Tentative Design Study of Ballasting Tank for Very Large IMT Unit

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Abstract: The ballasting tank is one of the key points in the design and construction of immersed tube tunnel. With the development of construction technology and social requirement, the size of IMT unit is becoming bigger and bigger. The design of ballasting tank will be more important in very large IMT unit. This article takes the Shen-Zhong Link IMT project which is under construction as example to express some design principles for ballasting tank. Particularly, the stability of unit during sinking will be emphatically analyzed for arrangement of ballasting tanks.

1. Introduction
At present, there are several construction methods for underwater tunnel construction: mining method, shield method, cofferdam open excavation method, buried pipe joint method (hereinafter referred to as immersed pipe method), underground excavation method, pneumatic caisson method, jacking method, etc. [1-2] In the large-scale underwater tunnel engineering, the immersed tube method and shield method are widely used in the world. However, due to the limitation of geological conditions, other construction methods are difficult to be popularized. Shield method and immersed tube method are more and more popular in the engineering field, and the immersed tube method has the shortest construction period, the shortest tunnel extension and less geological conditions. [3] Although the sinking of pipe joint has an impact on the channel, it is generally better than other methods. [4]

With the popularization of immersed tunnel in the world and the increasing traffic demand, large-scale and wide section immersed tunnel is increasingly becoming the development direction of immersed tunnel. Table 1 shows several representative immersed tunnels, from which we can roughly see this trend.

The common process of immersed tunnel construction is as follows: prefabrication and primary outfitting are carried out in the dry dock; after water injection in the dry dock, the pipe section floats relying on its own buoyancy; secondary outfitting is carried out for the pipe section; then, the pipe section floats to the tunnel site for mooring, and provides negative buoyancy for the pipe section through the ballast system for the pipe section sinking operation; after the pipe section is installed in place, it continues to be ballasted for settlement. It meets the requirements of anti floating safety factor of pipe joint.

In different construction stages, the anti floating safety factor of pipe joint is generally taken as follows:
1) During the sinking period of pipe joint: 1.015 ~ 1.02;
2) After the pipe joint is sunk in place: ≥1.05;
3) After the construction of pipe joint ballast concrete: ≥1.06;
4) After completion of pipe joint backfilling and covering: ≥1.15
The design capacity of ballast water tank mainly considers the construction requirements of stage 1) and 2).

| Tunnel name                                              | Total length of tunnel /m | Pipe section size (L × w × h) / m |
|----------------------------------------------------------|---------------------------|----------------------------------|
| San Francisco rapid transit tunnel (1970)                | 5825                      | 111×14.6×6.5                     |
| Helmsper tunnel in the Netherlands (1980)                | 1475                      | 268×21.5×8.7                     |
| Abel tunnel, Belgium (1980)                             | 336                       | 138×53×9.35                      |
| Immersed tunnel of Hong Kong Zhuhai Macao Bridge (2018) | 5664                      | 180×37.95×11.4                   |
| Immersed tunnel of Shenzhen passage (under construction)| 5035                      | 165 (standard tube) × 55.463 (widest) × 10.6 |

The most direct impact of large-scale pipe joint size on the immersed tube ballast system is that the size of the water tank will be correspondingly increased to meet the requirements of anti floating safety factor. With the increase of water tank size, the influence of free liquid surface of water tank on the stability of pipe joint becomes more prominent. This paper takes the pipe section of S08 contract section of Shenzhen tunnel as an example to discuss some basic considerations of water tank design of super large immersed tunnel, so as to provide some reference for the subsequent engineering cases.

2. Project overview
The steel shell concrete composite structure is adopted for the pipe section of the immersed tunnel of Shenzhen passage, and the prefabrication site for the pipe section of S08 contract section is located in the Huangpu Wenchong Shipyard of Guangzhou Nansha Longxue shipbuilding base. After prefabrication, the pipe joint is pulled to the mooring area of the harbor basin for secondary outfitting and joint commissioning outside the dock. At the same time, the immersed tube foundation treatment shall be carried out at the tunnel site. After all the preparatory work is completed, the appropriate weather window shall be selected, the pipe joints shall be floated from the Prefabrication Yard to the tunnel site for mooring, and the sinking and installation operation shall be completed.

