–Oakland Bay Bridge is comprised of eastern and western bridges connected via a tunnel on the Yerba Buena Island. This tunnel is actually a mountain tunnel (23 m wide, 18 m high, and 160 m long), and thus differs from the other BIT combined projects, which involve tunnels that have been constructed underwater.

The essence of a BIT project is a tunnel buried under the sea floor. The concept of an immersed tunnel was first applied to a BIT combined project with the Hampton Roads Bridge–Tunnel [13]. This tunnel was the world's longest immersed-tube tunnel, at that time, and the first to be constructed between two artificial islands.

The first successful use of a tunnel-boring machine (TBM) in construction of undersea tunnel occurred in the creation of the Channel Tunnel, between England and France in 1994. A few years earlier, in 1991, the construction of the Great Belt rail tunnel had been postponed due to the ingression of seawater, which drowned the TBMs. This project thus illustrates the importance of surveying before construction. In an area that lies in an earthquake zone, seismic action is another critical issue that must be addressed [14].

4.1. Immersed tunnels

The immersed tunnels that were adopted in these BIT combination projects did not differ significantly from those adopted elsewhere. Initial prefabrication of an immersed tunnel is usually performed by constructing and then sinking steel tubes that are

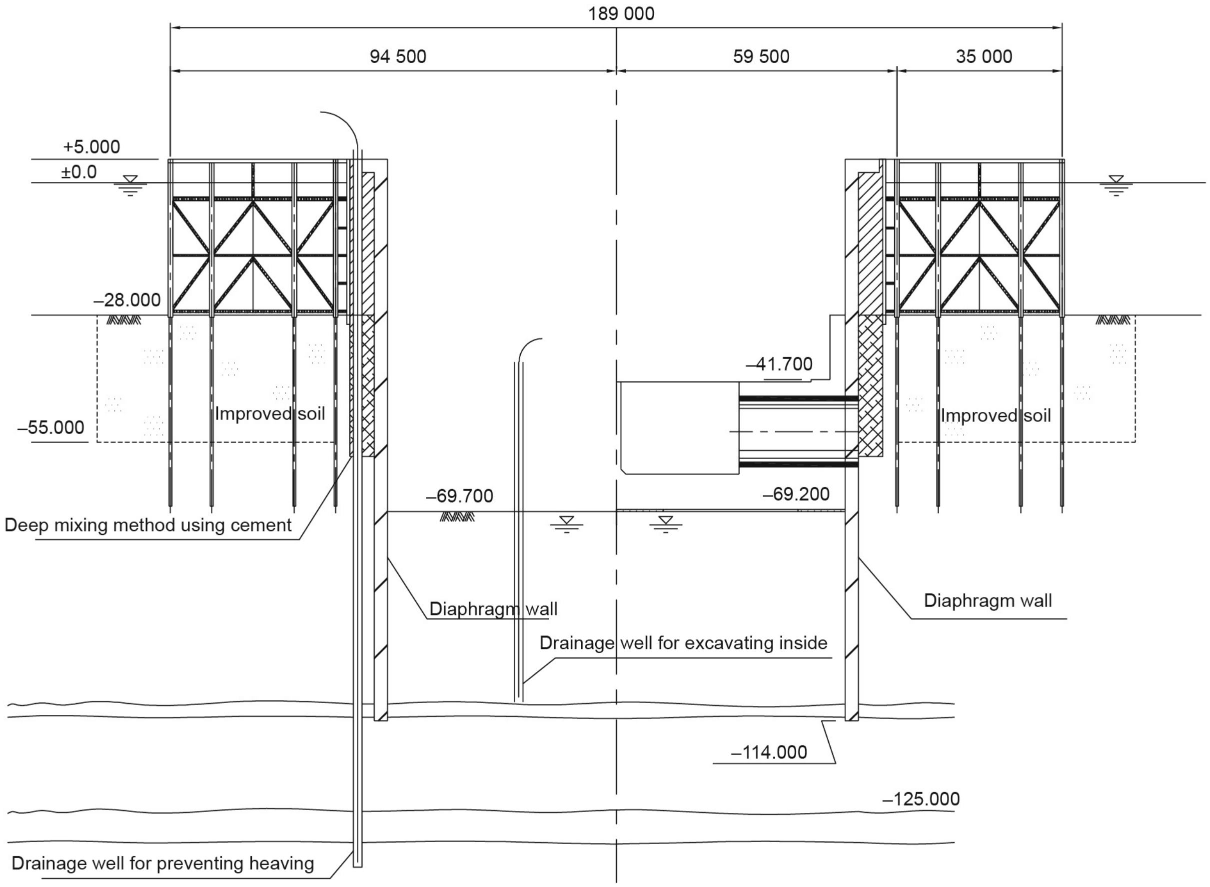


Fig. 5. Kawasaki Island. Unit: mm. Reproduced from Ref. [11] with permission of Ingenta, © 1993.

