

Analysis on the Construction Safety of Hongkong-Zhuhai-Macao Cross-sea Bridge

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Abstract. With the continuous development of highway and bridge construction in China, the number of cross-sea projects is increasing. The large scale and bad construction environment of cross-sea bridge project put forward a severe test to the construction safety. At present, although China has completed a large number of cross-sea projects, the analysis of construction safety is still insufficient. As a large cross-sea bridge, the Hongkong-Zhuhai-Macao Bridge is representative with harsh construction environment, complex geological structure and high environmental safety requirements. Therefore, this paper takes the Hongkong-Zhuhai-Macao Bridge as an example to analyze the construction safety. Firstly, the safety of construction platforms in different sea areas are discussed, and then, the construction of bridge substructure under complex geological conditions and natural environment are also displayed. In the face of these harsh construction conditions, the Hongkong-Zhuhai-Macao Bridge has adopted some targeted schemes, which provides a good reference model for the construction safety of other cross-sea projects.

Keywords: Construction safety, Hongkong-Zhuhai-Macao Cross-sea Bridge, construction platforms.

1. Introduction

With the continuous development of China's infrastructure construction, the scale of infrastructure has been in the world's leading level. The construction of roads, bridges, railways, etc. is constantly improving and the coverage area is increasing. According to the statistics of the Ministry of Transportation and Communications, "2022 Transportation Industry Development Statistics Bulletin", by the end of 2022, there were 1,033,200 highway bridges in the country, of which 8,816 were special bridges and 159,600 were bridges [1]. The ever-developing transport industry is very important in the construction of economically developed coastal areas, and major cross-sea bridges are constantly under construction. China has built Hangzhou Bay Cross-Sea Bridge, Hongkong-Zhuhai-Macao Bridge, Zhejiang Six Heng Bridge and other large-scale famous cross-sea bridges, while the Bohai Strait Cross-Sea Channel, the Qiongzhou Strait Cross-Sea Channel and other cross-sea channels are also in the planning and construction. For the construction of these major projects, construction safety is the top priority, in the construction of both the progress and quality of the project, but also to ensure construction safety, environmental protection of the construction site and other issues. Therefore, it's necessary to analyse the construction safety of cross-sea bridges. This paper takes the Hongkong-Zhuhai-Macao Bridge as an example to analyse the construction safety of cross-sea bridges.

As a large-scale cross-sea bridge and tunnel project connecting Guangdong, Hong Kong and Macao, as well as the longest overall span cross-sea bridge in the world, the bridge length is 55 km, and the main project is 29.6 km, including 6.7 km submarine tunnel river 22.9 km bridge. There are 224 piers and 7 towers. And the design service life is 120 years [2]. Hongkong-Zhuhai-Macao Bridge adopts a bridge-cum-tunnel engineering method in order to cope with the natural environment due to the complex hydrological conditions, variable geological conditions, low efficiency in the offshore environment, and the need to cross the White Dolphin Sanctuary and other construction technical difficulties [3]. The Hongkong-Zhuhai-Macao Bridge consists of three navigable bridges, a submarine tunnel, four artificial islands and connecting bridges and tunnels, non-navigable

continuous girder bridges in deep and shallow waters, and land liaison lines between Hong Kong, Zhuhai and Macao. The three navigable bridges are three large-span steel cable-stayed bridges with innovative modelling, incorporating local natural environment and social and cultural elements.

2. Analysis of Construction Platform

The sea construction platform is the cornerstone of the bridge construction, deciding whether the whole project can be carried out normally. Different from the construction of land and inland river Bridges, cross-sea projects are affected by hydrological and climatic conditions, and the construction is inconvenient, resulting in the need to build construction platforms.

2.1. Construction Platform of Bridge Section with Navigation Requirements

For the construction of large Bridges with navigable requirements, there are four common construction platform construction methods. They are driven steel pipe pile as a support platform; driven steel pipe pile and auxiliary steel pipe pile to build the platform; adopting steel cofferdam to build the platform for the steel pipe frame on both sides of the middle; and using steel buoyancy positioning platform, respectively [4].

