Subsoil Settlement Feature of Immersed Tube Tunnel in Deep Soft Subsoil with Heavy Siltation in Open Sea

Caractérisation du tassement sur sol mou de grande épaisseur d'un tunnel tube immergé soumis à un envasement important en condition de mer ouverte

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ABSTRACT: Hong Kong-Zhuhai-Macao Link that crosses the Pearl River Estuary is a connection bridge between Hong Kong, Macao and Zhuhai, which will improve the communication of these three places in China. The bridge is an oversized cross-sea project over the east and west coasts of the Pearl River. Relied on the undersea immeresed tube tunnel (IMT) for Hong Kong-Zhuhai-Macao Link project and focused on the consolidation settlement feature of the subsoil for IMT on deep soft subsoil under the conditions of large excavation, backfilling and siltation in open sea, a full stress path of subsoil was simulated for the process of compression in consolidation, unloading in excavation and re-compression in backfilling, by using of Geotechnical Digital Systems with on-site CPTU test results and the in-situ bored soil sample. Based on these results, the process of subsoil consolidation – excavation – tube location – backfilling – siltation as well as the re-excavation of channel was simulated by using gotechnical centrifuge, to find out the settlement feature of the subsoil during and after tunnel construction. The settlement and consolidation feature of the deep soft subsoil with heavy siltation in open sea was presented.

RÉSUMÉ : La construction de la liaison routière entre Hong-Kong, Macao et Zhuhai est un projet national en Chine, qui concerne particulièrement de grands ponts au-dessus et d'un tunnel au-dessous de la mer. Dans cet article, à partir de résultats d'essais CPTU in-situ et d'essais GDS en laboratoire, dans le but de préciser les caractéristiques de tassement et de consolidation de sols mous sous-marins de grande épaisseur soumis à de grandes excavations et à la mise en place d'un tunnel, la procédure complète du chemin de contraintes "compression de consolidation – décharge par excavation – recharge due aux remblais et au tunnel" appliquées effectivement pendant les travaux de fondation du tunnel immergé a été simulée. Un essai en centrifugeuse a aussi été effectué afin d'étudier les caractéristiques de tassement et de consolidation pendant et après les travaux. Les résultats nous permettent de mieux connaître le comportement de ce type de tassement dans la condition de mise en place d'un tunnel immergé avec un envasement important.

KEYWORDS: IMT; Settlement; Stress Path; Centrifugal Model

1 INTRODUCTION

The oversized Hong Kong-Zhuhai-Macao bridge which crosses the Pearl River Estuary, connects Hongkong, Macao and Zhuhai. The IMT approach was selected to pass LingDing West channel and TongGu West channel based on the aviation high limit of Hong Kong International Airport, the proposed channel, and on site investigation of Hong Kong-Zhuhai-Macao bridge.

The immersed tube tunnel has the characteristics of long tube, deep water, large silting on tube surface, weak and uneven foundation, difficult settlement control, stress concentration near between the island and the tunnel joints and complex construction process. Generally, Immersed tube tunnel is not sensitive to soil settlement. But uneven settlement will occur due to significant change in soil characteristics and load distribution along the tunnel. The load redistribution will lead to additional stresses. Thus it is important to estimate the subsidence quantity for immersed tube tunnel which is made of brittle concrete materials. Therefore, it is important to study the soil settlement with resilience-recompression characteristics in IMT under Hong Kong-Zhuhai-Macao bridge project.

2 THE DEFORMATION CHARACTERISTICS OF IMT FOUNDATION SOIL BASED ON SIMULATION OF STRESS PATH

2.*1 Soil engineering property and its simulated conditions*

In order to study the resilience-recompression characteristics of IMT foundation soil caused by different load condtions, the complete stress path of trench soil was simulated by numerical method and GDS triaxial test with standard stress path to understand the complete stress path, consolistaion and compression, and resilience-recompression characteristics. Through suveries and CPTU data, it was found that the tunnel foundation has 5 distinctive cross sections. Three sections are studied in this paper, as shown in Table 1 The distribution profile of the cross-sectional test points is shown in Figure 1. The basic engineering properties of the soil are presented in Table 2.

