Numerical research on soft clay foundation long-term settlement

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ABSTRACT

The long-term settlement of soft clay foundation is a difficult problem with great practical meaning. This paper analyzed the long-term settlement of dredger fill foundation based on an engineering case. The development of settlement and pore pressure variation within the foundation reinforcing treatment period and 1.5 years after treatment is calculated with finite element software. The finite element analysis results are compared with the in-site test results, and the long-term settlement development feature is concluded.

Keywords: soft clay foundation; finite element analysis method; settlement in reinforcing treatment period; long-term settlement feature

1 INTRODUCTION

The long-term settlement feature involves with both the foundation layers' physical property and the foundation reinforcing treatment. The distribution of foundation layers, features of each soil layer, and the foundation reinforcing treatment are modelled in numerical simulation model. The development of settlement is calculated, and the finite element analysis (FEA) model is calibrated with the in-site test results. The long-term feature is concluded based on the dissipation of the pore pressure.

Because of its importance to land reclamation treatment technique, the long-term settlement of the soft clay foundation in harbor engineering draws scholars' attentions. The settlement of a railway's subgrade constructed on soft foundation during decade years are tested and analyzed (Zhao 2000), and proposed prediction method which considerate the influence of filling's extensional fracture. The two dimensional formulas of viscous elastic BIOT's consolidation FEM based on MERCHANT's model are established (Tan 2001) and proposed the inversion correcting iteration method. The settlement of soft clay foundation is claimed that contains 4 phases "occurrence, development, stability, and limit", and the settlement curve appears "S" type (Zhao 2004). They also proposed a variable weight combination forecasting prediction method. The constitutive relation of the filling body with generalized Kelvin model is described and used three-dimensional finite element orthogonal numerical simulation and the combination of regression analysis and optimization analysis to inversion calculate the parameters (Lu 2005). The settlement prediction value of high filling embankment is in accord with monitoring results of actual project. The settlements of 60 sections located at the highway between Lianyugang and Xuzhou are analyzed and proposed hyperbolic prediction method for calculating final settlement (Zhang and Liu 2006). The settlement of foundation in a heap of the ore-port is calculated and used back analysis method to determine the soil compression modulus and coefficient of consolidation (Zhou 2009). Based on these analyses, they predicted the subsequent settlement and determine the next loading time and loading quantity. Based on the in-site monitoring data of seawall post-construction settlement, the consolidation coefficient with layer-wise summation method and the Terzaghi's one-dimensional consolidation theory are inverted (Qin 2012). And they proposed an improved fractal dimension prediction model to calculate the consolidation coefficient. The influence factors on the seawall post-construction settlement with fishbone diagram model instead of hierarchical model are analyzed and evaluated (Li 2013). They claimed that the main factors are "foundation treatment" and "soil layers' properties of foundation", the less important factors are "seawall's properties" and "construction" and the common factors are "settlement monitoring" and "external factors".

2 PROJECT PROFILE

The project is road engineering in some area of Tianjin Port. The design road is 282 m long and 40 m wide, and the foundation treatment area is about 24161

m^2. Vacuum combined with surcharge preloading is used in foundation treatment practice. The vacuum load is 85 kPa, lasting for 110 days. The draining boards are set into square shape with 0.8 m intervals and 15 m deep. Table 1 shows the soil properties of each layer.

Table 1 Parameter of soil properties

Layers	Thickness (m)	Saturated unit weight (kN/m^3)	Shearing strength	
			Cohesion c (kPa)	Internal friction angle $\varphi^{'}$ (°)
Dredged mud	6.1	17.5	11.91	9.38
Muddy-silty clay	2.2	17.8	12.81	9.67
Mud	2.7	16.8	12.75	9.57
Muddy clay	7.8	17.7	12.98	11.18
Silty clay	6.2	19.4	19	4.11
Silt fine sand	35	19.9	19	4.11

The in-site monitoring test on long-term settlement can be divided into two phases: Phase I is foundation reinforcement treating phase; Phase II is post-construction and road service phase. The surface settlement, layer settlements and pore water pressure monitoring devices are set in Phase I to obtain key index in foundation treatment quality assessment. Phase II mainly test the surface settlement and carried out some laboratory tests on soil samples withdrawing from reinforcement treating regions. Figure 1 shows the locations of each monitoring device.

Fig. 1 Location of monitoring points

3 FEA MODEL

The finite element analysis (FEA) is proposed with the FLAC 3D software. The soil layers and the foundation reinforcing process are model based on the engineering case. For calibrating the key parameters in the FEA model (in Table 2), the simulation settlement is compared with the in-site test result. The soil is simulated by Mohr-Coulomb Model and the corresponding soil parameters are shown in Table 2.

