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Chapter

Design of Immersed Tunnel and How We Research Submerged Floating Tunnel

Wei Lin, Ming Lin, Haiqing Yin and Xiaodong Liu

Abstract

This chapter begins with the discussion of the immersed tunnel design, concerning its reason of existence, historical review, general design, transverse and longitudinal design, the interaction, and the critical issues. The discussion is founded on the author's 10 year experience in building the Hong Kong-Zhuhai-Macao Bridge (HZMB) immersed tunnel as a site design engineer. The experience of building immersed tunnel is transferable to build the submerged floating tunnel, which has never been built. In author's opinion, the submerged floating tunnel (SFT) technique will be the next generation of IMT technique. In the second part of this chapter, the author proceeds to discuss the strategy of SFT research and the latest development in CCCC SFT Technical Joint Research Team.

Keywords: immersed tunnel, submerged floating tunnel, design, research, civil engineering

1. Introduction

Immersed tunnelling is an art of guiding the great natural force, the water, to do engineering works: "guiding" buoyancy for transportation, "guiding" water weights for immersion, and "guiding" hydrostatic pressure for connection. Submerged floating tunnel (SFT) is an even more extreme form of this art, as the full weight of tunnel or most of it is balanced by buoyancy. This chapter discusses the method of immersed tunnel design and SFT research.

2. Design of immersed tunnel

2.1 Reason of existence

"In order successfully to conceive and to plan a structure or building of any kind it is necessary to investigate and to know well its reasons for existence ..." is the first line of the book the *Philosophy of Structures* written by Eduardo Torroja. A city that has water barriers but has no bridge is like a mansion with no elevator, answered Strauss, the chief engineer of the Golden Gate Bridge. However, a bridge could have

its limitations: its span could disturb the ship traffic, and its tower could disturb the air flight if the bridge were built close to an airport.

When a bridge crosses a harbour, the water salinity in the harbour may change due to the slowed water exchange between offshore sea and the fresh inland water, as the bridge piers disturb the water exchange, giving impact to the living condition of sea resident in the harbour region. In Øresund tunnel compensate dredging was performed to eliminate the said effect. In Hong Kong-Zhuhai-Macao Bridge project, the two offshore artificial islands, which connect immersed tunnel and bridges, have a minimum length so that the total water blockage ratio of the entire link is controlled minimum. The water blockage ratio was defined as the projected area of the link that disturbs the water exchange along the axis of the link divided by that of the total area of the water.

The above is the reason of existence for a subaqueous tunnel. Whether to build a bored tunnel or immersed tunnel varies and depends on specific project condition. One commonly seen reason to choose immersed tunnel is more cost-effective because the immersed tunnel is buried shallower than bored tunnel; the latter requires typically a buried depth not less than 1–1.5 times of the bored diameter for construction. In the island and tunnel project of Hong Kong-Zhuhai-Macao Bridge (HZMB Island-Tunnel Project), there were two main reasons for choosing immersed tunnel. Firstly, as both ends of the immersed tunnel connect to bridges via two artificial islands (**Figure 1**), the length of the artificial islands would be twice smaller, leading to smaller water blockage ratio. Comparatively, the bored tunnel would be buried deeper than that of the immersed tunnel due to its longer transition length. Secondly, the geology risk such as encountering boulder for bored tunnel is high, and thus the risk of time delay for the entire 55 km long link is high.

Despite the advancing of technology, the understanding about the marine environment is still limited; the risk of construction of an immersed tunnel in the offshore condition is relatively high. “Stories” of sinking, flooding, and damage exist such as [1, 2]. Therefore, one aim of the design of an immersed tunnel is to find a way to mitigate the construction risk by proposing the appropriate scheme and technical requirement.



Figure 1.
Overview of HZMB link from Hong Kong side.

2.2 History and state of the art

The earliest attempt was in 1810. The British Engineer Charles Wyatt won the competition by proposing the immersed tunnelling concept, using brick-made cylinders, each around 15.2 m long, and sinking them to a dredged river bed, and then backfilling them. A test was carried out with much care by another British engineer with two specimens, each 7.6 m in length and 2.74 m in diameter. The test results are positive. However, the cost was overrun, the project terminated. It was not until 1893 when three sewer pipelines (diameter of which is only 1.8 m) were made by this construction method. The first traffic immersed tunnel was built in 1910 [1].

The immersed tunnel is, as per the defined term of ITA WG11, a tunnel consisting of several prefabricated tunnel elements, which are floated to the site, installed one by one, and connected under water. **Figure 2** shows the working image of the HZMB Island-Tunnel Project. This tunnel consists of 33 tunnel elements and a closure joint (**Figure 3**). The immersion had been completed on May 5, 2017. Since then it becomes the longest roadway immersed tunnel. This record will soon be broken by the Fehmarn tunnel, which will be around 18 km long and consist of 89 tunnel elements.

2.3 General design

The environment acting on the immersed tunnel depends on the location of the tunnel. Thus, the tunnel alignment needs to be fixed in the first place.

The plane alignment of the tunnel mainly depends on its two ends, the access point of the tunnel portal. For the vertical alignment, that is, the elevation of the tunnel, several considerations need to be taken. The elevation of the tunnel ends shall neither be too high nor too low. If the ends of the tunnel were too high, the immersion depth is inadequate for the hydraulic connection of the first tunnel

