Research on Key Design Technology of Shenjiamen Harbour Subsea Tunnel Engineering in Zhoushan

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Abstract: The Shenjiamen harbour subsea tunnel in Zhoushan, Zhejiang is the first pedestrian submarine immersed tube tunnel in China. In view of the characteristics of the fine soft immersed tube tunnel with large slope, the section of the immersed tube structure was reasonably chosen, the length of the pipe was partitioned, various subsidiary structures were finely arranged, the technology and parameters of the grouting were strictly controlled, and the deformation of end corner was taken as the important control parameter for the design of fine soft pipe joint. The new design technology of final joints with the combination of thrust bearing platform and water sealing wall can ensure the construction quality of final joints, as well as reduce the risk and cost of project. In the field of tunnel engineering, a new bank protection structure that double row steel pipe pile was combined with mould bag sand cofferdam had been researched and designed. Through these key technologies, it has accumulated a wealth of design experience for submarine immersed tube tunnels, which possesses an important reference value for similar projects.

1. Project overview
The Shenjiamen Harbour Subsea Tunnel in Zhoushan, Zhejiang is the first pedestrian submarine immersed tube tunnel in China [1]. The total length of the tunnel construction in recent is 404.97m, while that forward is 446.402 m, and the length of immersed tube is 218m [2]. Started in December 2008 and operated in December 28, 2013, the tunnel is in good condition at present.

Figure.1 The operation chart of immersed tube section

The tunnel is located in Shenjiamen, Putuo District, Zhoushan, Zhejiang Province, starting near the overseas Chinese hotel of Binhai Road, and with nearly vertical flow direction, straightly under the Shenjiamen harbor to LuJiaShi Island Fishing Gear Company. After going ashore to the West about 18.4 degrees, the tunnel reaches to the ground through the straight-through entrance in the east end of the planning square [3]. The immersed tube section should be reserved with the condition of installing the automatic sidewalk.
The tunnel adopts 1% slope at the bottom of the sea. In order to reduce the length of entrances of the two sides, the immersed tube is connected directly to the structure of the entrance on the side of the Shenjiamen, and the slope of LuJia-Shi side is set 15% to climb up the ground as soon as possible. The slope and length of the main tunnel from north to South are -8.00% (69.45m long), 1% (74m long), 8% (79m long) and 15% (23.3m long) [4]. The lowest point of the immersed tube section is -15.206m, and the top of the immersed tube is located under the 2m of the dredged seabed. The tunnel foundation of the immersed pipe section mainly consists of silty clay, silty clay and other soft soils. [5]

2. Design technology of large slope and fine soft immersed tube tunnel
The maximum longitudinal slope of the subsea tunnel section of the Zhoushan Shenjiamen harbour tunnel project is 8%, which is extremely rare due to the elevation of the channel control and the connection conditions between the two banks. Hence, for the large slope, it is much stricter to control the foundation treatment process of the immersed tube and the requirement of the docking attitude, and so on.

The cross-section size of the pipe section is 11.5 m×6.40m, which is different from the conventional immersed tube tunnel. The structure of the fine soft immersed tube is small, and the stiffness is small. The safety factor of pipe joint floating and anti-floating is very sensitive to the additional load of floating and sinking. The total weight of the pipe section is light and the pressure on the base grouting is sensitive to the effect of the pipe joint resistance. The longitudinal deformation of the structure is large, which puts forward higher requirements for the waterproof design of the joint.

2.1. Reasonable selection of the length of immersed tube and section of pipe section
The section length of pipe section of immersed tube tunnel is influenced by hydrologic conditions, channel requirements, precast site of pipe section, conditions of floating and sinking, construction period, cost and longitudinal force of pipe joint.

According to the planning of Binjiang road and Lu Jia Zhi at the site of the project, the total length of the tunnel immersed tube is determined to be 218m. Because of small pipe joint size, the immersed tube section need 2m of soil covering to meet the safety requirement of anti-floating in the operation period. Combined with the connection conditions of the two banks, and affected by the longitudinal
section factor of the tunnel (the maximum longitudinal slope is 8%), the immersed tube section is composed of 3 pipe joints that the E1 pipe section is 70m, the E2 pipe node 74m, and the E3 pipe node 74m, while the final end is located in E3 and the open excavation end of the south bank.

