Settlement Analysis of Sand Compaction Pile Composite Foundation in Transition Section of Immersed Tube Tunnel

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Abstract. The foundation of the immersed tube transition section of the Hong Kong-Zhu Hai-Macao Bridge Project is distributed with thick silty soil. The method of sand compaction pile + surcharge preloading is used to treat the soft soil ground. In order to determine the foundation consolidation settlement and subsequent residual settlement in the transition section of the immersed tube tunnel, a monitoring system using long wires combined with wireless transmission and long-distance data collection was developed to obtain the measured foundation settlements during the surcharge period. After comparing the measured value with the calculated value, the formula for the composite foundation of the sand compaction pile was revised to obtain a more reasonable residual settlement of the foundation, which could guide the design and construction of the immersed tube tunnel.

1. Introduction

The immersed tube tunnel of the Hong Kong-Zhuai-Macao Bridge is 5664m long and consists of 33 sections of immersed tubes and 1 final joint. It is the first offshore immersed tube tunnel in China. As it is located in the open sea, the foundation is mainly soft soil, and the soft foundation needs to be treated before it can be used as the foundation of an immersed tube tunnel. Especially in the transition section, the amount of foundation excavation is small, so the soft soil is deep, which is prone to excessive residual settlement, resulting in tube joint cracking and water inflow. The foundation treatment design of the immersed tube transition section of the west artificial island adopts the method of sand compaction pile + surcharge preloading. The sand compaction pile are arranged in a square shape, the spacing is 1.8m-2.2m, the pile diameter is 1.5m-1.7m, and the replacement rate is respectively 42\%, 55\% and 70\%, the pile length is 15.6m-25m. After the construction of the sand compaction pile is completed, the foundation is preloaded by the application of upper riprap, and the load is about 6MPa, and when the consolidation degree of foundation reaches more than 90\%, and the residual settlement of foundation is reduced through the surcharge preloading. In view of the situation where the water depth of the transition section is more than 20m, the offshore is more than 200m, and the environment is harsh, it is of great significance to develop appropriate monitoring methods to obtain effective measured data during the stacking period, and correct the settlement calculation method of sand compaction pile composite foundation and determine the reasonable residual settlement of foundation through the comparative analysis of calculated data and measured data, so as to ensure the safety of immersed tube tunnel.
2. Engineering Geology
The elevation of the original mud surface of the transition section of the immersed tube tunnel is about -8.0m to -10.0m, the surface layer is silt and silty clay layer, and the lower part is the super-consolidated soil layer (3) clay layer. The silt layer has high water content and high compressibility; the super-consolidated soil layer has greater strength and strong resistance to deformation. The foundation treatment penetrates the silt layer and enters the bottom of the super-consolidated soil layer (3) clay layer. The parameters of the formation to be treated are shown in Table 1.

Table 1. Stratum parameters.

| Stratum number and name | Bottom elevation (m) | Unit weight (kN/cm³) | Porosity ratio | Undrained strength (kPa) |
|-------------------------|----------------------|----------------------|----------------|-------------------------|
| (1) Silt and silty clay | (-28.3) to (-31.0)   | 16.2                 | 1.732          | 23.0                    |
| (2) Clay                | (-29.4) to (-31.78)  | 18.7                 | 0.866          | 42.7                    |
| (3) Clay                | (-34.92) to (-36.02) | 18.1                 | 1.052          | 124.0                   |

3. Settlement Analysis of Sand Compaction Pile Composite Foundation

3.1. Settlement Monitoring of Sand Compaction Pile Composite Foundation during Surcharge Preloading Period
The sand compaction pile are constructed by sand pile ships, and the top of the foundation is pre-loaded after the construction is completed. As the water depth of the surcharge preloading area exceeds 20m and the distance from the artificial island is more than 200m, it is very difficult to obtain foundation settlement data during the preloading period. The traditional manual measurement does not have the conditions for implementation, and it is necessary to use automated monitoring methods to obtain actual measurement data. Therefore, after the long wire is guided along the axis of the immersed tube tunnel to the steel cylinder of the artificial island, the method of automatic acquisition and wireless transmission is carried out. This method also avoids the underwater sealing treatment of automatic acquisition and transmission equipment, is convenient for maintenance, reduces the risk of the entire monitoring system, ensures the continuity and accuracy of data, and saves the costs. In this method, the protection of the wire is very important, so the wire is protected by a protective hose after passing through the hole, and fixed on the ground with a "U"-shaped clip, with a sand bag on it, so that the wire will not be protected from water flow and construction before being stacked, so as to ensure the acquisition of measured data.