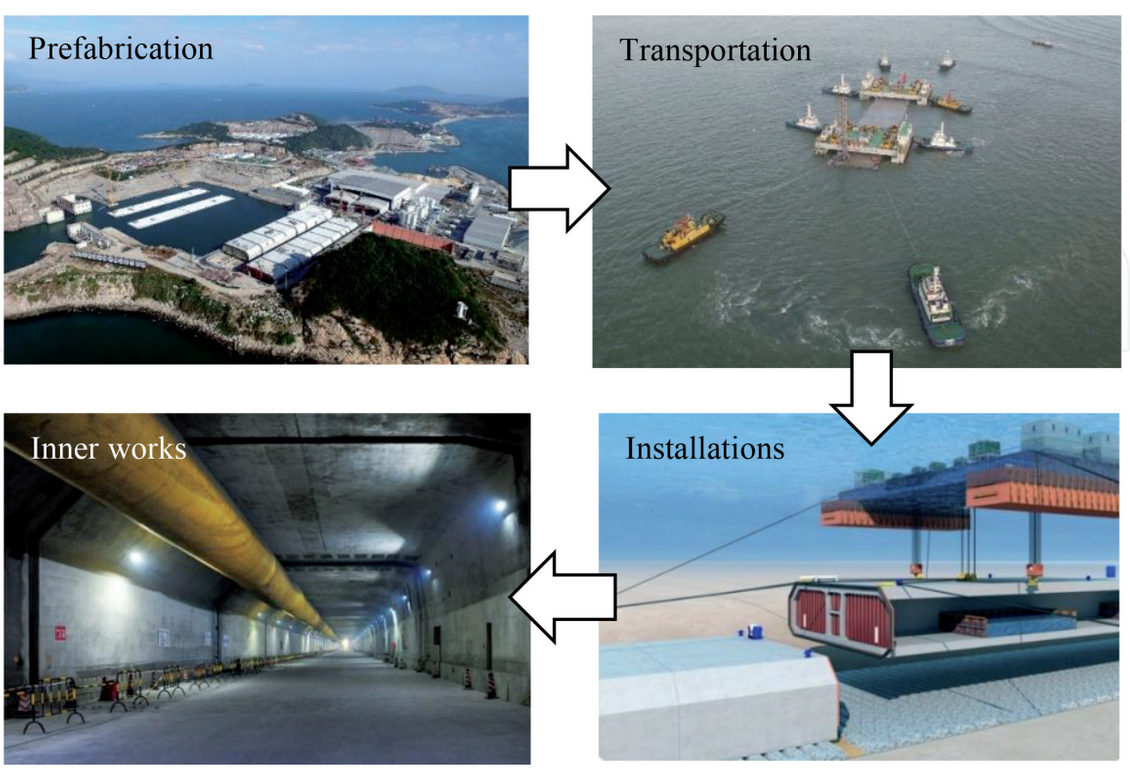


Figure 2.
Construction works of the immersed tunnel in HZMB Island-tunnel project.

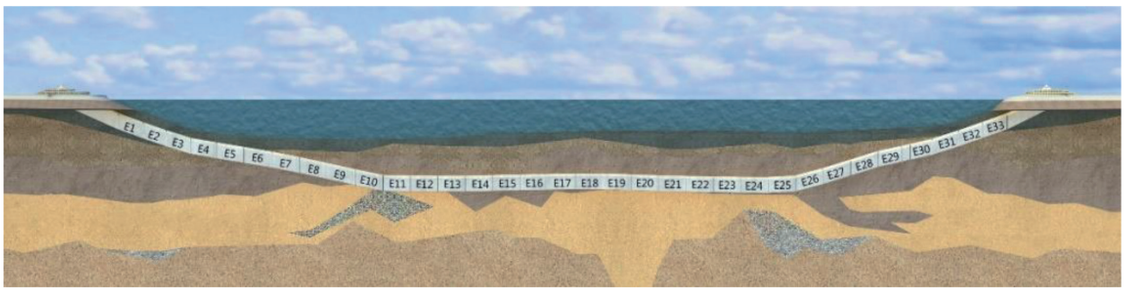


Figure 3.
Vertical alignment of the immersed tunnel consists of 33 tunnel elements in the HZMB Island-tunnel project.

element that connects to the land structure. If the ends of the tunnel were too low, the risk of flooding increases as more massive amount of water could rush into the tunnel due to rain or overtopping. Moreover, the elevation of the middle section of the tunnel depends on the navigational requirement of ships passing over the tunnel. After the elevation of tunnel ends, the section under the navigation channel was fixed. The remained work is to "draw a line" for the vertical alignment of the tunnel. The principle as an experience by the pioneer is to dive down or rise up as quickly as possible. In this way, the tunnel length will always be the shortest, as can be proven in **Figure 4**.

As long as the tunnel alignment is fixed and the environment that will be encountered by the tunnel is thus fixed, the actions such as wind, wave, current, and water depth can be defined as well. In short, structural design can be done.

The immersed tunnel consists of one or several tunnel elements. Therefore, the design of the immersed tunnel is, in fact, the design of tunnel elements. The design of each tunnel element usually distinguishes from each other. One reason is that each tunnel element exists in a more or less different environment and the actions on them are different. The other reasons can be seen in **Figure 5**, as an example from HZMB Island-Tunnel Project.

As for the design of each tunnel element, the problem can be further discretized into several subproblems, as will be elaborated in Sections 2.4 and 2.5.

2.4 Transverse structure

The transverse design needs to satisfy three aspects: the structural issue, the weight balance, and the interior space.

The structural issue is a familiar subject to structural engineers. Not only the permanent scenarios but also the temporary scenarios of construction shall be

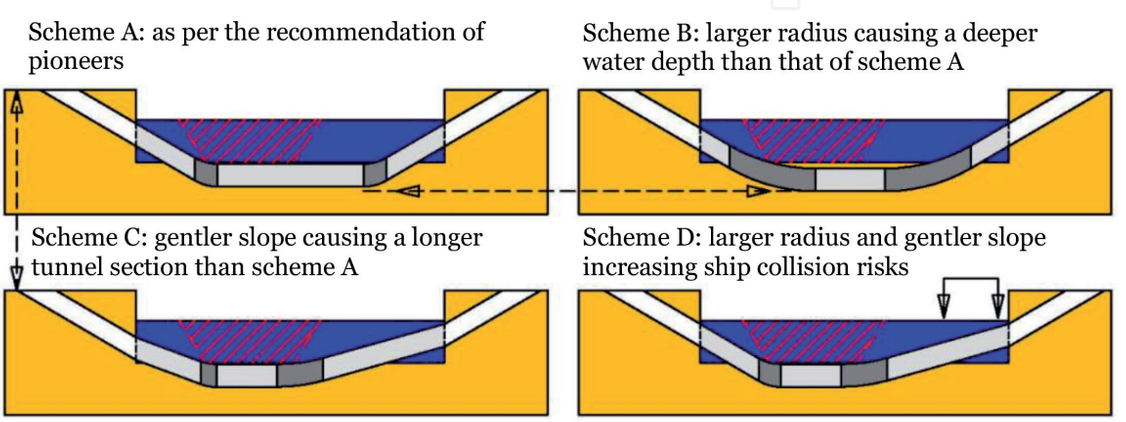


Figure 4.
Illustrative image showing the principle of drawing vertical alignment.

