Research on Surveying Technology of Special-shaped Immersed Tube Installation in Hong Kong NSL Tunnel

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Abstract. The advantages of immersed tunnel are shallow depth and large cross-section. Victoria Bay is spanned by the NSL tunnel in Hong Kong. Kowloon and Hong Kong Island are connected. The tunnel consists of 11 immersed tubes. Based on the study of the establishment of the coordinate system of special-shaped tube joints, the establishment and calibration of attitude surveying system, and the calibration of RTK-GPS, a set of surveying system for the installation and joint of special-shaped immersed tubes is developed to solve the problem in the construction of NSL tunnel. The installation of the E10 is guided. Compared with the traditional total station survey method, the installation and joint surveying system can meet the accuracy requirements and can be extended to similar immersed tunnel projects in the future.

1. Introduction

The Shatin to central link (Sha central line) project is a railway construction project extending from Kowloon to Hong Kong Island, connecting to the new station in Wan Chai North and then arriving at Admiralty terminus. The new cross-sea railway tunnel is constructed in the form of immersed tube tunnel, with a total length of about 1.7km. It is composed of 11 sections. Each section of immersed tube is about 156 meters long, 18 meters wide, and weighs about 23 thousand tons. All of them are prefabricated in Shek o dry dock. Among them, Traditional immersed tube tunnels are mostly regular three-dimensional. A lot of research has been done on the dynamic detection of the position of the immersed tube during installation, and some detection methods have been proposed [1-7]. The E11 pipe section is the opposite immersed tube with the largest bending radian, as shown in Fig 1. No scholars have proposed a solution to how to detect irregularly shaped immersed tubes in real-time. According to the requirements of dynamic detection of E11 section immersed tubes, this paper proposes a set of dynamic monitoring methods to solve this problem. Upon completion, the project will become the fourth cross-harbor railway tunnel in Hong Kong.
2. Positioning method of special-shaped immersed tube
The basic principle of docking and positioning of immersed tube is given [8], and its mathematical model is described as follows:
\[ X_p = X_{gps} + \Delta X \cdot R(p, r, h) \] (1)
\[ R(p, r, h) = R_p \cdot R_r \cdot R_h = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_r & -s_r \\ 0 & s_r & c_r \end{bmatrix} \begin{bmatrix} c_h & s_h & 0 \\ 0 & 1 & 0 \\ -s_h & c_h & 0 \end{bmatrix} \begin{bmatrix} 0 & -s_p & c_p \\ s_p & c_p & 0 \\ 0 & 0 & 1 \end{bmatrix} \] (2)

In the matrix, C is cosine function cos, s is sine function sin.
Where \(X_{gps}=(x, y, z)^T\) is the GPS position, which can be collected directly by RTK(Real-time kinematic); \(\Delta X=(\Delta x, \Delta y, \Delta z)^T\) is the relative position relationship between any point in the immersed tube coordinate system and GPS, which is a fixed value after the immersed tube coordinate system is established; \(R(p, r, h)\) is Euler rotation matrix, where \(p=\text{pitch}, r=\text{roll}, h=\text{heading}\).
Pitch, roll and heading are instantaneous attitude values of immersed tube, which can be measured by attitude sensor. Combined with the corresponding instantaneous GPS position information and attitude information, the coordinates of any point of the immersed tube are calculated, and how to realize the positioning function of the immersed tube [1-3]. Before sinking, it is necessary to measure the initial installation position of GPS and attitude sensor accurately.

2.1. Immersed tube coordinate system
In order to facilitate the later measurement and control, the two sections of the immersed tube are named as butt end and free end respectively. The butt end is directly connected with the immersed tube or the buried end of the bank, and the other end is the free end. The middle point of the steel end shell at the top of the butt end is selected as the coordinate origin, the upward direction perpendicular to the pipe joint is the positive direction of the Z-axis, and the middle point of the steel end shell at the top of the butt endpoints to the middle point of the steel end shell at the top of the free end is the positive direction of Y-axis.
A new definition of the coordinate system is adopted for the special-shaped immersed tube with a curved NSL tube. The definition of origin and z-axis remain unchanged, and the direction of the right steel end shell along the top midpoint of the butt joint is the positive direction of the x-axis. The whole coordinate system is shown in Fig 2-a.
After the establishment of the immersed tube coordinate system, according to the absolute coordinates of each immersed tube control point after sinking and the design coordinates of the center points at both ends of the immersed tube, the relative position relationship of each characteristic point (immersed tube control point and immersed tube end corner) on the immersed tube can be calculated, i.e. $\Delta X$ in the positioning principle.