The surface settlement under water is measured by a liquid differential pressure settlement instrument, and the layered settlement of the foundation is observed by embedding a layered single-point displacement meter. A total of 6 monitoring sections are set up, of which the sections A, D, E, and F are embedded with 3 sets of liquid differential pressure sedimentation meters and a group of layered single-point sedimentation meters. Sections B and C are only embedded with liquid differential pressure sedimentation meters. The 3 sets of liquid differential pressure sedimentation meters are respectively installed at the edges and the middle of the immersed tube tunnel; a single-point displacement meter is placed every 3m along the depth direction to form a layered sedimentation meter, which is placed in the middle of the immersed tube tunnel. The layout of monitoring points is shown in figure 1.
During the monitoring process, the sensor at point C was damaged due to the impact of the stacking construction, and the other measuring points were intact, and real-time, effective and continuous monitoring data were obtained.

3.2. Settlement Calculation of Sand Compaction Pile Composite Foundation

The existing domestic settlement calculations for sand compaction pile composite foundations are mostly estimated by the calculation method recommended by the Japanese code [1], and the calculation formula is shown in equation (1).

\[ S' = \beta \sum_{i=1}^{k} m_i \Delta P_i h_i \]  

In the formula, \( S' \) settlement of composite foundation, mm; \( \beta \) settlement reduction rate, and \( \beta = 1/(1+(n-1)m) \)%; \( n \) is the pile-soil stress ratio, \( m \) is the replacement rate of sand pile area,%; \( m_{vi} \) the volume compressibility of the soil layer \( i \); \( \Delta P_i \) the average additional stress of the soil layer \( i \), kPa.

According to this method, the calculated settlement results of each monitoring point of the sand compaction pile composite foundation in the transition section during the preloading period are shown in table 2.

According to the calculation results in table 2, it follows that due to the installation of sand compaction pile on the soft foundation, the settlement of the foundation is greatly reduced relative to the natural foundation, from the 274mm-407mm of settlement of natural foundation to about 52mm-109mm at 90% degree of consolidation, the settlement is greatly reduced, indicating that the use of sand compaction pile and surcharge preloading can effectively reduce the settlement of the foundation.

Figure 1. Layout of monitoring points.
Table 2. Settlement calculation value of sand compaction pile composite foundation during preloading period

| Monitoring point | Replacement rate (%) | Height of surcharge preloading (m) | Calculated settlement of foundation (mm) | Calculated settlement of 90% consolidation degree (mm) |
|------------------|----------------------|-----------------------------------|------------------------------------------|------------------------------------------------------|
| A1               | 42                   | 14.5                              | 308.7                                    | 78.8                                                 |
| A3               | 42                   | 14.5                              | 268.8                                    | 52.3                                                 |
| B                | 42                   | 15.5                              | 274.5                                    | 65.7                                                 |
| D                | 42                   | 13.7                              | 278.5                                    | 69.6                                                 |
| D2               | 42                   | 13.5                              | 340.6                                    | 79.8                                                 |
| D3               | 42                   | 13.3                              | 274.5                                    | 68.6                                                 |
| E1               | 55                   | 14.4                              | 382.6                                    | 100.6                                                |
| E2               | 55                   | 14.4                              | 314.1                                    | 86.1                                                 |
| E3               | 55                   | 14.4                              | 407.0                                    | 109.4                                                |
| F1               | 70                   | 15.6                              | 314.1                                    | 64.8                                                 |
| F2               | 70                   | 16                                | 407.0                                    | 101.8                                                |
| F3               | 70                   | 15.5                              | 382.6                                    | 94.2                                                 |

4. Result Analysis

4.1. Comparison of Calculated Value and Measured Data
The calculated value of foundation settlement at each monitoring point in Table 2 is compared with the measured value, as shown in Figure 2. It can be seen that the calculated settlement of the area where the replacement rate of sand compaction pile is 42% is close to the measured settlement. In areas with higher replacement rates of 55% and 70%, the calculated values differ greatly from the measured values. When the replacement rate is 55%, the difference between the theoretical calculation value and the measured value of the local position is nearly double. Therefore, when the high replacement rate of sand compaction pile is used for foundation treatment, the calculation result of the settlement formula of the sand compaction pile composite foundation is too large to truly calculate the consolidation settlement and residual settlement of the foundation, so the calculation formula needs to be modified[2,3].