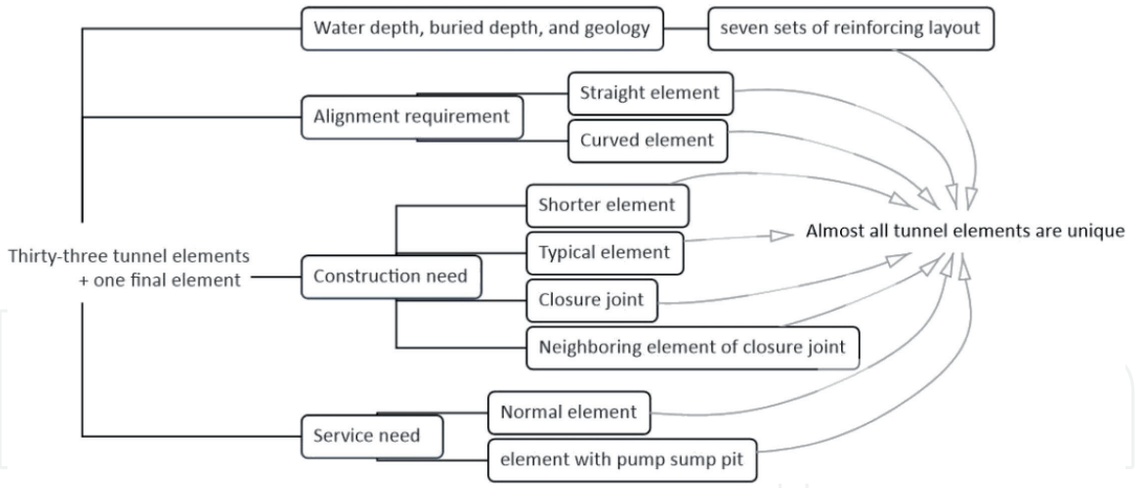


Figure 5.
Uniqueness of immersed tunnel element design in HZMB Island-Tunnel Project.

considered regarding the boundary condition and load and actions, because the permanent condition of the immersed tunnel may not govern the design as it would do for many other types of structures.

The weight balance means that the tunnel element can float when being transported and can sink for immersion and underwater connection; those are construction need. Further, in the service period, attention shall be paid to ensuring adequate safety factor against uplift, in case of extreme weather conditions. To note, the construction rigs may affect the freeboard of tunnel element when it was afloat (**Figure 6**).

The interior space requirement depends on the traffic clearance (i.e. the minimum space requirement for traffic defined by the relevant regulations/code), the space for interior installations such as ventilator and fireproof panels, and the extra space for accommodating construction tolerances from the prefabrication and immersion of tunnel element.

With the increased awareness of comfort design and life safety, more attention is paid to ventilation and evacuations, in addition to the above said three basic needs. **Figure 7** shows three ventilation solutions, namely, the longitudinal ventilation, semi-transverse ventilation, and transverse ventilation. The longitudinal ventilation

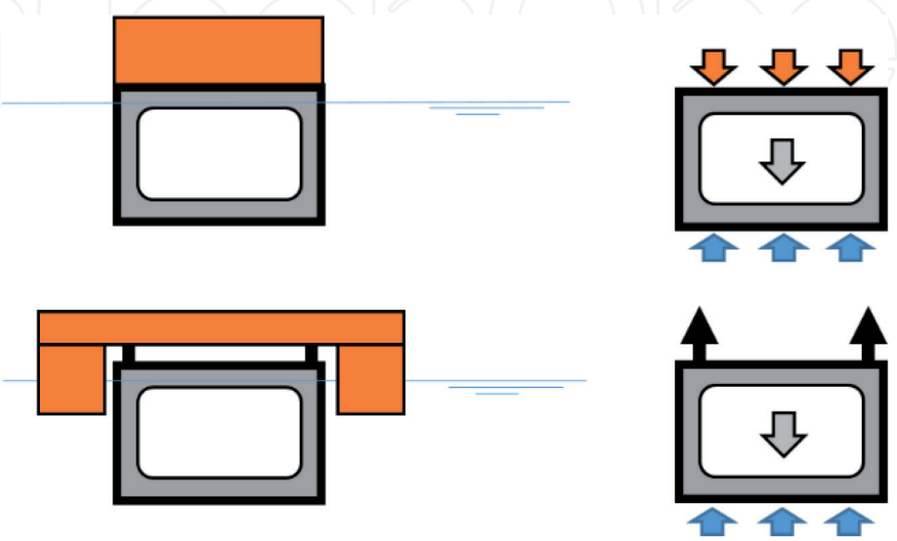


Figure 6.
Immersion rigs of pontoon sit on tunnel element and reduce the freeboard of the tunnel element while catamaran increases it.

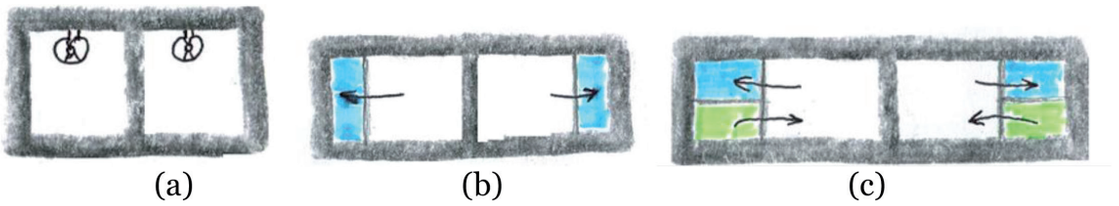


Figure 7.
Ventilation solutions of immersed tunnel: (a) longitudinal, (b) semi-transverse, and (c) transverse.

requires fans that increase the height of the tunnel, leading to a deeper foundation and more dredging works. The transverse ventilation requires special bores and thus increases the width of cross-section, also leading to more dredging volume. The semi-transverse ventilation was somewhere in between. Concerning the setting of the inner walls in the cross-section, **Figure 8** shows its relation with the safety concept. Also, purely from a structural point of view, the more inner walls, the less governing the largest span of the cross-section structure. In the 1990s Japan tunnel favoured a cross-section of two tubes with two galleries, and the double walls gave benefit to both the robustness of watersealing and the safety of the structure.