The whole research process was based on detailed engineering survey and the CPTU data. Using numerical simulation of the actual conditions, different characteristics of foundation soil stress is obtained, and then stress path simulation test is carried out. Saturated specimen was prepared based on dry density, which is 39.1mm in diameter and 80mm in height. First consolidation module K_0 was selected, and then K_0 consolidation test was performed. Through the back pressure volume measurement volume change, the target value of K_0 consolidation was stress value from the numerical simulation of the original stress state. Then take the stress path test module, simulation consolidation - excavation unloading - backfill reload - navigation path excavation and unloading. According to the numerical calculation results, set the stress path module of each phase of the set target value, then finish stress path simulation test with these methods. Through the test to obtain different stress paths condition of modulus of compression、modulus of resilience and recompression modulus, then the numerical calculation is carried out again by using these test modulus. Get new stress characteristics of different foundation soil. And compare with the original calculation results until the test results and calculation results are close enough to the acceptable level.

Table1 The test scheme

Test number	T-B (Deep groove section)	T-C (Thick soft subsoil section)	T-E(Waterway excavation section)
Mileage stake	K9+200 ~ K9+300	K9+500 ~ K9+600	K10+400 ~ K10+700
Test conditions	Consolidation-Excavation of the foundation trench-Backfilling-Back silting	Consolidation-Excavation of the foundation trench-Backfilling-Back silting	Consolidation-Excavation of the foundation trench-Backfilling-Back silting-Waterway excavation

Table2 Physical properties of various soil on natural foundation

The name of soil layer	μ	C (kPa)	φ (°)	Buoyant density (kg/m^3)
Silt	0.43	6.0	2.0	680
Clay and silt clay	0.39	22.0	22.0	940
Clay coarse	0.30	22.0	25.0	900
Coarse sand	0.30	18.0	32.0	1100
Fine sand	0.35	21.0	33.0	1000
Medium sand	0.32	20.0	34.0	1030

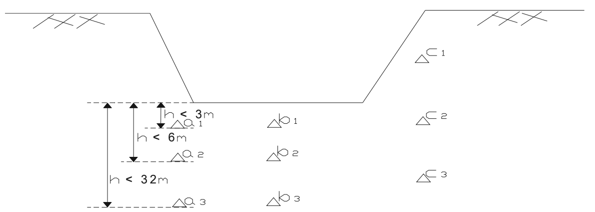
Figure1. Test point distribution

2.2 Rearch results analysis

The stress path figure of GDS stress path simulation test about different layers of soil stess path at different depths from GDS stress path simulation tests is shown in Figures 2 to 4.

Based on the compression modulus, modulus of resilience, recompression modulus and re-springback modulus (waterway excavation) from test, numerical analysis ground deformation characteristics of a typical cross-section. The test results is shown in Figures 5 to 8, where the displacement deformation values are relative displacement values.

From Figures 5 and 6, in the deep channel section of the natural foundation, the rebound curve of the bottom of the foundation trench has an arch-shaped distribution after excavation ; the rebound of foundation trench center is larger ; the recompression curve has a saddle-shaped distribution. The entire tube foundation cross-sectional displacement in the process of excavation and backfill is relatively small.