prepared in a ship-building dock [15]. This technology was also adopted by the Hampton Roads Bridge–Tunnel. With the evolution of immersed tunnel technology, the use of RC has gradually become more widespread in the construction of immersed tunnels [16]. The tubes of the tunnels are designed and prefabricated as either monolithic elements or segmental elements, based on the geological conditions and the loads to be considered during construction and operation. As shown in Table 3, recent BIT immersed tunnels that were constructed as RC segmental tunnels include the Øresund Fixed Link [12], the Busan–Geoje Fixed Link [17], and the HZM Bridge. Immersed tunnels that are prefabricated with a steel shell usually comprise monolithic elements. The projects of Hampton Roads Bridge–Tunnel and Chesapeake Bay Bridge–Tunnel were the examples of monolithic element of immersed tunnel.

Challenges that are often encountered in the construction of an immersed tunnel include digging a trench to hold the tube elements (or sections); improving the foundation in soft ground; prefabricating the elements; shipping, sinking, and aligning the

Table 3
Immersed tunnels of BIT projects.

			Hampton Roads Bridge–Tunnel	Øresund Fixed Link	Busan–Geoje Fixed Link	HZM Bridge
Conditions	Function		Road	Road and rail	Road	Road
	Length (km)		2.06 + 2.06	3.51	3.24	6.7
	Cross-section (m)		ϕ11.1 (ϕ9.9)[a]	38.8 × 8.6	26.46 × 9.97	37.95 × 11.4
	Depth to bottom (m) (below sea level)		33.9	30	50	44.5
	Strata		River sediments	Limestone, glacial deposits	Soft clay, medium sand	Soft clay, sand
	Earthquake zone		No	No	No	Yes
Design	Trench	Equipment	Digger	Dredger		
		Foundation	Gravel-bed	Screed gravel-bed, with hydraulic jack-up on wharf barge		
	Element (or section)	Type	Monolithic double-shell steel	Segmental RC rectangular box		
		Number	23	22	18	33
		Length	1 × 90 m	8 × 22 m	8 × 22.5 m	8 × 22.5 m
Construction	Prefabricating site		Ship-dock	Factory	Open dry dock	Factory
	Towing ship		2 tugs	4 tugs	4 tugs	12 tugs
	Sunk facilities		Steel framework straddling between two barges	Pontoon with external positioning system		

[a] ϕ is the diameter of a cross section of the immersed tube. The number in parenthesis is the inner diameter, the other one is outer diameter, of the tube.

sections; and then fixing the aligned tube with backfilled cover. In the construction of the first immersed tunnels, ditches were mainly dug by means of a digger installed on a barge, and tugboats were used to tow the sections. In order to lower a section of tube suspended between barges, cable machines were hired.

Several different methods can be used to fix the foundation of an immersed tunnel. One method involves pouring jetting sand or sandflow after aligning the sections of the tube; another method is to spread a gravel base with crushed stones before sinking the elements. Pile foundation may also be used in soft ground.

4.2. TBM tunnels

Although only three of the BIT tunnels were constructed using TBMs, each TBM tunnel broke the existing records for composite ground or soft ground (Table 4). The Great Belt Fixed Link [18] is used for rail transportation. The dual tunnels of the 9.6 km Trans-Tokyo Bay Highway [19] were shielded using eight TBMs, each of which constructed about 2.4 km. When two of the faced shielding machines met in the center of the tube portion, a connecting action was performed using ground-freezing technology at 60 m below sea level. To accommodate seismic action and ensure durability, a secondary lining with a thickness of 300 mm was designed, in addition to the segmental lining.

Ventilation is another key issue for long undersea tunnels [20]. In the Trans-Tokyo Bay Highway project, a prefabricated RC caisson was towed to the site and then sunk as a starting shaft for four TBMs.