2.5 Longitudinal structure

The longitudinal design needs to consider three aspects as well, namely, the structural system, element length, and joint configurations.

The earlier immersed tunnel had monolithic tunnel element. The cross-section is circular shaped; the structure type is steel shell. To increase the space use from 1937 to 1942, the first reinforced concrete box structure tunnel element was made. Around 10 years later, the segmented-type tunnel element made of reinforced concrete was developed in the Netherlands. In Øresund tunnel, factory method was

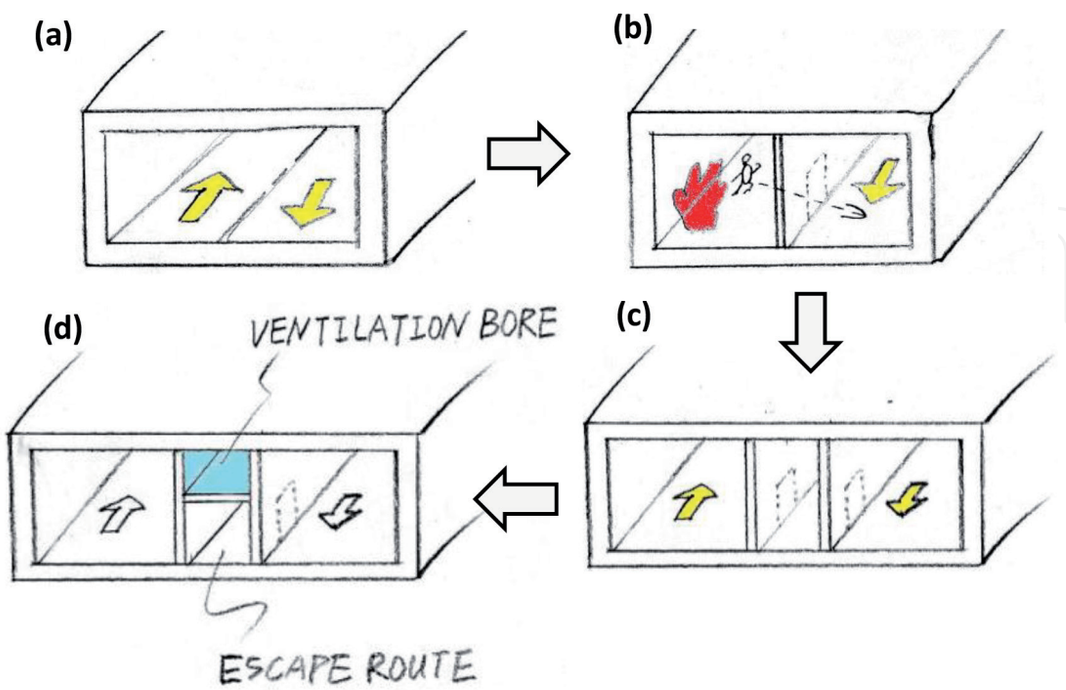


Figure 8.
Safety and transverse design: (a) two-way traffic in one bore, collision risk is relatively high; (b) two traffic bores separated by a wall, evacuated people could be hit by vehicle on the other bore; (c) two traffic bores separated by two walls; (d) the centre part is further split into two bores, one for evacuation and the other for smoke extraction.

invented to produce tunnel element of 55,000 tons in a production line [3]. That method was used in the HZMB Island-Tunnel Project (**Figure 9**) for the second time; the production line was capable of incrementally launching the 76,000 t tunnel elements (in which five of them were plane-curved tunnel elements with curvature R5500) without cracking them. In around 1990 in Japan, no more place along the shore can be found to prefabricate tunnel element. Further, the experienced concrete vibration workers were not adequate. In this background, the steel-concrete-steel sandwich structure box-type immersed tunnel element was developed as its concrete requires no vibration; the pouring of concrete can be completed in the floating stage of the tunnel element.

The length of the tunnel element determines the number of tunnel element, given the fixed tunnel length. On the one hand, the longer tunnel element reduces the total number of element and thus reduces the total number of immersion joint, the main works of which are bulkhead and its embedded part, Gina gasket water-stop, and so forth. Further, fewer tunnel elements mean fewer times of the immersion works and thus less risks of construction. On the other hand, the shorter is the tunnel element, the less is the total prefabrication cost as less area of land near the water is needed for prefabrication of tunnel elements, and the less sensitive of the tunnel element structure to the differential settlement issue, hence the less cost of the prestressing system. The above shows that the element length design is a matter of keeping a balance and finding the optimum.

The immersion joints need to ensure watersealing in tunnel's service period taking into account all the unfavourable scenarios such as earthquake, differential settlement, and accident like sunken ships; it also needs to provide a way of connection of tunnel element for construction. **Figure 10** shows immersion joints of a typical tunnel element in prefabrication yard.

2.6 Interaction

To optimise the scheme, the works described in Sections 2.4 and 2.5 may be named as "analysis", and the subsequent work, on the contrary, as described in this section, can be named as "synthesis", that is, understanding the links between the factors and then looking for the most satisfying design schemes by means of design iterations.

In the transverse structure of the immersed tunnel, the three aspects mentioned in Section 2.4 are interlinked. For example, strengthened structure causes thickened slab or more densely arranged reinforcing bars, either of them would give additional weight to the structure; the weight balance is broken and thus needs to be rebalanced by adjusting the inner space of the tunnel. Taking another example,

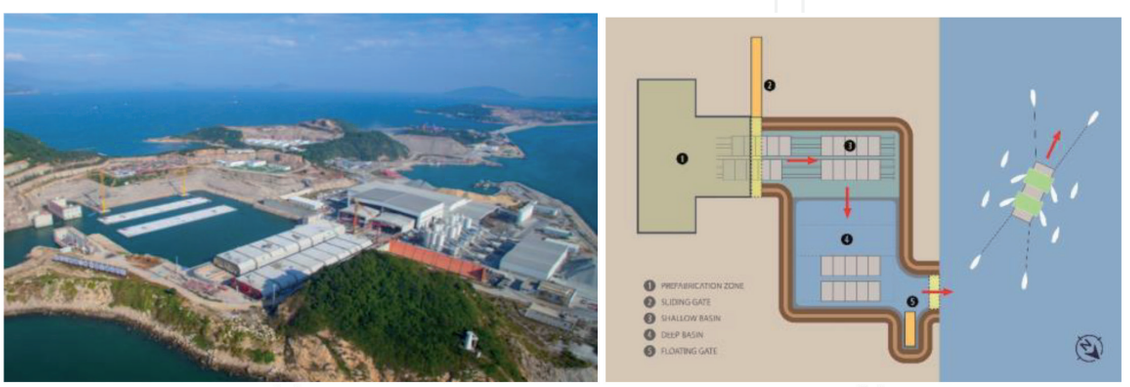


Figure 9.
Factory for prefabrication of immersed tunnel element. (a) Photo HZMB Island-tunnel project and (b) plane layout.



