Long-term settlement prediction of fast constructed artificial island

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ABSTRACT

With the development of the marine traffic engineering in China, it is needed to develop the construction method of artificial island in open sea. An artificial inland of 97962 m² was built in a cross sea bridge project in southeast sea of China. The seawater depth at low tide at the location is 10 m depth and the seawater level at low tide is considered as standard level. The thickness of 6 m seabed mud (-10 m to -16m from standard level) was replaced by sand first. The steel cylinders were inserted into the impermeable soil layer (-40 m) and then the seawater were pumped. The PVDs was inserted from -8 m up to -33 m and the sand was added up to +4m to improve the soft ground by dewatering preloading. The settlements at three typical sections, east section of the island which has deepest burial depth of tunnel (section 1), central section of the island (section 2) and west section of the island which has thickest soft clay layer (section 3), were measured during stage the soft ground improvement. The 3D finite difference method was used to simulate the construction process of the fast-constructed artificial island. The fluid-mechanical interaction method and equivalent hydraulic conductivity is used to predict the degree of consolidation. The settlement curves predicted by numerical method are compared well with the measured results in the field up to 150 days. The numerical results show that the long-term settlements (2400 days) of sections 1, 2 and 3 reach to 2.74 m, 2.91 m and 2.80 m, respectively. The residual settlements after two years of finishing the tunnel construction (1550 days) are 1 cm, 12 cm and 10 cm, respectively. The settlement rate and final settlement of artificial island calculated by the present method using one-dimensional consolidation theory are smaller than the measurement values in the field and the values predicted by numerical simulation. So the predicted settlement results by present method need to be modified according to field data, and numerical simulation method should be used to predict the long-term settlement.

Keywords: long-term settlement, artificial island, equivalent hydraulic conductivity, fluid-mechanical interaction method

1 INTRODUCTION

The artificial island as a platform linking up the tunnel and bridge plays an important role, its construction directly influences the laying of immersed tunnels, and the docking with the bridge. The ground of the artificial island consists of thick silt and soft clay, with high water content, high compressibility and low strength, low permeability and long consolidation time. Therefore, how to accurately estimate the settlement of soft clay ground became the main problem of engineering design. It is essential for guiding the construction practice, evaluating the construction quality, laying the tunnel effectively and butt joint safety between bridge and tunnel. Therefore, analyzing the surface settlement of soft clay ground of artificial island, choosing a reasonable ground improvement method and controlling the long term settlement of ground are significant to the construction safety of the tunnel and bridge project on the artificial island. The effective monitoring method and technique is important to measure the ground settlement actually. It is helpful to find and solve the problem in constructing, and also provide firsthand information for further research of long-term settlement on artificial island. It is helpful for guaranteeing the construction and maintenance of the project, avoiding unnecessary waste, and reducing construction period and costs.

Qin et al (2012) inversed the consolidation coefficient of the soil by splitting summation method and Terzaghi one-dimension consolidation method, based on seawall’s early post-monitoring data in the initial stage of construction, adopt the improved variable dimension fractal prediction models to forecast the consolidation coefficient with strong trends; and predict the contingent long-term post construction settlement of seawall. Based on settlement data
measured in field, Zhou et al. (2008, 2009) obtained the compressibility modulus and consolidation coefficient of soil layers by back analysis method for predicting the long-term settlement of the seaport. Shi et al. (2009) introduced the Mesri creep model to depict the creep deformation behavior of the soft ground, and inversely the viscoelastic parameters of Mesri model by back analysis of field monitoring data. Wang et al. (2006) and Deng et al. (2009) introduced the Asaoka’s method to predict the long-term settlement of soft clay. Li et al. (2013) analyzed the factors of the sea dikes' post-construction settlement with the fish bone cart method, and reported that the main factors of the settlement were foundation treatment and soil layers. Zang (1999) used grey system method to forecast the seawall’s residual settlement and advised that GM (1, 1) model was effective to predict the residual settlement in seawall construction.

The construction of a cross sea bridge in south east china was chosen to analyze in this study. The 3D finite difference method is used to simulate the process of the fast-constructed artificial island. The numerical simulation results are compared well with the in-situ measured results in the period of soft ground improvement. The long-term settlement of the artificial island was predicted using the numerical method.

