Analysis on foundation settlement and island wall deformation of offshore artificial island

Jinfang Hou ⁱ⁾, Ruiqi Zhang ⁱⁱ⁾ and Xiaoqiang Kou ⁱⁱⁱ⁾

i) Senior Engineer, Key Laboratory of Soft Soil Engineering Character and Engineering Environment of Tianjin, CCCC Tianjin Port Engineering Institute, Ltd., Key Laboratory of Port Geotechnical Engineering, Ministry of Communications, PRC, Key Laboratory of Geotechnical Engineering of Tianjin Department of Civil Engineering, Dagou South Road No.1002, Hexi District, Tianjin, China.

ii) Engineer, CCCC Tianjin Port Engineering Institute, Ltd., Key Laboratory of Port Geotechnical Engineering, Ministry of Communications, PRC, Key Laboratory of Geotechnical Engineering of Tianjin Department of Civil Engineering, Dagou South Road No.1002, Hexi District, Tianjin, China.

iii) Engineer, CCCC Tianjin Port Engineering Institute, Ltd., Key Laboratory of Port Geotechnical Engineering, Ministry of Communications, PRC, Key Laboratory of Geotechnical Engineering of Tianjin Department of Civil Engineering, Dagou South Road No.1002, Hexi District, Tianjin, China.

ABSTRACT

It is introduced that the construction process of west artificial island of Hong Kong-Zhuhai-Macao Bridge. The emphasis is the settlement of foundation and the deformation of island wall which are calculated by finite difference method (FDM) during construction. By analysis, consolidation settlement of soft clay foundation and steel cylinders deformation under every construction process are known. And key process are discovered for guiding design and construction. The results show that two construction process backfilling sand in the island and riprapping outside the island to be slope are key processes, because they have greater influence on steel cylinders and foundation of island. Foundation settlement speed in the construction period is far greater than the specification requirements, while foundation crack and other accidents are not available. The reason is steel cylinders restricting lateral deformation of soft clay foundation. Therefore, the foundation settlement control standards in such artificial island should break through the requirements of specification. Meanwhile, it is known that the maximum settlement of soft clay foundation of artificial island is 2.92m. Residual settlement is 13cm. Maximum vertical displacement of the steel cylinder top is 28.5cm, and lateral displacement is 8cm.

Keywords: settlement, construction process, steel cylinder, soft soil foundation

1 INTRODUCTION

Hong Kong-Zhuhai-Macao Bridge is an important project to connect Guangdong province, Hong Kong and Macao and to develop the economy in the Greater Pearl River Delta. The project consists of bridges, artificial islands and tunnels, and is about 35,000m in length. In Lingding West and Tonggu Channel sections, subsea tunnel is adopted, for which two artificial islands named west artificial island and east artificial island are built to connect the bridges and subsea tunnel. The plane distance is 5,584m between two artificial islands. The artificial islands are designed just like "Oyster Shell"; each one covers a total area of 97,962 m², and is 625m long and about 183m wide at the widest point, and the water depth reaches 8m. Since the artificial islands are located at the open sea and the foundation of the artificial island is covered with very thick soft clay due to marine sediment of Holocene series, making the construction of the artificial islands very difficult. Therefore, the study is conducted on the west artificial island, in which, FLAC3D finite

difference method is adopted to analyze the deformation characteristics of island wall and foundation during construction process, Dong et al. (2008), so as to optimize the construction process and ensure the safety of construction and operation period.

2 CONSTRUCTION PROCESS OF ARTIFICIAL ISLAND

The wall of west artificial island is composed of steel cylinders which are inserted into impervious soil, and the island is formed by filling sand in the closed area by steel cylinders. The whole island is divided into 4 parts: interior island area A1, interior island area A2, cylinder area B and off-island area C, which can be seen in Fig.1. The interior island area is divided into A1 and A2 according to requirements of construction period. Area A1 is constructed much earlier than Area A2. The cylinder area B is the first step to build an artificial island. After the excavation of the foundation trench, totally 61 steel cylinders in diameter of 22.0m, wall thickness of 16mm and height of 37m-47m will be

inserted into the foundation trench. These steel cylinders are connected by lattices to enclose a closed area. The island can be formed by backfilling sand, dewatering and preloading. The construction work of the island-tunnel connecting section can be started after the excavation of the foundation. The foundation of the exterior island area C is sand compaction pile composite foundation on which the revetment will be built. So far the west artificial island is formed.