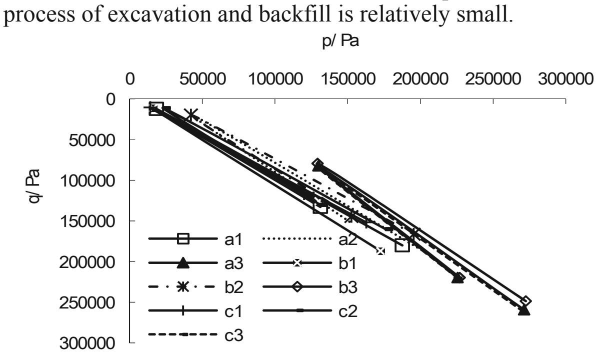

Figure2. Stress path of B sectional test points

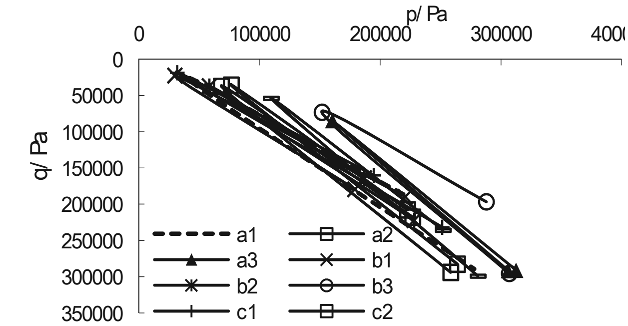

Figure3. Stress path of C sectional test points

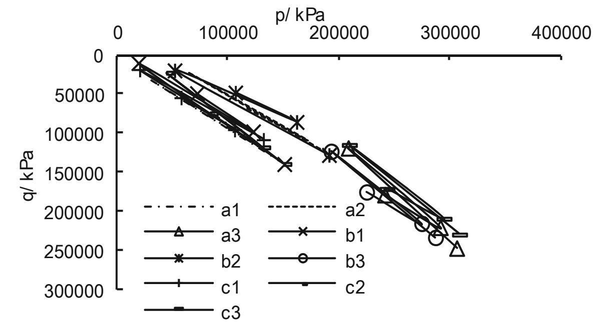

Figure4. Stress path of E sectional test points

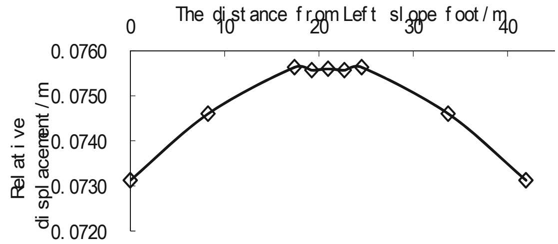

Figure5. Springback displacement of the bottom of B section foundation trench after excavation

From Figures 7 and 8, in the main channel excavation section, the recompression and re-springback curve of tube foundation soil in E section has a saddle-shaped distribution. And the cross-sectional displacement in the process of backfill and re-excavation is relatively small. The re-excavation of channel has limited impact on the uneven settlement deformation.

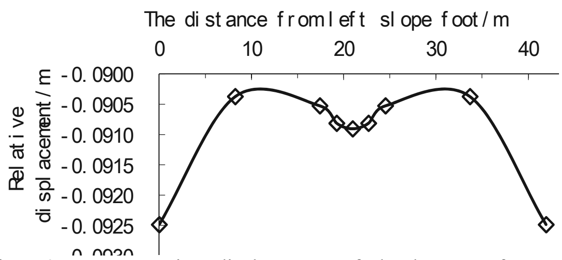

Figure6. Recompression displacement of the bottom of B section foundation trench after backfilling

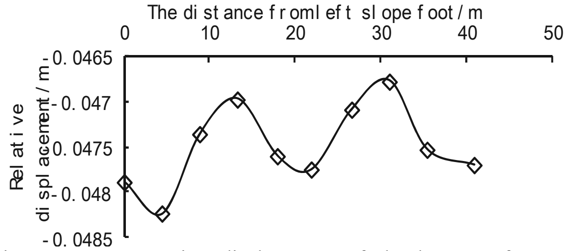

Figure7. Recompression displacement of the bottom of E section foundation trench after backfilling

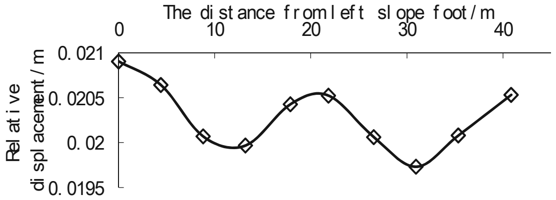

Figure8. Re-springback displacement of the bottom of E section foundation trench after waterway excavation

3 THE DEFORMATION CHARACTERISTICS OF IMT FOUNDATION SOIL BASED ON CENTRIFUGE MODEL TEST

3.1Design and preparation of the model

Before the experiment, with detailed surveying data numerical analysis was performed to simulate loading conditions using modulus from stress path tests. Due to the limition of the centrifugal box size and the fact that the slope excavation of the model upper foundation trench is larger than the actual condition, so immersed tube tunnel foundation was simulated which was influenced by the difference between the slope excavation of the foundation trench and actual condition in centrifugal model test. The model used in the centrifugal simulation test was verified by comparison analysis. The centrifuge type is TLJ - 3 geotechnical centrifuge. Its maximum capacity is 60g·T, the effective radius is 2.0 m and the maximum centrifugal acceleration is 200 g. The model box size is 70×36×50 cm^3. The model scale was selected to be 100g based on the box's headroom size and the prototype scope of simulated model. The preparation of the model foundation soil is controlled by the nature of the prototype foundation soil (See table 2) and centrifugal similar rate. Every foundation soil thickness is determined by scaling down the thickness of the section in corresponding condition according to the geometric scale. The dry density of cushion layer and coarse grained soil and the strength parameters of the other soil must be in aggrement with prototype.

IMT model is the key structure in the test. This test adopts full section simulation. The high and width of the prototype IMT is 11.5 m and 40 m. Due to the limitation of test model height, the height of IMT model must be controlled in 5cm. The width of IMT section is reduced in proportion accordingly. The organic glass is used as IMT model materials. The height and internal dimension of model are controlled by the axial stiffness EA, bending rigidity EI and pressure stress from immersed tube to foundation of the prototype. Upper backfill on IMT is simulated using the steel plate of the same weight. So the height of the model is effectively reduced. Since the steel plate has almost no deformation, the deformation of the upper plate can be directly measured to obtain the sedimentation of IMT in construction operation.