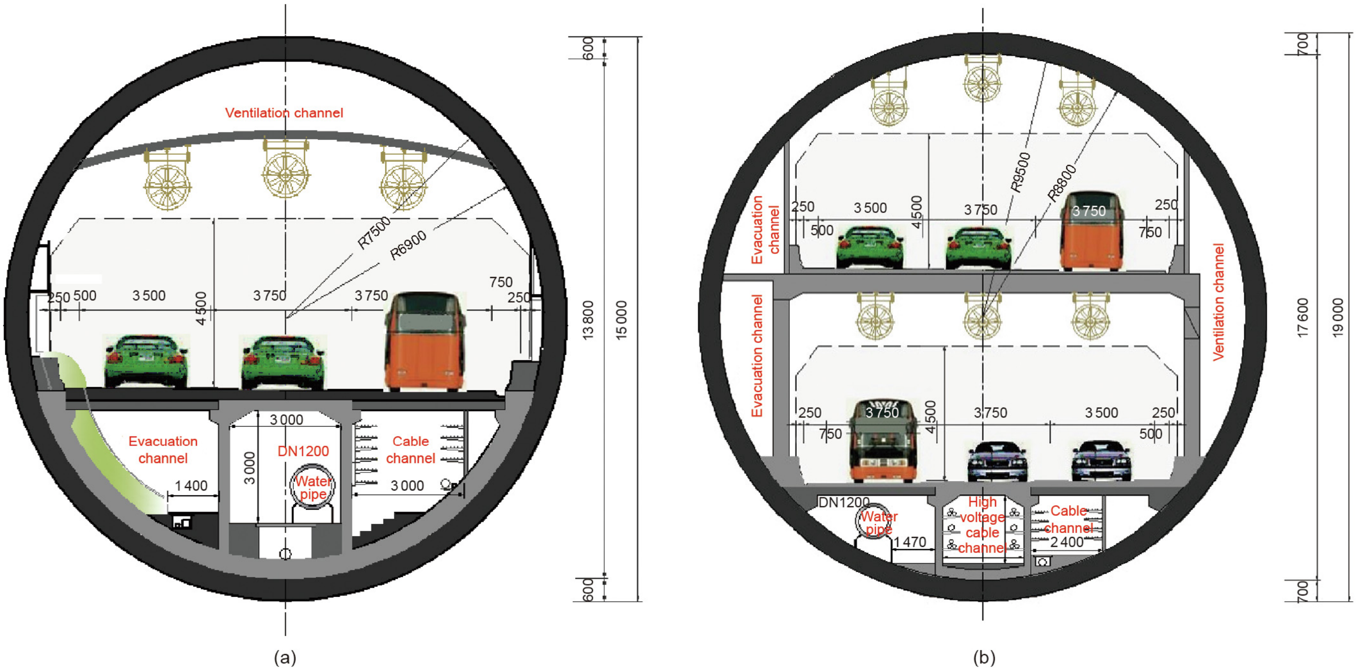
The Shanghai Yangtze River Tunnel and Bridge [21] held the records at that time for the largest diameter TBM machine (15.43 m) used for a road tunnel in operation, and for the longest shielding distance without a change cutter (7.0 km) in soft ground. More recently, starting in 2013, a larger earth pressure balance (EPB) TBM (ϕ17.45 m) was used in the Seattle SR99 Tunnel project in Washington, USA. The Tuen Mun–Chek Lap Kok Link, which provides an alternative route to the artificial island of Hong Kong International Airport via subsea tunnel, has a length of 4.2 km; its construction, which began in 2015, used a ϕ17.6 m mix-shield TBM. Large-diameter TBM tunnels continue to be in demand, as illustrated in Fig. 6.

Table 4
TBM tunnels of BIT projects.

			Great Belt Fixed Link	Trans-Tokyo Bay Highway	Shanghai Yangtze River Tunnel and Bridge
Conditions	Function		Rail	Road	Road
	Length (km)		8.02 + 8.02	9.6 + 9.6	7.47 + 7.47
	Depth to bottom (m) (below water level)		75	60	50
	Strata		Glacier residuals, mud limestone	Soft deposits	Soft clay, medium sand
	Earthquake zone		No	Yes	Yes
Design	Linings	Segments	5 + 1	11 + 1	9 + 1
		Dimensions (mm)	400 × 1650	650 × 1500	650 × 200
		Inner lining (mm)	Without	300 (RC)	Without
Construction	TBM	Type	EPB	Slurry	Mixed-slurry
		Diameter[a] (m)	ϕ8.7	ϕ14.14	ϕ15.43
		Number	4	8	2

EPB: earth pressure balance.

[a] Here, diameter refers to the bore diameter of the TBM tunnel.



(a)

(b)

Fig. 6. Cross-section of a TBM tunnel for mixed vehicles. (a) One deck, three lanes; (b) double deck, three lanes. Unit: mm. Source: CCCC Highway Consultants Co., Ltd.