The construction platform analysis of the Hongkong-Zhuhai-Macao Bridge has a navigable bridge section, and the construction area of the section is selected as an example. Qingzhou Bridge bridge section hydrology, shipping conditions are complex, construction safety received a great threat. For this reason, the construction platform of the Qingzhou Bridge section innovatively uses steel pipe composite piles, which do not need to be dismantled after construction, eliminating the risk of dismantling after construction. In order to enhance the stability of pile foundation and ensure that the bridge can reach the design life of 120 years, the steel pipe composite pile is used to make the pile body and the concrete combination jointly stressed, so as to improve the stability of pile foundation. The drilling platform is 135m long and 49m wide, with an area of 6615m², on which living area, drilling area, equipment and material storage area are set up. The platform consists of $\Phi 1020 \times 10$ mm steel pipe piles, $\Phi 2500 \times 25$ mm steel barrels, berth beams and section steel distribution beams, 10mm patterned steel plates and other parts [4].

2.2. Non-navigable bridge section

For the construction platform of non-navigable borehole bridge in shallow water area, there are usually two ways: steel pipe pile+steel section and integral truss steel structure. The steel pipe pile + steel section method is a common way to build the drilling platform, but the complicated process and high requirements on the installation environment have a greater impact on the efficiency of the project.

The choice of truss steel structure for the non-navigable bridge section of the Hongkong-Zhuhai-Macao Bridge effectively reduces the potential risks caused by bad weather on the sea surface. Meanwhile, the truss structure can be assembled in the factory, reducing the on-site gas-cutting and welding work and lowering the installation risks. The platform is supported by 6 composite pile steel tubes and 8 $\varnothing 600$ mm \times 8mm supporting bull legs, and the platform skeleton adopts bidirectional truss structure, with the top dimension of the platform of 31.5m \times 22.0m and the bottom dimension of the platform of 31.5m \times 1.8m. The chord of the truss is made of HN400mm \times 200mm section steel, with the height of the truss of 3.0m, and the diagonal bar adopts HM300mm \times 200m or HW200mm \times 200m, with the height of the truss of 3.0m; and the diagonal bar adopts HM300mm \times 200m or HW200mm \times 200m. HM300mm \times 200m or HW200mm \times 200mm section steel is used for diagonal bar, and HW200mm \times 200mm section steel is used for vertical bar, which is locally strengthened in the construction area of crawler crane. The platform panel is made of 4mm thick pattern plate, under which it is strengthened by I14 steel with a spacing of 500mm; between the I14 steel, it is strengthened by 6mm thick stiffening plate with a spacing of 400mm. the platform panel system is welded into a whole with a weld of 6mm in height in the contacting part of the platform panel system and the

skeleton. The upper and lower channels are composed of 20a type channel steel and 4mm thick pattern plate. The railing is made of 48mm×3.5mm welded pipe structure, and the railing is made into movable type to facilitate lifting and dismantling. The docking system is made of 529mm×6mm steel pipe. On the side of the platform, the boat leaning system is independent and separated from the platform [5]. Table 1 shows the comparison of the two methods. By choosing truss type steel construction platform, there is no need to consider too much about the influence of weather in the erection process. At the same time, it improves the installation efficiency and safety, and reduces the loss of materials.

Table 1. Comparison of construction methods.

	Steel Pipe Pile + Section Steel	Truss type steel structure
Construction method	On-site assembly	Factory assembled and lifted on site
Construction period	15 days	3
Material consumption	337t (2% for reverse consumption)	259t

3. Safety Analysis of the Lower Part of the Bridge

Pile foundation is the cornerstone of cross-sea bridge construction. In order to ensure the stability and safety of the cross-sea bridge under the instability of shallow soil in the sea, steel pipe piles are required to cope with the situation that the strength of shallow soil is unable to support the load of the new structure. Hongkong-Zhuhai-Macao Bridge is located in the sea-land interaction zone, the geological environment is complex, the project stratum is divided into silty soft soil layer, clay and silty clay layer, medium-coarse sand layer, residual soil layer and bedrock with different degree of weathering in five layers [6]. The details of each layer are shown in Table 2.

Table 2. Characteristics of geotechnical layer types [6].