Figure 10.
Photo of immersion joint of tunnel element in HZMB Island-tunnel project.

enlarged inner space leads to the increased buoyancy, which requires an added weight by thickening the walls to balance the extra buoyancy.

It does the same to the longitudinal structure of the immersed tunnel element. Moreover, the longitudinal structure is interlinked with the transverse structure. Following the above example, the thickened wall allows for larger shear key, which could increase the capacity of shear key; it also means the ability of survival of tunnel element against differential settlement increases. In this way, the tunnel element can be made longer.

Another link is that the design of immersed tunnel is related to time and space, as shown in **Figure 11**. The prefabrication of tunnel element, the installation, and the inner works of tunnel often take place in three different locations. Moreover, to complete the work, there are sequences to follow. This figure shows that the immersed tunnel design, to some degree, cannot be reproduced; hence, the nature of the design work for an immersed tunnel is indeed to eliminate the gaps of space or discontinuity of time of the immersed tunnelling works.

2.7 Two fatal issues

The success or failure of an immersed tunnel project largely relies on the prefabrication yard and the water sealing of tunnel. For the former, in HZMB Island-Tunnel Project, great efforts were made to find a suitable place, six locations were investigated, and the final selected location was on an island for three advantages. First, the geological condition is hard rock, suitable for the incremental launching system of the factory method. Second, the transportation distance of the tunnel element for immersion works is shortened to only 11 km. And third, the prefabrication yard is capable of producing two tunnel elements while store six tunnel elements inside the dock, eliminating the risk of tunnel element damage from the frequent typhoon in summer time of each year.

2.8 The latest technological developments and the future

To the author's best knowledge, in Bosporus Strait, the immersed tunnel had been built around 70 m below the water surface. In Busan immersed tunnel, special facilities were invented to position the tunnel element under the water accurately and to make direction correction of the tunnel element automatically.

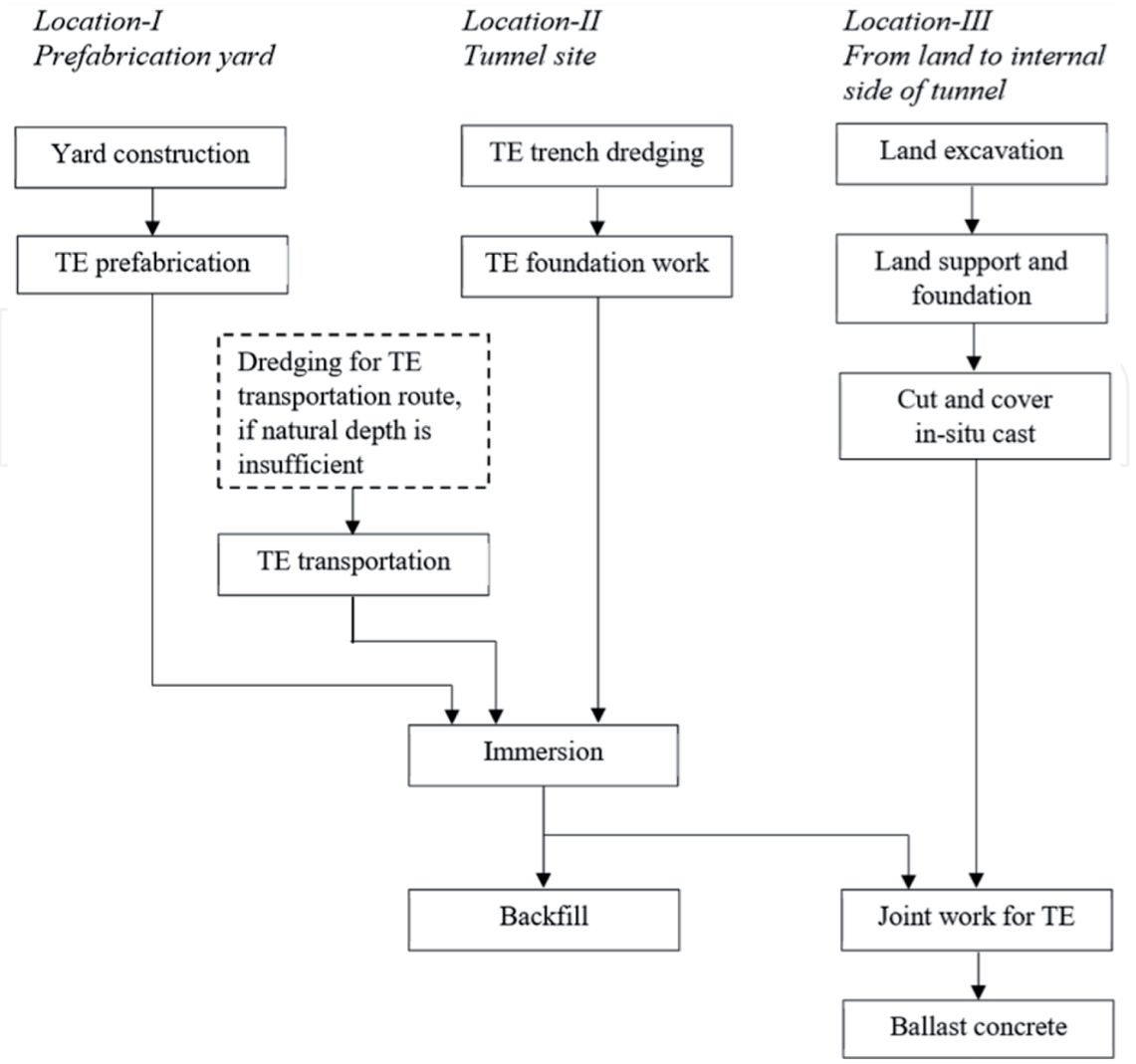


Figure 11.
The workflow of the immersed tunnel shows the discontinuity and gaps of space and time.