There are 10 pipe sections in S08 contract section, among which E23~E27 are class II standard pipe sections with main dimensions (length×width×height) of 165m×46m×10.6m, E27~E32 are curve widened pipe sections with main dimensions of 123.8m×(46m~55.46 m)×10.6m. The plane dimension of the widest section pipe section E32 is shown in figure 2.

Figure 1. Geographical position
According to the design documents, the water weight in the construction area is 1009.59 ~ 1026.53 kg/m³, and the concrete weight of the main structure is 2330 ~ 2360 kg/m³ [5].

The capacity of the pipe joint ballast tank should meet the anti-floating safety factor after the pipe joint is sunk.

\[
\gamma = \frac{W}{B} = \frac{W_m + W_w}{\rho \cdot V} \geq 1.05 \rho
\]

In the formula:
- \( \gamma \) — Anti-floating safety factor;
- \( W \) — The weight of the pipe joint, \( W_m \) is the weight of the main structure of the pipe joint, \( W_w \) is the water storage capacity of the ballast tank;
- \( B \) — The buoyancy of the pipe joint, where \( \rho \) is the water weight and \( V \) is the drainage volume of the pipe joint.

The design of ballast water tank must be coordinated with ballast concrete replacement construction [6], which will not be repeated in this paper.

Taking the widest pipe section E32 as an example, the drainage volume of the pipe section is 70425.9 m³. For conservative consideration, the upper limit of the water weight in the construction area is taken for the calculation of the buoyancy of the pipe section, and the lower limit of the water weight is taken for the calculation of the ballast tank capacity. For the main structure weight of pipe joint, it mainly consists of steel shell, main structure concrete, welding materials, embedded parts, etc. in order to ensure the safety factor, all weights are calculated according to the lower limit of density, and the positive tolerance of steel plate is not considered. The specific decomposition is shown in table 2.

| Serial number | Project        | Weight / t         |
|---------------|----------------|--------------------|
| 1             | Steel shell    | 9205.81            |
| 2             | Welding material | 300               |
| 3             | Concrete       | 55815.38          |
| 4             | Total          | 65321.19          |

From equation (1), it can be calculated that the required ballast tank capacity of E32 pipe joint is at least 10487 m³.

According to the relevant experience of similar pipe joints of Hong Kong Zhuhai Macao Bridge, two full section ballast tanks are initially set up in the upper and lower lane holes of pipe joints, with the
longitudinal dimension of each tank of 28.5m. Considering the longitudinal slope (-0.83%) of E32 after installation, the width of the water tank in the upper lane hole is 22.049m, and the width of the water tank in the lower lane hole is 22.988m. Therefore, the height of the water tank can be calculated to be at least: \( \frac{10487}{[(28.5 \times (22.049 + 22.988)) + 28.5 \times 0.83\%]} = 4.32 \text{m} \). Considering a certain safety factor, the height of ballast water tank is determined as 5m.

4. Optimization of water tank layout

After the initial determination of the tank size, several layout principles need to be considered.

4.1. Plane position relation of water tank

When the pipe joint is completely flooded, the position of its weight \( W \) and center of gravity \( g \) does not change when it tilts at a certain angle. Therefore, its stability completely depends on the relative position relationship between center of buoyancy \( B \) and center of gravity \( G \). \[7\]

![Figure 3. Stable/Unstable equilibrium of submerged tube](image)

(a) The center of gravity \( g \) is below the center of buoyancy \( B \), and the direction of MR is opposite to the direction of heel, so the floating body can return to the original equilibrium state, so it is called stable equilibrium, as shown in figure 3 (a).

(b) The center of gravity \( g \) is above the center of buoyancy \( B \), and the direction of MR is the same as that of heel. Therefore, the floating body will continue to tilt without returning to the original equilibrium state, so it is called unstable equilibrium, as shown figure 3 (b).