Number of layers	Type	Thickness/m	Specific conditions
1	Soft silty soil layer	5.2-57.6	Continuous distribution throughout the region, thick in the west and thin in the east
2	Clay and silty clay	0-30	Widely distributed, intermittent
3	Medium-coarse sand	1.7-90	Continuous distribution, developed in the south and west, thin in the northeast
4	Residual soil layer	/	Localised, discontinuous
5	Bedrock layers with different degrees of weathering	/	/

In order to cope with the complex geological environment, the Hongkong-Zhuhai-Macao Bridge innovatively uses steel pipe composite piles. Through the use of steel pipe composite piles, the stability of the pile foundation is improved to ensure the safety of subsequent construction. The steel pipe composite piles in the high pier area have a steel pipe section diameter of 220cm, no steel pipe section diameter of 200cm, a steel pipe length of 20m-25m, and a pile length of 27-78m. In the low pier area, the steel pipe section diameter is 200cm, no steel pipe section diameter is 180cm, the steel pipe length is 4.5m-35.5m, and the pile length is 12m-85m [6].

In the process of steel pipe pile driving, mobile guided frame is used for pile driving. By using mobile guided frame, the accuracy of piling can be greatly improved to ensure the safety of the project and provide guarantee for the subsequent construction and building. The mobile guide frame consists of mobile guide frame, piling boat, GPS, laser scanner, inclination sensor, data transmission system, computer control system and piling software system. Among them, the system determines the absolute position by GPS, the relative position using laser scanner, and then the plane position and verticality of steel pipe piles by laser scanner of different heights. Through the use of high-tech equipment, the accuracy of steel pipe piles is greatly improved and construction safety is guaranteed.

4. Security Analysis of the Natural Environment

4.1. Meteorological, Hydrological and Marine Environment

4.1.1. Problem analysis

Hongkong-Zhuhai-Macao Bridge is located in the outer sea belongs to the southern subtropical maritime monsoon climate, the average annual temperature of about 22 °C. Meteorological and hydrological conditions are complex. Summer thunderstorms, and typhoons often occur. Under the action of the wind, high toughness of the steel beams may be due to the same frequency of the resonance phenomenon on the bridge to cause irreparable damage. In addition, the Pearl River Estuary in the typhoon attack when the formation of the near-shore waters of the typhoon storm surge, the water level has a significant lift. And the winter is affected by the monsoon climate, cold wave phenomenon is more common. Many climate problems for the construction have brought inconvenience.

Seawater contains a large number of corrosive ions, such as sodium ions, chloride ions, and sulfate ions. Under the action of concrete structure, the surface of concrete will deteriorate. While seawater sulphate crystals in the concrete inside the concrete will be swollen cracks, so that the reinforcement leakage outside. Reinforcement bars are easy to corrode, and will corrode quickly to fracture after contact with seawater.

4.1.2. Construction measures

In order to solve the above problems, the construction of the bridge has achieved great innovations and breakthroughs in design, materials and construction. The durability of the bridge is an important issue. Suitable concrete mix ratios as well as compositional control of the corresponding raw materials substantially reduce the possibility of salt action and expansion reactions within the concrete [6]. In addition, the influence of seawater corrosion on the bridge can be reduced by controlling the quality of the protective layer concrete, the thickness of the protective layer and the selection of rebar [7]. All are made of high-performance epoxy rebar with high bending resistance, high impact resistance and high wear resistance. Compared with ordinary epoxy rebar, the coating thickness, breakage rate and pinhole rate are improved, and the anti-delamination ability of the coating is enhanced. In addition, coating protection is also an important step in the design of anti-corrosion engineering. Aiming at the corrosion protection problem of steel box girder and steel cable tower in atmospheric area, the method of metal thermal spraying (arc spraying Zn-Al alloy system) is put forward. Steel guardrail and other small steel components anticorrosive design (such as guardrail beams, columns, bases) after sandblasting or shot blasting surface treatment, using a fluorocarbon paint coating. The composite pile of steel pipe adopts epoxy coating inside and outside the steel pipe (double layer epoxy powder coating on the outer wall and solvent-free liquid epoxy coating on the inner wall) and sacrificial anode cathodic protection.