In HZMB Island-Tunnel Project, 35 times of installations were carried out in 3 years in offshore condition with no major accident. The novel foundation solution of composite foundation layer and underwater surcharge were implemented, and the settlement of the immersed tunnel had been controlled within 5–8 cm. Nearly 100 million cubic metres of concrete were cast for the main structure of the 5.664 km long immersed tunnel element with no cast crack. Further, the tunnel element was deeply buried below the seabed; maximally 22 m thick sediment will cover on the roof of the tunnel element. And this extremely high overload (as for the tunnel element structural design of immersed tunnel longitudinally) is overcame by the structural innovation of semi-rigid tunnel element structure, setting permanent prestressing; the structure can become more robust taking the advantage of both monolithic and segmented tunnel element (**Figure 12**). The memory bearing can prevent concrete cracking at immersion joint [4]. The deployable element [5] is a highly effective and rick-manageable way to build the closure joint of the immersed tunnel.

The technological development has been pushing the boundary of application in immersed tunnelling regarding length and depth. However, to cross much deeper and broader water, all existing solution of bridge and tunnel would fail; in that case, the SFT shows its good reason of existence. The pioneer engineer of immersed tunnel Walter Grantz left one thought: "all immersed tunnels are briefly SFT's while they are being lowered into position."

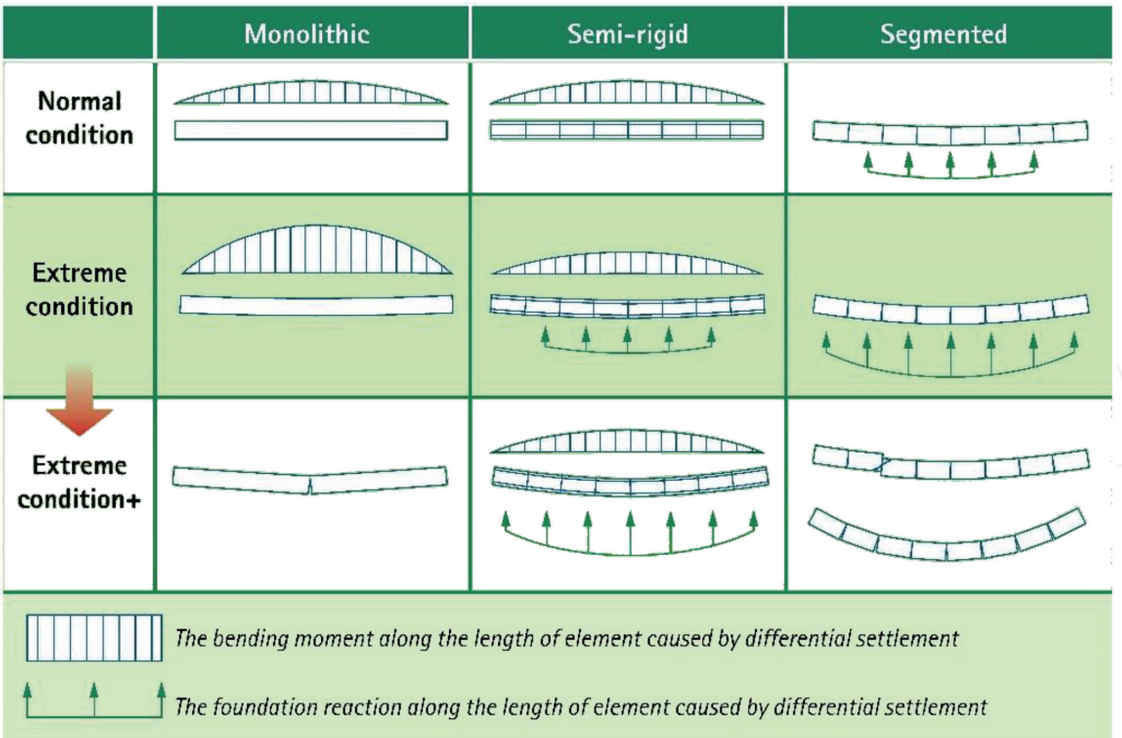


Figure 12.
The mechanism of the novel semi-rigid tunnel element structure.

3. How we research submerged floating tunnel

3.1 Main threads

The SFT is, as per the term defined by ITA WG11, a tunnel through water that is not in direct contact with the bed. Moreover, it may be either positively or negatively buoyant and may be suspended from the surface or supported from or tied down to the bed (**Figure 13**). It has been proposed a century ago but has never been realised due to various reasons, such as fear of invasion, fishery problem, or ship collision. Therefore, to realise SFT attention must be paid to safety. The safety is in direct connection with SFT's structural form and environment. The former can be designed and developed as per our will and, hence, should be the main threads of SFT's research. Further, the more details the SFT's structural form being developed, the more risk issues regarding it will be raised. Therefore, the risk should

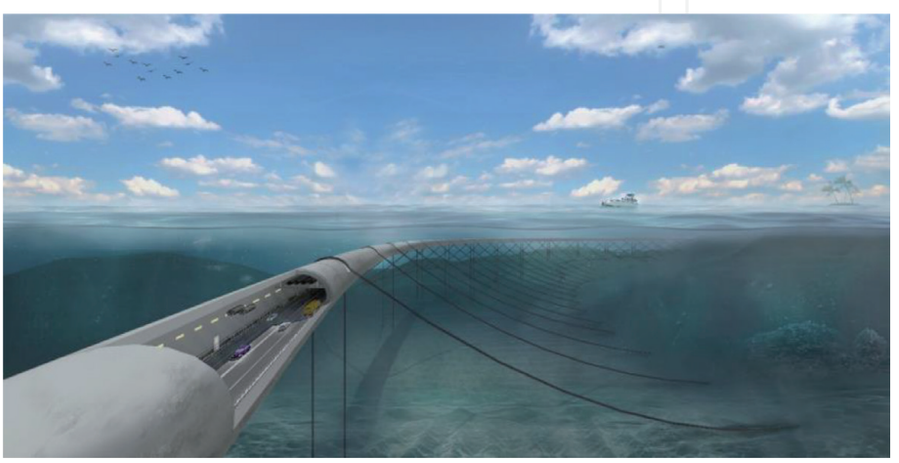


Figure 13.
Image of an SFT with positive buoyant tied down to sea bed.

be regarded as an accompanying thread in addition to the main thread of SFT's research. The study of risk can be carried out both quantitatively and qualitatively.