After the calculation of the structure and the calculation of buoyancy and anti-floating, two types of cross sections are developed: the rectangular section and the folded plate section. Because the folded plate structure can improve the stress characteristics of the long-span structure, make full use of the structural material characteristics, turn the flexural member into the bending member, reduce the structure size, facilitate the floating of the pipe section, reduce the floating and pressing facilities, and reduce the cost of the project, the folding plate section is recommended.

The net height of the tunnel structure is 4.8m, while the net width is 10.00m. In the folded plate structure, the thicknesses of the top, bottom and side wall are 0.90M, 0.70M, 0.75 m, and the section size of the pipe section is 11.5×6.40 m. The minimum soil covering thickness of the immersed tunnel is 2.0 m. The cross section of the tunnel is detailed in the following figure.

Figure 4. Cross section diagram of immersed tube

2.2. Subsidiary equipment and facilities for fine outfitting

The anchor is laid around the immersed tube dry dock. The winch is used to carry out the in-dock and out-dock operation. The floating barge and hanging boat are used to carry out the floating and docking operation at sea [7]. The section width of the pipe section is small, and a variety of outfitting equipments and facilities are carefully arranged, such as the manhole, the measuring tower, the hanging point, the system column, the pulling and hoisting jack base.

Figure 5. Arrangement of pipe section and outfitting equipment

2.3. Joint opening control

According to the general layout requirements, the Shenjiamen harbour tunnel has one start joint of intersection between pipe and bank, two intermediate joints and one final joint of shore.

The flexible joint is the most typical type of immersed tube joint. It requires that the joint be adaptable to the larger deformation under the premise of ensuring the water tightness of the pipe joint [8].

Because of the requirement of water tightness, different types of GINA water stop belt correspond to the allowable range of different joint opening. If the joint opening amount is greater than the
permissible range of the GINA water stop belt, the leakage of water or more disasters will occur, so the joint opening is a very important control index in the waterproof design of the immersed tube.

The main factors affecting the amount of joint opening are listed as the follows:

(1) Precast error of pipe section, which is mainly the geometric error of the flatness and parallelism of the steel end shell.

(2) Pipe joint sink and docking error, including horizontal error and vertical error.

(3) The displacements in the operation period of the immersed tube, including horizontal and vertical rotation of joint caused by uneven settlement and the expansion of joints caused by temperature difference.

(4) The opening of the joint caused by an earthquake.

Through the analysis of the above factors, it is known that in the process of construction, the main measures to control the opening amount of the joint are to strictly control the horizontal and vertical errors of pipe joint, the installation error of steel end shell and the quality of immersed tube foundation treatment. After calculation, the specific control index is as follows.

The end precision of the end steel shell: the surface roughness should be less than 3mm, the unevenness within each extension should be less than 1mm, the lateral perpendicularity (the difference between the left and right two points) should be less than 3mm, and the vertical inclination (the difference between the upper and lower two points) should be less than 3mm.

The horizontal and vertical error of each pipe joint is less than 20 mm. The allowable settlement value at the base of the joint is not more than 50 mm.

Through the joint opening control analysis, on-site construction can meet the design requirements, and the joint position has ideal waterproof effect.

2.4. Grouting foundation treatment and process control

According to the experimental results of the silt back test, the total siltation of the foundation pit for 15 days is about 5cm. Through the field proportional model experiment, the mortar mix ratio is determined as: Cement (42.5 universal silicon): Sand: Fly Ash: bentonite: water =189:1134:264.6:37.8:378, with consistency of 102mm; horizontal spacing 6m of the grouting hole and vertical spacing 5.75m of double row arrangement; grouting pressure is +10KPa at the static water pressure at the grouting part.

In actual construction, the dynamic grouting device adopts a special extrusion pump for mortar, the maximum grouting pressure of the equipment is 0.6MPa (adjustable), the grouting pressure gauge adopts the anti-blocking diaphragm pressure gauge, and the grouting pipe adopts the 152mm- diameter pipe, with the steel wire winding the rubber tube with the pressure resistance 2MPa. The mixture ratio of slurry and the grouting process is determined by the test.

2.5. Design parameters and control of floating and anti-floating

2.5.1. Floating and anti-floating design parameters of pipe joint

Floating and anti-floating design is an important part of immersed tube tunnel design. The fine soft immersed tube tunnel is more sensitive to the change of floating and anti-floating parameters. In order
to ensure the reliability of immersed tube tunnel construction, different parameters should be adopted for floating and anti-floating calculation.

The floating stage: the bulk density of reinforced concrete is 25kN/m³, the bulk weight of plain concrete is 23kN/m³, the bulk density of water is 10kN/m³, and the additional weight of the construction equipment is considered according to the actual construction needs.