2 ARTIFICIAL ISLAND PROJECT

The area where the artificial island constructed has thick soft clay such as muck and muck clay (Fig. 1), which has low strength and high compressibility (Table 1). It should be improved before the tunnel and bridge construction on the island.

The artificial island is mainly composed of steel cylinders and filling sand. The process of the island construction is as follows: a) excavating trench; b) inserting steel cylinders; c) filling the trench with sand; d) inserting PVDs and pumping water (ground improvement); e) filling sand to top; f) excavating ditch; g) constructing tunnel; h) covering backfill.

![Fig. 1 Analysis sections of artificial island](image)

The settlements of three typical cross sections of the island are monitored as shown in Fig. 1. Section 1, where the ditch is excavated to bury the tunnel structure, is at the east of the longitudinal island. Section 2, which is largest section of the island, is at the middle of the longitudinal island. Section 3, which has thickest soft clay layer, is at the west of the island. The settlements of the three sections were measured during the stage of soft ground improvement.

3 NUMERICAL SIMULATION PROCESS

3.1 Numerical model mesh

The settlements three sections shown in Fig. 1 are simulated by 3D finite difference method. The numerical model mesh is shown in Fig. 2. The thick of the model is 11 m, which is the radius of a steel cylinder, because it can be treated as a plain strain problem near each section and the symmetry. The other geometry sizes are according to the actual size. The soil layers are based on the drilling profile up to medium sand layer or gravel layer.

The Mohr-Coulomb soil model is adopted in the simulation. The steel cylinder and tunnel are considered as elastic materials. The units for backfill, installation and excavation in each steps have their own material properties. The contact surface model is used on the surface between steel cylinder and soil to simulate deformation compatibility between steel cylinder and ground.

The construction process is simulated according to the actual construction steps. The units are activated for the backfill parts in the numerical calculation process, and the units are temporarily removed for the excavation parts in the simulation step. The simulation steps are as follows: (a) foundation trench excavation; (b) set steel cylinder; (c) the foundation trench backfill; (d) set PVDs; (e) backfill up to the top of the island; (f) preloading by dewatering; (g) foundation pit excavation; (h) tunnel construction; (i) cover backfill.

The consolidation settlement process in the construction process is simulated by fluid-mechanical coupling method (Konder, 1963; Mesri, 1981), and a series of changes in the hydraulic boundary conditions are adopted to simulate preloading effect of dewatering on the settlement in the construction process.

3.2 Numerical model parameters

In this study, the numerical model parameters are according to laboratory test data of soil samples drilled in the field. The equivalent permeability method, equivalent analysis to the ground, is adopted to simulate the soft ground improved by PVD (Chai et al. 2001, 2005).

4 RESULTS AND DISCUSSIONS

4.1 Comparison result of measured and predicted settlements

Figures 3-5 show the comparison results of measured and predicted settlement curves in the stage of soft ground improvement (sand backfill and dewatering stage). It can be seen that the calculated
values by the numerical model are compared well with the measured values, and it indicates that the constitutive model and parameters adopted can accurately simulate the construction process in the field.

It should be noted that the calculated settlement curves are stepped and are different with the measured continuous curves in the process of preloading due to the complex of the sand backfill process in the field and the separate calculation of instantaneous deformation and consolidation deformation in the numerical simulation. After finishing the sand backfill, the calculated settlement curves are compared very well with the measured settlement curves in the process of dewatering.

Table 1. Soil properties

| Soil Layer       | γ (kN/m³) | Void ratio e | c (kPa) | φ (°) | Permeability k_v and k_h (10⁻⁷ cm/s) | Modulus of compressibility E₀.1-0.2 (MPa) |
|------------------|-----------|--------------|--------|------|-------------------------------------|------------------------------------------|
| ①_1 Muck        | 15.4      | 2.00         | 8.1    | 14.3 | 6.82 30.00                          | 1.73                                      |
| ①_2 Muck        | 15.7      | 1.79         | 11.6   | 14.8 | 7.11 13.40                          | 1.75                                      |
| ①_3 Mucky clay  | 16.8      | 1.38         | 10.9   | 14.8 | 3.24 8.68                           | 2.0                                       |
| ②_1 Silty clay  | 19.2      | 0.76         | 13.8   | 18.9 | - -                                 | 4.69                                      |
| ③_2 Silty clay  | 18.3      | 0.93         | 16.8   | 22.4 | 44.0 -                               | 4.91                                      |
| ④_1 Mucky clay  | 18.6      | 0.88         | 17.2   | 20.4 | 4.13 1.48                           | 4.52                                      |
| ⑤_1 Silty clay  | 18.1      | 1.01         | 20.0   | 17.8 | 0.58 0.73                           | 4.26                                      |