In natural ground segment of IMT, B section is deep excavation section; C section is thick clay section and E section need to excavate a channel after the construction, it involves excavation unloading problems after the backfill back silting. Therefore typical cross sectional B, C and E of standard conditions were simulated in the test. The test of C section with 1 m cushion layer and the most adverse conditions was conductedto compare with standard conditions experimental results.

3.2The arrangement of the measuring points in the model

Earth pressure cell and pore water pressure cell were buried in the foundation soil (Soil pressure box main layout in the boundary of different soil layer) and laser shift sensor were mounted in the top of model box in order to monitor vertical stress distribution of foundation soil, stress distribution of basement, development process of pore water pressure and vertical rebound recompression displacement of basement during the test procedure. As shown in Figure 9(S1-S9 are earth pressure cell; P1and P2 are pore water pressure cell; W1 and W2 are laser displacement sensor).

High sensitivity strain gauges were mounted on the bottom and sides of immersed tube in order to measure the strain of immersed tube during the test process. All above tests data was automatically collected by DDS data acquisition system.

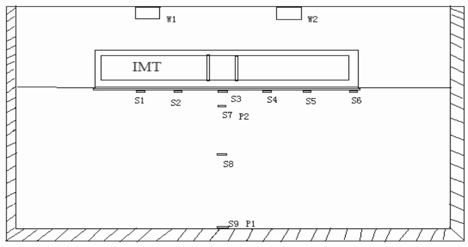

Figure9. The layout of pressure cell

3.3 Research results analysis

The stress distribution curve of IMT base groove bottom surface of B section after construction is shown in Figure 10. The stress distribution curve with time of IMT base groove bottom surface of B section within 3 years after the completion of the construction backfill is shown in Figure 11.

Figure 10 indicates that test results are the same as the numerical results. The stress distribution of foundation trench bottom has a saddle-shaped distribution. The basal stress of IMT' carriageway is relatively small. While the largest basal stress value comes from both sides of IMT, and the second largest basal stress comes from the partition wall. The difference between the maximum and minimum stress values is not more than 38 kPa.

Figure 11 indicates that stresses level off after initial increasesThe stress increment is relatively little, which is about 10kPa.

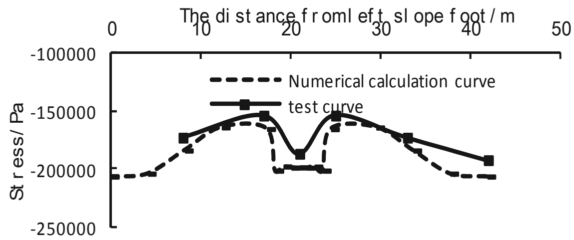

Figure10. Stress distribution of the bottom of B section foundation trench

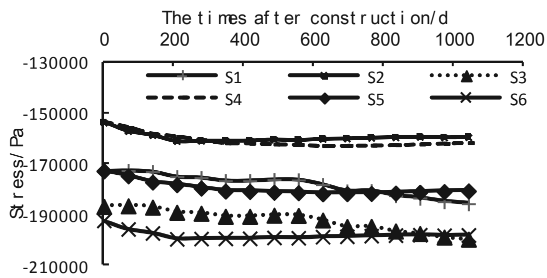

Figure11. Stress-time distribution of the bottom of B section foundation trench

The stress distribution curve of IMT base groove bottom surface of E section after backfilling and channel excavation is shown in Figure 12.

In Figure 12, the stress distribution of foundation trench bottom has a saddle-shaped distribution. The basal stress of IMT' carriageway is relatively small, both sides of IMT have maximum basal stress value, and the basal stress of partition wall have the second largest basal stress. The difference between the maximum and minimum stress values is not more than 52 kPa.

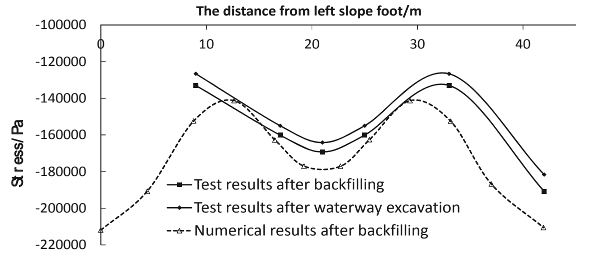

Figure12. Stress distribution of the bottom of E section foundation trench

The stress distribution curve of IMT base groove bottom surface of C section under the standard condition (1.5m cushion) and non-standard condition (1m cushion), 3 years after backfilling is shown in Figure 13.