Anti-floating stage: the bulk density of reinforced concrete is 24.6kN/m³, the bulk weight of plain concrete is 22.5kN/m³, and the bulk density of water is 10.05kN/m³.

The anti-floating weight of immersed tube is different according to the size distribution of actual pipe sections, and the weights of sections, outfitting and water tanks are calculated in sections and parts.

It is calculated that the freeboard height of each pipe section is 10 ~ 16cm and the floating coefficient is 0.98~0.99. Even according to the maximum allowable error, the error of the freeboard height is 5cm. It can meet the requirement of can make the port 10 ~ 15cm by adjusting the construction order and thickness of the roof guard layer.

After completion of the pipe joint foundation treatment, when there is no backfill at the pipe top, the anti-floating safety factor is 1.105, which is greater than 1.10. After the pipe top is backfilled, the anti-floating safety factor is 1.26, which is greater than 1.2. So it meets the requirements.

2.5.2. Analysis of measures to improve the floating and anti-floating capacity of pipe section

Due to the small cross-section of the pipe section in this project, structural weight, dimensional geometric parameters, and deck outfit are very sensitive to the effects of floating and anti-floating of the pipe section. Therefore, the structural weight that affect the weight of pipe sections and the weight of the deck outfit are analyzed in design.

The section of the pipe section is small and the weight of the structure is also small. However, many deck outfits are needed for the pipe section. In order to accurately analyze the floating and anti-floating capacity of the pipe section, the building weight is calculated according to the actual design of the fitting. Considering that the section and length of the pipe section are not large, only one manhole is considered in the design. Combining with the characteristics of this project, the design of the tank adopts a steel structure and optimizes the structure to improve the bearing capacity and deformation capacity of the tank structure. Moreover, it also makes full use of the structural side wall as part of the tank structure to reduce the weight of the tank and improve the floating and anti-floating capacity of the immersed tube.

2.5.3. Quality control requirements of pipe section floating and anti-floating

There are two main factors affecting the floating and anti-floating of pipe section: the volume of concrete and the size deviation of pipe sections.

Structure weight control range: 25.0±0.25 kN/m³.

Body size control: inner hole width 0 ~ +10mm; inner hole net height 0 ~ +10mm; wall thickness 0 ~ -5mm; pipe section width 0 ~ +10mm; pipe section height 0 ~ +10mm; pipe section length -20 ~ +20mm.

Quality control requirements for pipe sections, including proper mix ratios and on-site technical control measures for trial mix experiments, are strictly required to ensure the requirements of anti-floating and floating for immersed pipe tunnels on site. Meanwhile, the actual freeboard height for each pipe section construction is in the range of 10 ~ 15 cm.

This project adopts a rational selection of immersed pipe structure section, divides the length of the pipe section, finely arranges various ancillary structures, and strictly controls the grouting technology and parameters. Through regarding the deformation of the end corner during the construction of the pipe section as a content and measure of the waterproof design, the design quality of the fine immersed tunnel is ensured and various construction requirements are met.
3. New technology for final joint design

According to the construction method, the final joints have a dry construction method, an underwater concrete method, a water stop plate method, a joint box method, and a V-shaped box method [5]. In combination with the characteristics of this project, in order to shorten the total construction period of the tunnel, reduce the construction difficulty, and reduce the time for immersed pipe construction to occupy the navigation channel, the design of the south bank onshore dry method final joint is adopted. The final joint between the last section of the immersed tube (E3) and the south bank excavation section is set to a final length of 1.5 m.

Due to the need for a large horizontal thrust for pipe section crimping, its horizontal thrust is provided by seawater. After E2 and E3 pipe sections are crimped, the water pressure of the E3 pipe section at the excavation end of the south bank is 4160 to 6860 KN (The design height and low tide are 2.34m and -1.38m respectively); after pumping water of the joint between the E3 and the south bank excavation section, the sea pressure at the end of the E3 section will disappear. At the same time, it is necessary to provide the corresponding thrust force at the south end of the E3 pipe section to prevent the joints between the E2 and E3 pipe joints from relaxing.

The anti-thrust design of the tunnel is to be sealed by a water stop concrete, side sealing plate, and a steel pipe support. The final joint water-proof plate is installed after the immersed tube is completed; afterwards, the underwater concrete under the cover is poured in the water-stop plate to fill the gap between the pipe joint, the water-stop plate and the thrust bearing platform; thus, the bottom seal and the initial thrust of the immersed tube are reached; finally, the longitudinal thrust of the dry joint construction of the final joint of the immersed tube is achieved by using the both sides of the closure plate and the internal support of the steel tube. Using a water-stop plate as an outer mold, an inner-membrane stent is erected, and a reinforced concrete is poured to achieve the closure of the immersed tube tunnel. The final joint layout is shown in the figure below.