4.2. Geological Environment

The seabed environment is complicated. The silt on the seabed surface is deep and silty, forming a weak bottom layer. The underlying bedrock surface fluctuates greatly and crosses many strata. All the immersed tube sections are located in weak foundation, and the uneven settlement of foundation directly affects the safety and waterproof of immersed tube structure [8].

The construction unit uses sand or gravel to replace the soft soil to improve the foundation strength, and uses sinker piles to control the foundation settlement at the soft clay (using the natural foundation conditions to maximise the bearing capacity of a single pile) and other methods to improve the foundation parameters. The immersed tube tunnel foundation scheme adopts SCP composite reinforcement scheme, the whole tunnel is divided into three sections, the head section of the artificial island, the transition section of the slope outside the island, and the middle section of the tunnel adopts rigid pile composite foundation, SCP and natural foundation respectively. The crushed stone and block layer is laid under the tunnel floor to obtain longitudinally coordinated foundation stiffness,

while the adverse effects of siltation can be mitigated by the first laid underwater compacted block layer [9].

4.3. Ecological Environment

The Hongkong-Zhuhai-Macao Bridge project needs to cross the Chinese White Dolphin Protection Zone, of which the core area is about 9 km and the buffer zone is 5.5 km. The works in the protection zone mainly include artificial islands and submarine immersed tube tunnels [10]. The hazards to white dolphins during the construction process include noise pollution, pollution of the marine environment by industrial waste, and so on. The analysis of the impacts of the construction of the island tunnel project on white dolphins is shown in Table 3.

Table 3. Analysis of the impact of the island tunnel project construction on white dolphins [10].

Construction project	Construction Activity	Impact factors
Artificial island, submarine immersed tube tunnel	Dredging operation	Suspended materials, bait and others
Artificial islands	Steel Cylinder Laying	Low frequency noise
Artificial island, submarine immersed tube tunnel	Extruded sand piles	Low frequency noise, suspended solids and others
Artificial island, submarine immersed tube tunnel	Rock Throwing	Suspended matter
Artificial island, submarine immersed tube tunnel	Construction vessel traffic	Noise, impact

Therefore, the project has strict requirements for ecological protection. During the construction process, the project construction unit continuously optimises the design scheme, formulates a series of protection measures and strengthens the construction management. The use of rapid island formation technology greatly reduces the amount of excavation and dumping, and minimizes the pollution to the sea. Sand Compaction Pile composite foundation construction all use natural materials, instead of steel pipe piles, greatly reducing the pollution to the water body. The submarine immersed tube tunnel adopts a new semi-rigid structure of immersed tube, which avoids the large-scale dumping of lightweight backfill, thus reducing environmental pollution [10].

5. Conclusion

This paper mainly analyzes the construction platform requirements of navigable bridges, the construction platform analysis of shallow water non-navigable bridges, the construction safety of bridges under complex geological conditions and the safety of natural environment, and draws the following main conclusions.

(1) In the aspect of construction platform safety, it can be divided into two parts for analysis. For bridge sections with navigable requirements, steel tube composite piles are selected as the foundation for the construction platform. There is no need to remove the steel tube composite piles after the bridge is completed, and the steel tube composite piles are put into use as part of the bridge pile foundation, greatly improving the construction efficiency and safety of the platform. For non-navigable bridge sections in shallow water areas, trussed steel structures can be considered as construction platforms. Such platforms can be built on land and then transported to the construction site for hoisting, effectively reducing the time and amount of work at sea and improving construction safety.

(2) In terms of the construction safety of the lower part of the bridge, the stability and safety of pile foundation are improved by using steel pipe composite pile. In the construction process, the mobile guide frame can be used, and advanced technologies such as GPS, laser scanners and tilt sensors can ensure the accuracy in the piling process, thereby improving the construction safety of the lower part of the bridge.

(3) In terms of natural environment, taking typhoon, seawater erosion, and weak foundation and crossing the white dolphin protection area as the main problems. In order to overcome the difficulties caused by natural conditions, new steel bars, special coatings, SCP composite foundation technology and special immersed tube structure are proposed.

(4) These techniques are not only a reference for cross-sea bridges whose overall situation is similar to that of the Hongkong-Zhuhai-Macao Bridge, but also a great reference for the targeted solutions to the difficulties in each part.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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