Figure 13 indicates that the basal stress curve of non-standard condition has large gradient, which means that the basal stress extremum difference under the non-standard conditions is larger than the basal stress extremum under standard conditions. 1.5m cushion is better than 1m cushion in terms of foundation stress uniformity. For both sides base disengaging of IMT condition, the center stress of IMT' base is smaller than the center stress of IMT' base under the standard condition. But the basal stress with voids underneath is significantly higher than the stress under the standard condition; the basal stresss close to both sides of IMT is larger than the stress under the standard condition. The reason is that because of both sides base disengaging of IMT, in the overlying loads, backfilling leads to the cushion bearing loads at the begining, then clay was squezzed out and underneath voids were formed. Stress concentration occured at the boundaries of voids b under IMT' base . Since IMT is of a certain stiffness, the strain of both sides of IMT will not increase excessively and the basal stress of void beneath is relatively reduced.

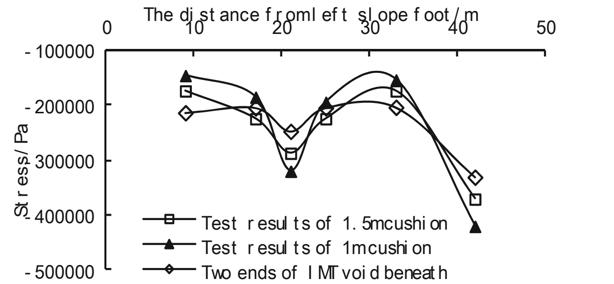

Figure13. Stress distribution of the bottom of the C section foundation trench

The typical cross section ground deformation curve with time, within 3 years after the completion of the construction backfill is shown in Figure 14.

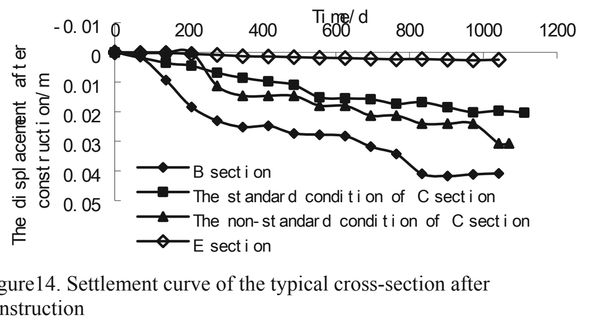

Figure14. Settlement curve of the typical cross-section after construction

From the Figure 14, after construction the amount of base recompression change is small, and after 3 years the maximum recompression amount is 0.0407m. The largeest settlement between each section is about 0.01m.

In the standard condition of C section, 3 years after construction, the largest settlement is 0.02035m. In the condition of 1m cushion, the largest settlement is 0.0307m after construction, which indicates that reduced cushion makes settlement larger than the settlement of standard conditions. After the test, the cushion under the standard condition (1.5m cushion) has no significant change in centrifuge. But under the non-standard condition (1m cushion), most gravel cushion has been incorporated into the clay layer in centrifuge after the test, which blend the part of cushion and clay layer. And the cushion lost its attempted function, which is also the main reason for the difference between non-standard conditions and standard conditions.

4 CONCLUSIONS

For the special conditions of Hong Kong-Zhuhai-Macao bridge undersea IMT on Deep Soft Subsoil with Heavy Siltation in Open Sea, the stress process of IMT foundation soil in different conditions is simulated by using of Geotechnical Digital Systems and numerical simulation based on on-site CPTU test results and the in-situ bored soil sample. The stress path of the process of the foundation soil consolidation- excavation - backfill recompression - waterway excavation are studied. The deformation characteristics of foundation soil at typical cross section is simulated by numerical analysis.

Based on these results, a construction simulation was performed with geotechnical centrifuge for the process of subsoil consolidation – excavation – sinking IMT – backfilling – siltation as well as the re-excavation of channel. The results show that the settlement of IMT foundation soil in construction and post-construction is smaller. After 3 years of operation, the foundation cumulative settlement amount on deep channel section and thick soft clay ground is not more than 0.0407m. In the process of excavation and backfill recompression, the stress and settlement distribution of foundation cross-sectional has a saddle-shaped distribution, and the different deformation value between foundation cross-sectional and longitudinal section is small. Waterway excavation has less effect on the stress and deformation of the IMT foundation soil. Cushion thickness has a greater impact on the settlement of IMT, and 1.5m cushion thickness is reasonable.

5 ACKNOWLEDGEMENTS

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