![Figure 7. The layout of final joint](image)

![Figure 8. The final joint](image)
The immersed tube and the final joint are treated as construction joints, and the joint between the final joint section and the on-shore cast section is treated as a deformation joint.

The new design technology of final joints with the combination of thrust bearing platform and water sealing wall can ensure the construction quality of final joints, as well as reduce the risk and cost of project.

4. New type revetment structure design technology: double-row steel pipe piles plus mould bag sand cofferdam revetment structure

4.1. Overview of the programme
The north bank entrance and exit structure was arranged along the coastal embankment. It was a side-by-side sea and the other side was supported by the bias structure of the bank. In view of the characteristics, a double-row steel pipe pile plus mold bag sand cofferdam was studied and applied to land the water area. Besides, this cofferdam considered both the foundation pit enclosure and the bank protection structure.

The main tunnel section of the north tunnel of the tunnel had a large dig depth, thus double-row steel pipe cofferdams were used; the other side of the tunnel was shallow for digging depth and sand bags were used for cofferdams. On the sea side, \(\varphi 1200 \times 14\text{mm}@1400\text{mm}\) steel pipe piles were used. On the back sea side, \(\varphi 1000 \times 12\text{mm}@1400\text{mm}\) steel pipe piles were used. The pile length was 22.00/24.00m. The distance between the inner and outer steel pipe piles was 10.00m. A crown beam was placed on the top of the pile, and the crown beam and the steel pipe pile were connected into a whole. There were two lateral connections between the inner and outer steel pipe piles. The concrete crown was used for the crown beam part of the pile. The high strength bolt connection was set at the height of 0.00m. The steel pipe piles were backfilled with mould bag sand, and the prefabricated panels were used between the steel-pipe piles on the sea side to prevent the flow from reciprocatingly flushing the internal mould bag sand.

The mold bag sand cofferdam was filled with coarse sand in the geotextile, the filling thickness of each layer was 50-60cm, the width of the cofferdam top was 5.0 m, the bank slope was 1:2 on the sea side, 1:0.5 on the inner side, and the elevation of the dome was 3.00 m. On the sea side of the mold bag sand cofferdam, the concrete of the C20 bag was set to prevent the flow from reciprocatingly flushing the hollow bag sand.
4.2. Cofferdam calculation

Double-row steel pipe piles and sand bags for model bags are considered in accordance with the temporary structure [9]. They should meet the requirements for cofferdam construction period load and foundation trench excavation and revetment requirements: bearing the cofferdam dead weight, loading tidewater, post-filling backfill load, as well as overloading of enclosure construction ground, excavation load of foundation pit and excavation load of foundation trench.

The double-row steel pipe piles shall be calculated according to the internal forces and deformations of the gravity retaining wall and the double-row pile frame structure, including the overall stability of the cofferdam, the internal force and deformation of the steel pipe pile structure.
The calculation of the stability and anti-sliding stability of the double-row steel pipe pile cofferdam was determined according to the overall force of the two-row pile + soil between the piles and the instability of the soil between the piles.

The double-row steel pipe pile cofferdam thickness is 10.0m. After the cofferdam, the ground surface overload is considered to be 30kPa. It is controlled by the design low water level of -1.38m working condition, the elevation of the cofferdam outer seabed surface is -6.0m, and the cofferdam cantilever height is 9.0m. The side of the sea side adopts protective measures against back pressure and foot protection of slab stones, and the elevation of the top of the counter-pressure slab is -3.00 m. The postload load is calculated according to the Langxin active earth pressure. The pressure above the seabed surface is calculated according to the water pressure below the design low water level. The pressure below the sea floor is considered as the resting earth pressure. The calculation results show that the double-row steel pipe pile cofferdam's anti-overturning safety factor is 1.58 and the anti-slip safety factor is 2.18, so the overall cofferdam safety is reliable.