Fig. 1. Sketch of partitions in the west artificial island.

The foundation soil of the west artificial island includes three layers. Table 1 is the parameters of soil.

Table 1. Parameters of soil.

Name	Bottom evaluation (m)	Unit weight ($\text{kN}\cdot\text{m}^{-3}$)	Permeability coefficient $/(10^{-7} \text{ cm}\cdot\text{s}^{-1})$	
			K_v	K_H
① ₂ Sludge	-14.8~-24.9	15.7	7.11	13.40
① ₃ Mucky clay	-25.6~-32.4	16.8	3.24	8.68
② ₁₋₁ Silty clay	-29.4~-37.1	19.2	13.8	18.9
③ ₃ Silty clay	-32.2~-34.4	18.6	4.13	1.48
③ ₂ Silty clay with sand inclusion	-41.26~-43.9	18.3	44.0	-
③ ₄ Clay	-38.2~-51.3	18.1	20.0	17.8

The construction process of foundation treatment includes: excavating the foundation trench to -15m firstly, backfilling the medium-coarse sand to -5m, putting the plastic vertical drainage plate to the third layer, and then dewatering to -16m; lastly backfilling the medium-coarse sand to +5m and carrying out the preloading. Typical section is shown in Fig. 2.

Fig. 2. Sketch of foundation improvement section.

3 DEFORMATION OF STEEL CYLINDER

The typical section model of the island is built up in accordance with design drawings and actual conditions of the project. And the deformation analysis of the steel cylinders during the construction process is done by FLAC3D finite difference method, Chai et al. (2001). The deformation of steel cylinders under main construction process is shown in Fig.3, from which the analysis can be concluded as:

(1) Step I: inserting steel cylinders and backfilling, and the backfilling construction of foundation inside and outside the island. The steel cylinders are deformed vertically and tilt to the inner side of the island; (2) Step II: sand backfilling construction inside the island. The vertical deformation of the steel cylinders is increased and the lateral deformation becomes obvious. What's more, the steel cylinders begin to bend near their center lines; (3) Step III: riprap construction outside the island. The vertical deformation of the steel cylinders still remains and the upper parts of the steel cylinders bend relatively obviously; (4) Step IV: foundation pit excavation and re-backfilling construction inside the island. Both the settlement and the lateral displacement of the steel cylinders do not change much, indicating that the construction of island-tunnel connecting section has little effect on steel cylinders.

Fig. 3. Deformation of steel cylinder.

During construction, the consequence of sand backfilling construction inside the island and riprap

construction outside the island has an obvious effect on the deformation of steel cylinders, which can be seen in Fig. 4. It can be observed that the top lateral displacement of steel cylinder will be differed by 7cm and the bottom lateral displacement differed by 13.1cm for different construction process (sand backfilling construction inside the island first or riprap construction outside the island first). It shows that lateral displacement difference of steel cylinders can be caused to the problems like leakage if we do not carry out the two above-mentioned construction processes at the same time. Thus, these are key construction processes and shall be controlled and also be carried out strictly.

Fig. 4. Deformation of steel cylinders under different construction process.

During the process of forming the island, the steel cylinders have the biggest settlement after two key construction procedures, which is as high as 28.5cm. The maximum lateral displacement is 8cm.

4 ANALYSIS OF FOUNDATION SETTLEMENT INSIDE THE ISLAND

4.1 Results of Settlement

The numerical calculation results are rechecked with the method of back analysis based on field monitoring data, and the numerical calculation parameters are adjusted. Fig.5 is the comparison between numerical calculation results and field monitoring data, and the monitoring point is located at the center of the interior island area A2.

Fig. 5. Comparison between field monitoring data and numerical calculation results.