Figure 2. Comparison between calculated value and measured value.
4.2. **Modification of Calculation Formula**

In view of the large deviation of the settlement calculation results of the sand compaction pile foundation with high replacement rate, a fitting correction method to the original formula is proposed based on the field measured data. In order to further clarify the settlement law of the sand compaction pile foundation and eliminate the discrete influence of the different stratum distribution of each section on the settlement law of the foundation, the settlement reduction ratio coefficient of sand compaction pile composite foundation is introduced [2, 4], which is the ratio of settlement of sand compaction pile composite foundation to that of natural foundation.

In figure 3, it shows the distribution of the measured settlement reduction ratio under different replacement ratios for the composite foundation of sand compaction pile in the transition section of the immersed tube tunnel. The curve in the figure is the calculated settlement reduction ratio curve. Compared with the measured data, it can be seen that as the replacement rate increases, the settlement reduction ratio has a significant decreasing trend. However, after the replacement rate is greater than 50%, the overall distribution trajectory of the measured data is quite different from the theoretical calculation formula ($\eta = 1$ in figure 3), and the distribution is more consistent with the curve characteristics of $\eta = 2.5$.

![Figure 3. Settlement reduction ratio coefficient.](image-url)

Therefore, the settlement reduction rate $\beta$ in the formula (1) for the settlement calculation formula of the sand compaction pile composite foundation is corrected to, and the calculation formula is equation (2).

$$
\beta' = \frac{1}{1 + \eta (n-1)m}
$$

(2)

In the formula, $\eta$, empirical correction coefficient, when the replacement rate $m < 0.5$, take 1~1.5, when $m \geq 0.5$, take 2.5.

This modified formula is used to calculate the settlement of the composite foundation with high replacement rate sand compaction pile in other areas, as shown in figure 4. It can be seen that except for individual points and factors affecting the complex situation of measured data, the both are relatively consistent, indicating that the modified formula has good applicability and can be used as the prediction, calculation and analysis of settlement of high replacement rate sand compaction pile composite foundation.
Figure 4. Comparison of the calculated value and the measured value.

Using this formula, the residual settlement of the foundation in the transition section of the immersed tube is calculated, and the residual settlement is less than 10mm, indicating that the soft foundation has been well strengthened.

5. Conclusion
According to the above analysis, the conclusions are as follows:

(1) The settlement of the composite foundation of high-replacement sand compaction piles calculated by the commonly used formula is quite different from the actual situation, and the calculated settlement is too large. When the replacement rate of sand compaction pile reaches more than 50\%, the reduction rate should be corrected before the settlement can be more accurately estimated.

(2) In engineering application, appropriate monitoring technology should be adopted according to actual engineering conditions. This time, the long wire is guided along the axis of the immersed tube tunnel to the steel cylinder of the artificial island, and then automatically collected and wirelessly transmitted on land, which reduces the risk of the entire monitoring system for the transition section of the immersed tube tunnel of the Hong Kong-Zhuhai-Macao Bridge and ensures the continuity and accuracy of the data.

(3) The sand compaction pile + surcharge preloading treatment method makes the soft foundation of the immersed tube transition section better improved, and the residual settlement is small, which can meet the service requirements of the immersed tube transition section.

References
[1] Mo J Y, Huang J S. 2009 Application of sand compacted pile for ground treatment of oceanic shore protection engineering works [J] Port & Waterway Engineering 87-92.
[2] Xu Z H. 2011 Calculation of composite foundation’s bearing capacity by high replacement ratio sand compacted pile in soft clay [J] Port & Waterway Engineering 131-5.
[3] Zhang D. 1999 Analysis and computation of the deformation modulus of the pile in the composite foundation [J] Chinese Journal of Geotechnical Engineering 205-8.
[4] Xu Y, Xu G P, Fu B Y, He X. 2020 Research on foundation settlement control of immersed tunnel at the joint of offshore artificial island and island tunnel [J] Tunnel Construction 88.