The force calculation of double-row pile cofferdam structure is analyzed as a gate-style frame. Meanwhile, the finite element program SAP84 V6.5 is used to calculate and analyze the elasticity basis beam. The steel pipe piles are modeled with circular-section structural beam elements, the concrete crown beams and tie rods are modeled with beam elements, and the high-strength anchor rods are modeled with tie rod elements. Simultaneously, compression springs are used to simulate the resistance between the double-row steel pipe piles and the resistance of the soil layer on the seaward side to the steel pipe piles. The steel pipe piles on the side of the foundation bear the active earth pressure, and the steel pipe piles on the sea side are subjected to the static earth pressure. Moreover, the low water level is designed as control conditions.

According to a pile spacing calculation, the calculation model and calculation results are shown in the figure. The results show that the internal force and deformation of the cofferdam meet the design requirements.

Based on the gravity structure of the mould bag sand cofferdam, the minimum safety factor of the cofferdam slope is 1.14 when the water level before the radon falls to a multi-year average low tide level of -1.13 m. The use of wooden pile reinforcement, sand cushion and geogrid, back pressure platform and other measures to improve the stress of the cofferdam bottom to meet the requirements of the bearing capacity of the foundation. The stability coefficient of anti-sliding stability between the layers of the mould bag sand cofferdam is 1.78, which meets the requirements.

4.3 Site construction
Steel pipe piles are hammered into piles, and double control is performed according to penetration depth and penetration index (less than 40mm) [10]. After analysis of monitoring data, the cofferdam
ensures the safety of excavation of foundation pits and immersed tube foundation trenches. At the same time, the new bank protection structure is recycled after construction, which is economical and environmentally friendly.

Figure 14. Site construction of cofferdam

5. Conclusion

Combined with the characteristics of the project, the natural geographical environment and the technical requirements for the immersed tunnel, a number of key technical problems in the design of subsea immersed tunnels were explored and some results were achieved in the process of designing the Shenjiamen Harbour Subsea Tunnel in Zhoushan.

(1) In view of the characteristics of the fine soft immersed tube tunnel with large slope, the section of the immersed tube structure was reasonably chosen, the length of the pipe was partitioned, various subsidiary structures were finely arranged, the technology and parameters of the grouting were strictly controlled, and the deformation of end corner was taken as the important control parameter for the design of fine soft pipe joint.

(2) The new design technology of final joints with the combination of thrust bearing platform and water sealing wall can ensure the construction quality of final joints, as well as reduce the risk and cost of project.

(3) In the field of tunnel engineering, a new bank protection structure that double row steel pipe pile was combined with mould bag sand cofferdam had been researched and designed. Therefore, these key technical studies are of great significance for guaranteeing the construction safety and construction quality as well as ensuring the smooth operation of the Shenjiamen Harbour Subsea Tunnel Project in Zhoushan, which have a relatively beneficial reference for similar projects in the future.

References

[1] China's first subsea immersed tunnel tunnel built by China Railway Tunnel Group - Shenjiamen Port subsea tunnel in Zhoushan completed the immersed tube placement at the end of the main structure [J]. Tunnel Construction, 2012, 32(06): 886.

[2] Ning Maoquan. Introduction of the design of the immersed tunnel at Shenjiamen Port [J]. Modern Tunneling Technology, 2008, 45(06): 61-69.

[3] Ning Maoquan, Xiao Mingqing. Key technology design and analysis of subsea immersed tunnels [J]. Journal of Railway Engineering. 2008 (06):50-57.

[4] Ning Maoquan. Waterproof design of subsea immersed tunnels [J]. Railway Construction. 2008 (10):58-61

[5] Liu Yanfeng. Research and Analysis of Key Technologies for Immersed Tunnel Engineering [D]. Southwest Jiaotong University, 2017.

[6] Li Ke, Du Jialun, Huang Xingchun. Influence of Slope on the Diffusion Characteristics of Grout in Foundation Treatment of Immersed Tunnel [J].Journal of Shanghai Jiaotong University, 2011, 45(5):629-633.

[7] Deng Jianlin. Construction control technology for floating and sinking of the immersed tunnel in Shenjiamen Port [J]. Tunnel construction. 2015, 35(09): 914-919.
[8] Chen Hong, He Chunning, Qiao Zongzhao. Design of Shanghai immersed tube tunnel (11) - Segment joint design [J]. Underground Engineering and Tunneling, 2016(1):15-19.

[9] Huang Xueyang. Stability analysis of sand bags with small transverse dimensions on soft soil foundation [D]. South China University of Technology, 2015.

[10] Bao Yourong, Qian Chao. The application of double-row steel pipe pile cofferdam in the construction of coastal soft soil foundation [J]. Water Resources Construction and Management, 2016, 36(09):21-23.