Fig. 5 shows that the monitoring settlements agrees well with the numerical calculation results. From inserting the plastic vertical drain boards to the end of dewatering, field monitoring lasts nearly 5 months. So, Fig. 5 provides a comparative analysis on the construction process of this period. The construction process includes: inserting the plastic vertical drain boards, backfilling medium-coarse sand to -5 m, backfilling medium-coarse sand to +5m, dewatering to -16m, preloading and consolidating for 4 months, stopping dewatering, and unloading.

The backfilling construction can be started after finishing inserting the plastic vertical drain boards. The numerical analysis is carried out through calculation in accordance with backfilling step by step whereas the actual construction is not carried out in strict accordance with backfilling step by step. Thus, there is a relatively large difference between the numerical analysis result and the actual monitoring data. At this stage, the settlement speed reaches 7cm/d, while there are no failure like cracks or uplifts ever happening to the foundation. There is no big difference between the calculated settlement and the monitored settlement during unloading for the former is 2.47m and the latter is 2.52m, they both are same basically. They are in a good coincidence with each other at the consolidation settlement stage. The slight difference is caused by partially uneven field backfilling, which has no influence on the final settlement and residual settlement.

4.2 Settlement speed

As stipulated in "Code for Soil Foundations of Port Engineering" (2010), the settlement speed of the base center shall not be greater than 1.5cm /d when the foundation of vertical drainage is set during the preloading construction period. But the standard may be relaxed properly if the reinforced foundation soil is very soft and thick.

According to the calculation result, the settlement speed is 6cm/d at maximum, and the field monitoring data show that the maximum settlement speed reaches 7cm/d, which are already far beyond the value specified in the code, and the foundation is also free from uplifts and cracks. It shows that the steel cylinders being inserted around restrain the deformation of soft soil foundation inside the island, prevent the formation of sliding surface, and significantly reduce the occurrence of foundation shear failure. Therefore, the foundation settlement control standards in such artificial island should break through the requirements of specification.

4.3 Residual settlement

Construction procedures such as excavation, tunnel construction, backfilling inside the island will be carried out after unloading. Fig. 6 is the whole settlement process of foundation. It can be seen that there is a slight foundation rebound after the foundation

pit excavation and that there is another settlement after the tunnel construction and backfilling again. The overall foundation settlement reaches 2.79m. After handing over the project, the foundation consolidation settlement is ended in 2 years, and the total settlement reaches 2.92 m, thus the residual settlement is 13cm.

Fig.6. Curve of Progress of Ground Settlement.

Fig. 7 is the pore water pressure of every soil layer. It can be observed that: the No.③₄ clay layer which is characterized by low permeability coefficient and long consolidation time is distributed at a deep location of the foundation, the plastic vertical drain boards are not driven into this layer, thus the dissipation of pore water at this layer is very slow. So the excess pore water stress is still not dissipated completely before the excavation. Later, with the foundation pit excavation and unloading, the pore pressure at deep layers is dissipated largely. However, the dissipation is mainly caused by the upper unloading and the consolidation degree of deep soil caused by early dewatering is still relatively small. Therefore, it is suggested to prolong the dewatering time in deeper location of ③₄ clay layer during construction for the purpose of foundation retreating effect. The excess pore water pressure will be basically dissipated and the consolidation settlement will also be finished in 2 years after handing over the project, Jiao et al. (2012).

Fig.7. Pore Water Pressure.

5 CONCLUSIONS

(1) Backfilling sand construction inside the island and riprap construction outside the island are key construction procedures, which shall be controlled and carried out strictly in order to avoid lateral displacement difference that may cause problems like leakage.

(2) As for artificial islands of Hong

Kong-Zhuhai-Macao Bridge, the island wall is composed of steel cylinders, which restrain the lateral deformation of soft soil foundation inside the island and prevent the formation of sliding surface. The settlement control speed during construction period is far beyond the ordinary soft soil foundation. Therefore, the foundation settlement control standards in such artificial island should break through the requirements of specification..

(3) The maximum settlement of soft soil foundation is 2.92m, and the residual settlement is 13cm; the maximum top settlement of steel cylinders is 28.5cm, while the lateral displacement is 8cm.

(4) The third thicker clay layer is characterized by low permeability coefficient and long consolidation time. Therefore, the dewatering time at this soil layer should be appropriately prolonged to guarantee the foundation retreating effect.

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