5. Conclusions

This article reviews the state-of-the-art construction technology for bridges, artificial islands, and tunnels that was used to build eight SCFL projects with BIT combinations. The key construction technologies of sea-crossing bridges can be categorized into navigational channel bridges, non-navigational approach bridges, and deep foundations. The most outstanding technological contributions to navigational channel bridges come from long-span suspension bridges and cable-stayed bridges with single or double main spans. The most significant aspects of non-navigational approach bridges are the method of whole-span girder-hoisting construction using a huge floating crane, and the evolution of structural materials from concrete, to steel, and finally to steel–concrete composite structures. The deep foundations of sea-crossing bridges are primarily created as pile foundations of driven or bored piles, or caisson foundations made with concrete or steel.

The two main methods of artificial island construction are as follows: ① First fill in an existing islet or reef, and then protect the bank; or ② first reclaim the sea, and then fill it in. The two main undersea tunnel-construction methods include the immersed-tube tunnel method and the TBM method. Significant challenges that must be overcome with technical innovation in the construction of immersed-tube tunnels include: digging a trench to hold the tube elements (or sections); improving the foundation in soft ground; prefabricating the elements; shipping, sinking, and aligning the sections; and fixing aligned tube. The selection of machine in accordance with ground condition is important in the TBM method. Ventilation and evacuation systems are detrimental issue for undersea tunnels. In regions with seismic action the ways to improve seismic resistance, such as by means of a secondary lining TBM tunnel and aseismic joint for immersed tunnel, are also very important technologies.

References

[1] List of bridge–tunnels [Internet]. Wikipedia; [cited 2018 Dec 24]. Available from: https://en.wikipedia.org/wiki/List_of_bridge–tunnels.

[2] Nagai M, Yabuki T, Suzuki S. Design practice in Japan. In: Chen W, Duan L, editors. Bridge engineering handbook. Boca Raton: CRC Press; 1999.

[3] Shao C. Conceptual design of long span continuous composite box girder bridge. Bridge Constr 2008;1:41–3.

[4] Middlebrook RF, Moldova RV. San Francisco-Oakland Bay Bridge. Struct Mag 2014 Feb:26–8.

[5] Yordy SW. The Chesapeake Bay Bridge and tunnel parallel crossing. In: Proceedings of the Structures Congress; 2006 May 18–21; St. Louis, MO, USA. Reston: ASCE; 2006.

[6] Zuo M. Design and construction of bridge over Øresund Strait. China Harbour Eng 2001;1:5–9.

[7] Lu Y, Shao C. Engineering design and key technology research of Shanghai Yangtze River Bridge. Shanghai Constr Sci Technol 2006;2:5–8. Chinese.

[8] Hu Y, Zhou P. Introduction of Busan–Geoje Fixed Link. World Bridges 2006;4:5–6. Chinese.

[9] Gimsing NJ. Cable supported bridges—concept and design. New York: Wiley; 1997.

[10] Miller FP, Vandome AF, McBrewster J. Great Belt Fixed Link. Riga: Alphascript Publishing; 2010.

[11] Shioi Y, Arakawa T. Man-made islands, Trans-Tokyo Bay Highway, Japan. Struct Eng Int 1993;3(3):155–7.

[12] Hampton Roads Bridge–Tunnel history [Internet]. Norfolk: VDOT. c2019 [cited 2018 Dec 24]. Available from: http://www.hrbtexpansion.org/learn_more/hrbt_history.asp.

[13] Yu HT, Yuan Y, Xu GP, Su QK, Yan X, Li C. Multi-point shaking table test for long tunnels subjected to non-uniform seismic loadings—part II: application to the HZM immersed tunnel. Soil Dyn Earthquake Eng 2018;108:187–95.

[14] Grantz WC. Steel-shell immersed tunnels: forty years of experience. Tunn Undergr Space Technol 1997;12(1):23–31.

[15] Rasmussen NS. Concrete immersed tunnel: forty years of experience. Tunn Undergr Space Technol 1997;12(1):33–46.

[16] Janssen WPS, Lykke S. The fixed link across the Øresund: tunnel section under the Drogden. Tunn Undergr Space Technol 1997;12(1):5–14.

[17] Janssen W, Haas PD, Yoon YH. Busan-Geoje Link: immersed tunnel opening new horizons. Tunn Undergr Space Technol 2006;21(3–4):332.

[18] Odgård A, Bridges DG. Design and risk analyses for the Great Belt East Tunnel. Struct Eng Int 1995;5(4):216–7.

[19] Uchida K. Trans-Tokyo Bay Highway. Struct Eng Int 1998;8(1):7–9.

[20] Yamada N, Ota Y. Safety systems for the Trans-Tokyo Bay Highway Tunnel project. Tunn Undergr Space Technol 1999;14(1):3–12.

[21] Huang R. The Shanghai Yangtze River Tunnel. Theory, design, and construction. Boca Raton: CRC Press; 2008.