If the SFT is small, we can hold it in our hand; our research method is to produce hundreds of SFT prototypes, test them, improve them, and perfect them. However, our research resources are so limited compared to the real size of SFT; we can hardly build one SFT prototype, not to mention to agitate and test the real SFT. Therefore, the applicable way to research SFT is to build SFT model instead. The model can be further distinguished by tangible and intangible one, which is, in a researcher's language, the mathematical model and the physical model. The model supports the SFT's thread to gain the true knowledge of SFT.

Another support to the research is the development of the construction method. An SFT design scheme that can satisfy all needs and requirements but cannot be built in realistic work is of little value/use to the engineering knowledge. Sometimes we can hardly resist our temptation to study the details and believe that our work can improve the efficiency of the work; in fact, the parallel study on construction method can help shorten research period and lower the overall cost. Construction experiences from other relevant works such as immersed tunnel (**Figure 14**) and offshore structures may be transferable to SFT.

3.2 Structural form

In order to understand the links between the SFT structure and its risk, we need to discretize the structural form of SFT into elements, part of which needs to be further discretized into sub-elements. By changing a parameter of the element or sub-element, we can observe how the change affects the structural behaviour or safety of SFT. In this way, we gradually understand SFT's nature. **Figure 15** shows the author's understanding of the relation of structure and safety. This figure needs to be further expanded to cover the full picture of understanding of SFT before making a real one.

The safety belongs to our feeling and judgement, while the element or sub-element of an SFT is a matter; how do the two interact with each other? Mathematics is the gear of interaction. For example, if we set δ as deflection and t as time, then $\partial^2 \delta / \partial t^2$ stands for the deflection's second derivative to time, that is, acceleration. The deflection not only determines the member force of the structure but also affects our safety feeling if we pass through an SFT. The acceleration will make us have "seasickness", if the value of it is large due to improper design of the structure.

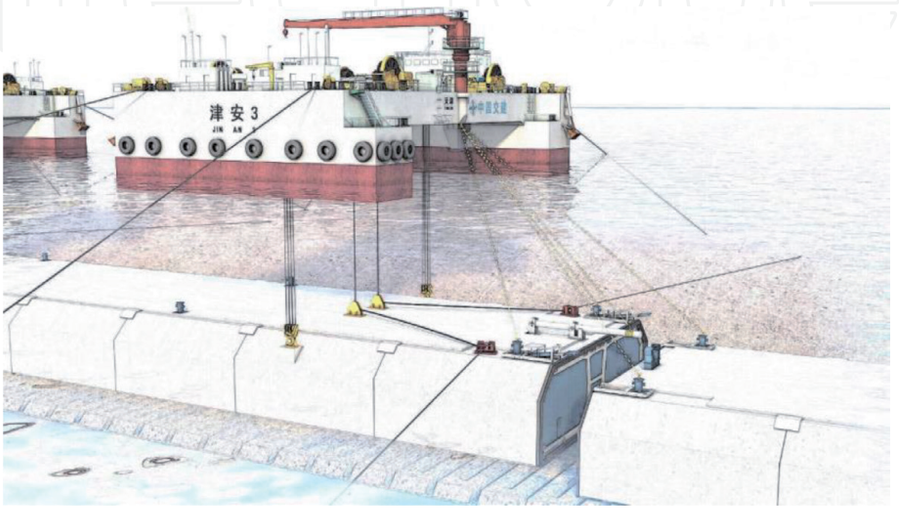


Figure 14.
Image of immersion works of a typical tunnel element in Hong Kong-Zhuhai-Macao Island-tunnel project, showing immersion rigs, lines, and positioning system.

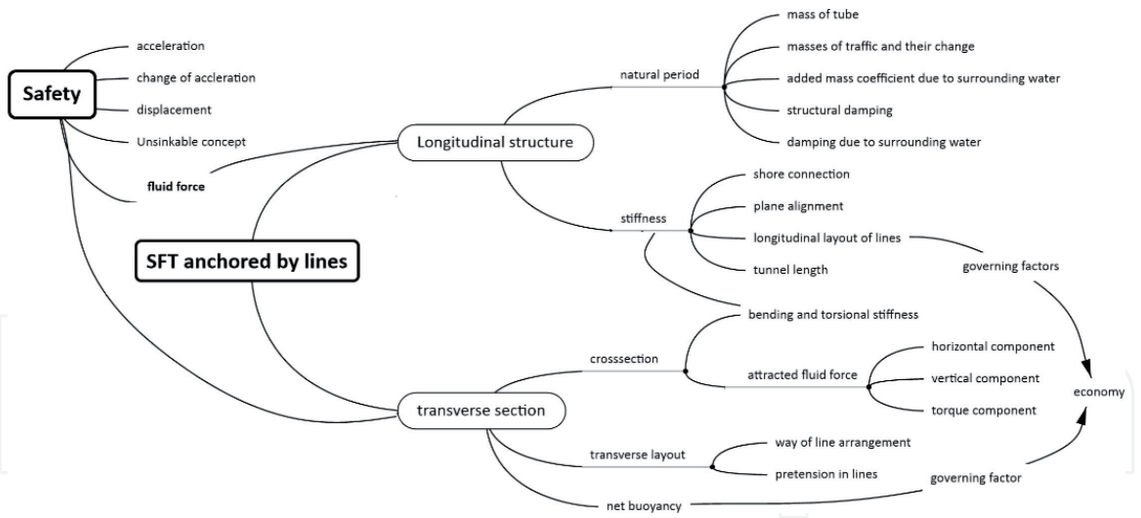


Figure 15.
Relation of structural element and safety.

For another example, if we set $\overline{T}$ as the natural vibration period of an SFT and T as periodic loading acting on it due to natural waves, then $\overline{T}/T$ represents their ratio. In structural design, we need to avoid resonance by letting this ratio far away from the value of 1. We can either change the mass of the tube or the stiffness of the lines or introduce more damping into the system.