Table 2. Equivalent permeability in numerical simulation

| Soil layer       | Section 1 | Section 2 | Section 3 |
|------------------|-----------|-----------|-----------|
|                  | Thick (m) | Equivalent permeability (10⁻⁷ cm/s) | Thick (m) | Equivalent permeability (10⁻⁷ cm/s) | Thick (m) | Equivalent permeability (10⁻⁷ cm/s) |
| ①_2 Muck        | 8         | 63.4      | 1.8       | 16.5       | 0.7       | 85.2                                |
| ①_3 Mucky clay  | 7         | 31.2      | 10.3      | 52.5       | 11        | 59.5                                |
| ③_1 Silty clay  | 2         | 5.69      | -         | -          | 9.3       | 11.0                                |
| ③_2 Silty clay with sand | - | - | - | - | - | - |
| ③_4 Clay        | -         | -         | 7.9       | 3.0        | -         | -                                   |

Table 3. Final and residual settlement calculated by theory and predicted by numerical

| Settlement       | Section 1 | Section 2 | Section 3 |
|------------------|-----------|-----------|-----------|
| Final (m)        | Numerical prediction | 2.74 | 2.91 | 2.80 |
|                  | Theoretical calculation | 2.19 | 2.41 | 2.17 |
| Residual (m)     | Numerical prediction | 0.01 | 0.12 | 0.10 |
|                  | Theoretical calculation | 0.21 | 0.23 | 0.17 |
settlements (2400 days) of sections 1, 2 and 3 reach to 2.74 m, 2.91 m and 2.80 m, respectively.

It can be seen that predicted settlement values increase after finishing the preloading by dewatering because of the foundation fit excavation. Then the settlement values decrease again because of the tunnel construction and cover backfill. The settlement values do not decrease much after the cover backfill because the ground improvement in the early stage.

The residual settlements of sections 1, 2 and 3 after two years of finishing the tunnel construction (1550 days) are 1 cm, 12 cm and 10 cm, respectively. The residual settlement value in section 1 is obviously smaller than those in sections 2 and 3 because the tunnel has deepest burial in section 1.

The settlement values are calculated by one-dimensional consolidation theory. It is found that calculated values by one-dimensional consolidation
theory is obviously smaller that the filed measurement values in the preloading stage. It is because that the settlement induced by the lateral deformation of soft clay layer in the construction process is not considered in the one-dimensional consolidation theory. Also, the settlement will be rebounded in the process of unloading (foundation pit excavation), and this process cannot be analyzed through one-dimensional consolidation theory. The one-dimensional consolidation theory can only consider simple case and cannot be used in the project with complex construction process. The settlement rate and final settlement of artificial island calculated by the present method using one-dimensional consolidation theory are smaller than the measurement values in the field and the values predicted by numerical simulation. So the predicted settlement results by present method need to be modified according to field data, and numerical simulation method should be used to predict the long-term settlement of the artificial island.

CONCLUSIONS

Rapid construction of artificial island is needed for large bridge construction in the sea, and effectively predict and control the settlement of artificial island under which soft clay existed is the key of whole bridge project. Based on the filed measurement and numerical simulation results, the following conclusion can be drawn.

(1) The settlement curves predicted by numerical method are compared well with the measured results in the field up to 150 days. The numerical simulation results show that the long-term settlements (2400 days) of section 1, section 2 and section 3 reach to 2.74 m, 2.91 m and 2.80 m, respectively. The residual settlements after two years of finishing the tunnel construction (1550 days) are 1 cm, 12 cm and 10 cm, respectively.

(2) The settlement rate and final settlement of artificial island calculated by the present method using one-dimensional consolidation theory are smaller than the measurement values in the field and the values predicted by numerical simulation. So the predicted settlement results by present method need to be modified according to field data, and numerical simulation method should be used to predict the long-term settlement.

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