(c) The center of gravity \( g \) coincides with the center of buoyancy \( B \), MR=0, and the floating body can be balanced at any position, which is called neutral equilibrium, as shown in figure 3 (c).

![Figure 4. Centroid of ballasting tank in cross section](image)

It can be seen that the center of gravity \( g \) of the immersed tube must be below the center of buoyancy \( B \) in order to ensure its stability. The setting of ballast water tank should be based on the principle of not affecting the position of the center of gravity of the pipe joint, and try to ensure that the connecting line of the center of gravity and the center of buoyancy of the pipe joint overlaps with the symmetrical center line of the section of the pipe joint. Specifically, transverse: the intersection of the centroid of the water tank is on the line between the center of gravity of the pipe joint and the center of buoyancy, while...
longitudinal: the intersection of the centroid of the water tank should be as close as possible to the center of gravity of the pipe joint itself, as shown in figure 4 and figure 5.

Figure 5. Centroid of ballasting tank in cross section

4.2. Influence of free surface of water tank on initial stability during pipe joint sinking
In order to explore the influence of free surface of water tank on initial stability during pipe joint sinking, the following four schemes are compared and selected for water tank layout.

(a) The water tank is not divided into compartments (As shown in figure 5)
According to the above water tank layout, GHS software is used to analyze the initial stability value of pipe joints under each scheme, and the results are shown in table 3.

Table 3. Stability analysis for different tank arrangement

| project           | Unit | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|-------------------|------|----------|----------|----------|----------|
| Pipe section      | t    | 2,007    | 1,937    | 1,952    | 1,880    |
|                         | t·m   | 108,415 | 26,980 | 107,847 | 26,818 |
|-------------------------|-------|---------|--------|---------|--------|
| Free surface inertial distance | t     | 70,360  | 70,360 | 70,361  | 70,360 |
| Pipe section displacement | m     | 10.59   | 10.59  | 10.59   | 10.59  |
| Average draft           | m     | 21.91   | 23.07  | 21.92   | 23.07  |
| Initial stability height | m     | 21.91   | 23.07  | 21.92   | 23.07  |

The above only discusses the transverse initial stability of the pipe section, so the longitudinal subdivision of the water tank has little effect on it, which is also the reason why the results of scheme 1 and scheme 3 and scheme 2 and scheme 4 are close. Generally, the longitudinal stability is high, and the length L of the pipe section is the same order of magnitude, which can ensure the longitudinal stability of the pipe section, so the longitudinal stability is generally not calculated.

According to the above analysis, the longitudinal subdivision of the water tank does not have a great impact on the initial stability of the pipe joint, while the transverse subdivision can play a more obvious beneficial effect on the stability of the pipe joint.\(^{[6-9]}\) The moment of inertia of the free surface of scheme 2 and scheme 4 is obviously one order of magnitude smaller than that of scheme 1 and scheme 3. However, considering the adverse effect of liquid sloshing on the adjustment of the pipe joint motion attitude during the sinking process, the construction should be started from the safety point of view, the layout of E32 pipe joint is finally determined as the fourth scheme of transverse and longitudinal subdivision.

5. Conclusion
In this paper, the design of ballast water tank of E32, the widest pipe section of S08 contract section of Shenzhong channel, is taken as the research sample.

1) The capacity design of the pipe joint ballast tank mainly considers the anti floating safety factor after the pipe joint is sunk;
2) The setting of ballast water tank should be based on the principle of not affecting the position of the center of gravity of the pipe joint, and try to ensure that the connecting line of the center of gravity and the center of buoyancy of the pipe joint overlaps with the symmetrical center line of the section of the pipe joint;
3) The free surface of ballast tank should consider the influence of pipe sinking on initial stability;
4) In order to reduce the influence of liquid sloshing on the attitude control of the pipe joint, an appropriate compartment should be added to ensure the stability of the pipe joint.

Ballast water tank is the key temporary auxiliary structure along with the whole life cycle of immersed tunnel construction, which plays a vital role in the construction of immersed tunnel. This paper gives some basic conclusions, which can provide some reference for similar projects in the future.

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