3.3 Model

The slenderness and the size of an SFT are like a bridge, and the submergence of it is like a ship or submarine, while the slenderness, the size, and the submergence of SFT are comparable to nothing. Moreover, no real SFT exists. Thus, no mathematical model has ever been validated. Therefore, the physical model is essential.

The ultimate purpose of building a model is not to obtain figures but to obtain the tools that can obtain the figures and to see through the figures, beyond them. A scaled (and simplified) prototype of an SFT is a physical model, and a reproduction of a physical model is a mathematical model. Once the mathematical model is calibrated and validated by the physical model, it can then be used to predict the behaviour of the prototype by scaling the model up in the computer. However, one problem in this procedure is the scale effect, which may distort our understanding and judgement. The SFT structure is submerged in the water. Thus, the scaled effect exists in both structure and fluid. In HZMB Island-Tunnel Project, comparison of the current drag force was made to the scaled physical model and the measured data; great discrepancy exists between the two [6]. In the design of the steel-concrete-steel composite structure of closure joint for the immersed tunnel for the same project [7], special measures were made to strengthen the structure since the size is larger than the previous application in Japan.

To deal with the disturbance of scale effect, one countermeasure is to subdivide the physical model test into three stages, the mechanism test, the parameter test, and the validation test. The mechanism test focuses on the understanding of the structural behaviour to guide the direction of structural form; hence, the influence of scale effect may be neglected. In the parameter test, we ensure that the scale of the model is large enough so that the results of the test can be used either directly or by extrapolation to calibrate the mathematical model. The validation test is the last-stage test for validation of the overall designs to ensure the robustness and comprehensiveness of the SFT structural system. Engineers or engineer researchers may find that the mathematical model cannot match with the physical model and that limitation can be effectively solved by asking help from applied mathematicians or physicians.

To study the overall structural behaviour in water and from current and waves, the author proposed and designed a 1:50 physical model test in 2018; the tube model is 24 m long, with a circular cross-section of 252 mm in diameter, representing a 1.2 km long, two-lane traffic road SFT. **Figure 15** shows the design of the tube model. A steel bar is in the centre of the tube for simulating bending stiffness and covered by the form that simulates the volume. Steel hoops were on the external side of the form simulating weight. Some hoops were welded with eyes for connecting to steel wire lines; the lines were connected with springs to simulate the stiffness of mooring lines. The lines are spaced at 3 m longitudinally. Both ends of the model were fixed. By setting up a reference model and altering structural parameters such as net buoyant, line arrangement (**Figure 16**), and boundary conditions, the change

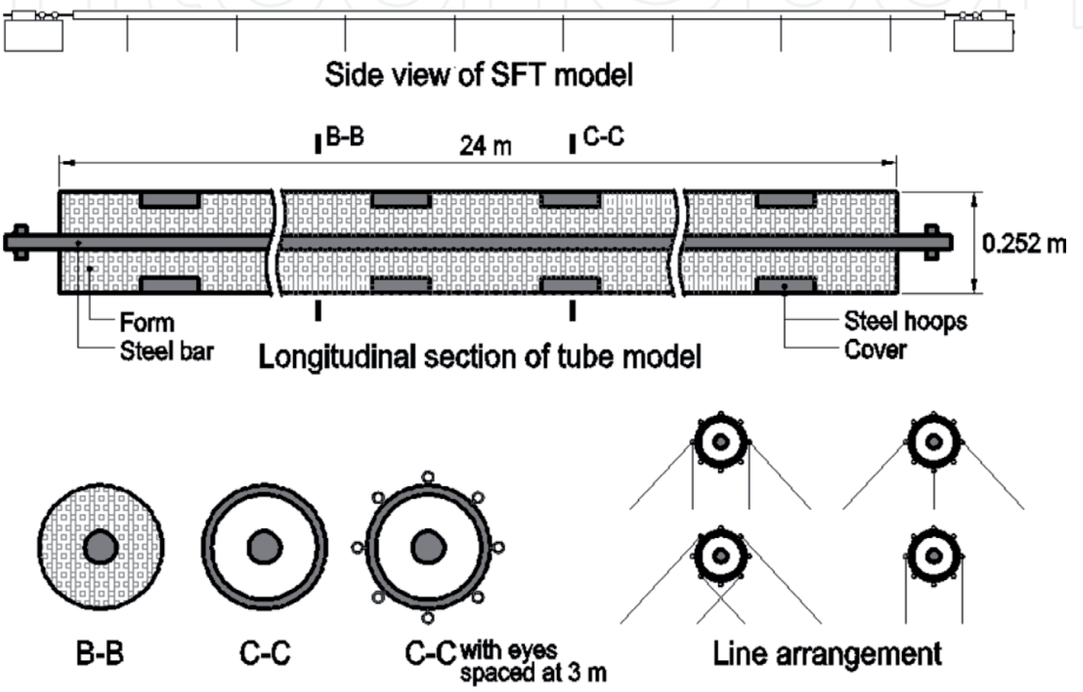


Figure 16.
Schematic design drawings.



Figure 17.
Photo of SFT overall structural behaviour test sponsored, designed, and led by CCCC; SFT model and sensors prepared by DUT; and basin built by TIWTE.

of structural behaviour subjecting to the change of structure can be observed. This test is now being prepared (**Figure 17**) as the first case in the world; results are expected to guide the direction SFT structural form design.

4. Conclusions

The high risk of immersed tunnel construction requires a risk reduction through design. Due to varied location, environment, and construction/operation need, almost each tunnel element design varies from each other. The interior space, structural resistance, and tunnel element weight determine the transverse design of the immersed tunnel, while the structural system, element length, and joint configuration determine the longitudinal design of that. Multifactors of the structure were interlinked and linked to construction, time, and space; hence, a satisfying design requires a spiral-up iteration process including the works of analysis and synthesis. The selection of prefabrication yard for tunnel element, the transportation channel, and the water sealing of tunnel element are detrimental for the project.

SFT can cross broader and deeper waterbody. The main threads of our SFT research are structural form and risk, supported by construction method, mathematical model, and scaled physical model. We will find what is unknown, understand the mechanism, obtain parameters through physical model tests, and understand SFT's behaviour by mathematical measures. When encountering our limit, we need to cooperate with physics and mathematics.

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Conflict of interest

The author declares no conflict of interest.

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