2.2. Establishment and calibration of attitude surveying system

In order to ensure that the measurement results of the attitude monitoring system can be used as the attitude of immersed tube, the y-axis parallel line of the coordinate system is lofted through the control points in the tube, and the heading direction of the attitude sensor is parallel to the Y-axis of the coordinate system. A set of the attitude monitoring system is installed at both ends of the immersed tube, one for operation and one for standby. It can be ignored while the y-axis coordinate system is established. Therefore, it is an installation deviation between the collected data of the attitude system and that of the immersed tube system in roll and pitch. The calibration mainly calculates the roll pitch deviation between the collected data of the attitude instrument and the immersed tube coordinate system.

The calibration of the attitude sensor is completed in the dry dock, which is divided into roll calibration and pitch calibration. Both can be calibrated by the static total station measurement method, as shown in Fig 2-b. Besides, the roll value calibration also can be calibrated using the reading of the connected tube in the tube.

For the curved immersed tube, the coordinates and elevation of the projection points 2A and 3A on the steel end shell are obtained by using the immersed tube coordinate system. The positions of the projection points 2A and 3A on the steel end shell are set out and marked with the total station. The three-dimensional coordinates of points 1-4, 2A, and 3A were obtained by observing the whole station. The actual roll and pitch values of the immersed tube are obtained by using the trigonometric function relationship.

Figure 2. Immersed tube coordinate system,
Fig a: Coordinate System Definition of Cure Tube, Fig b: Attitude Calibration by Total Station
After calibration, the difference between the actual roll and pitch values of the immersed tube and the data collected by the attitude sensor is the correction value of the attitude sensor. After correction, the attitude measurement data can be used as the roll and pitch values of the immersed tube system.

2.3. Calibration of RTK GPS
The RTK GPS antenna can be fixed only after outfitting the survey tower. After the installation of the equipment, select any control point of the immersed tube to set up the total station, and use another or more control points as the back view to observe the position of other control points on the pipe surface and the prism position at the top of the measuring tower, and record the roll and pitch values of the immersed tube during the observation of the total station. The coordinates and elevation of RTK-GPS antenna and prism are calculated after the tilt correction of longitudinal and transverse inclination, which are used as the offset of measuring equipment during pipe joint sinking. After several groups of measured values are calculated independently, the average value is taken as the final equipment calibration result.

3. Development of surveying system
The monitoring system for the installation and docking of immersed tube is written with C# language and WPF technology. Aiming at the installation process of immersed tube, RTK is integrated GPS, attitude monitoring system, wireless data communication, and other equipment, through stable and reliable data transmission, scientific and efficient data processing and analysis, vivid data display and complete and practical data management, combined with the design position and water depth terrain of immersed tube, realize the real-time positioning of the pipe joint, and guide the installation of immersed tube.

The system has typical object-oriented characteristics. By using object-oriented design methods such as encapsulation, inheritance and polymorphism, the immersed tube, equipment and terrain involved in the system are abstracted into classes with attributes and methods, which improves the readability of the code and the maintainability of the system, and makes the system easy to expand. Using C# as the development language of the system has the advantages of high development efficiency, concise code and clear structure. The system uses WPF technology to build a user interface, provides a unified programming model, language and framework, to separate the work of interface designers and developers, and also provides a new multimedia interactive user graphical interface [9-11]. Fig 3 shows the monitoring system interface when the E10 section bending special-shaped immersed tube is installed and butted.
4. Result of installation
The installation and docking of the first section of immersed tube were completed on June 10, 2017. The following table 1 shows the axis deviation of the special-shaped immersed tube E10, which positively indicates the left side of the pipe section axis, and negative indicates the right side of the pipe section deviation axis.

| NO. | Surveying System (mm) | Total Station (mm) |
|-----|------------------------|-------------------|
| E10 | -30                    | -13               |

It can be seen from the table that the difference between the axis deviation of the pipe joint obtained by the monitoring system and the result measured by the total station is less than 20 mm. Taking the through measurement of the total station as the final acceptance result, the installation error of curved special-shaped immersed tube is less than 50 mm, which shows that the monitoring system method is feasible and the results are accurate and reliable.

5. Conclusion
At present, the construction of immersed tube tunnels is in the ascendant in China. The immersed tube tunnel projects represented by Hong Kong Zhuhai Macao Bridge and Nanchang Honggu tunnel have been completed and opened to traffic. At present, the projects under construction include Shenzhen-Zhongshan Link, Xiangyang east-west axis tunnel, Guangzhou Jinguangdong tunnel, Guangzhou Chebei tunnel, etc. The special-shaped immersed tube installation and docking monitoring system developed for the NSL tunnel can not only realize the installation and docking of large arc bending immersed tube, but also complete the installation and docking of the conventional rectangular immersed tube, which has important guiding significance for site construction, greatly improves the efficiency and accuracy of immersed tube installation, effectively reduces the operation risk and cost, and can be used for reference by other sinking in tunnel engineering.
6. References

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