Table 2 Parameter of soil in the Model

Layers	Module (MPa)	Poisson's ratio	Permeability coefficient	
			Vertical (cm/s)	Lateral (cm/s)
Dredged mud	0.57	0.2	2.15E-07	2.95E-07
Muddy-silty clay	6.45	0.24	6.67E-07	4.56E-07
Mud	1.14	0.2	2.85E-07	4.37E-07
Muddy clay	3.52	0.28	1.64E-07	3.38E-07
Silty clay	8.86	0.34	2.7E-08	3.27E-08
Silt fine sand	0.57	0.2	2.15E-07	2.95E-07

Figure 2 shows the settlement of the whole foundation in foundation reinforcing treatment. Figure 3 shows the surface settlement curve in foundation reinforcing treatment.

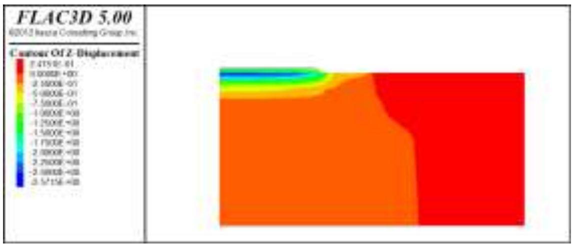

Fig. 2 Foundation settlement distribution in reinforcing treatment process

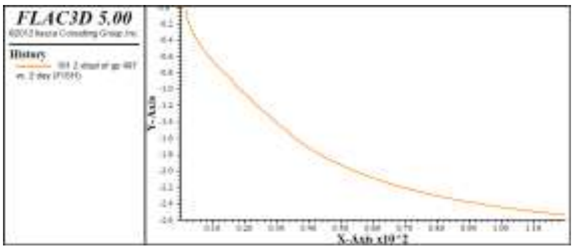

Fig. 3 Foundation surface settlement curve in reinforcing treatment process

As Figure 2 shows, the foundation is consolidated in the reinforcing treatment process, and the settlement distributes widely and heavily in the whole foundation. The total settlement in foundation reinforcing treatment is 2.572 m. The settlement concentrates under the hydraulically-filled mud layer. Figure 3 illustrate that the soil almost finish consolidation in the later stage of reinforcing treatment process.

Figure 4 shows the comparison between FEA calculation results and the in-site settlement data.

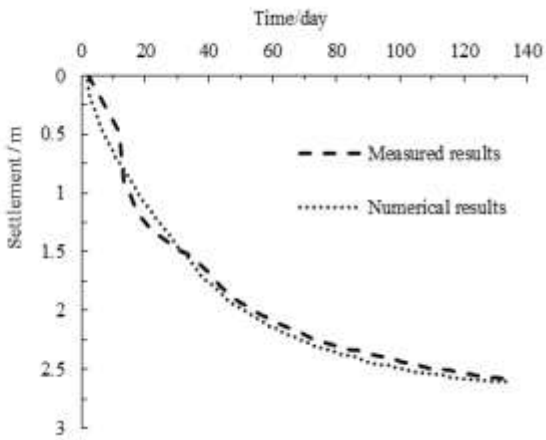

Fig. 4 Comparison between the FEA results and the in-site settlement

As Figure 4 illustrated, the FEA results have some different comparing with in-site settlement. This is due to the in-site monitor data missing in plastic drains setting phase. The FEA results almost equal to the in-site monitor data in the later phase. The key parameters of FEA model is suitable for simulating this case and can modeling foundation deformation well.

4 RESULTS AND ANALYSIS

The calibrated FEA model is used to calculate the long-term settlement in different period.

Figure 5 shows the pore pressure distribution in the foundation reinforcing treatment period.

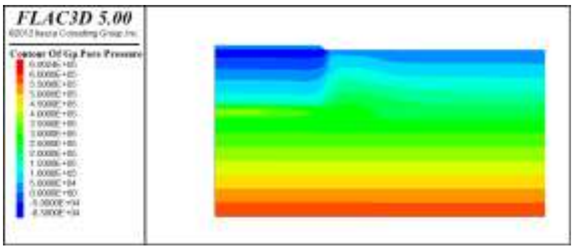

Fig. 5 Pore pressure distribution when foundation reinforcing treatment finished

Figure 5 shows that the pore pressure is significant lower than the hydrostatic pressure due to the vacuum loading in the foundation reinforcing treatment. The surface pressure is -85 kPa, and the pressure increases with the increasing depth within the plastic drains setting area. There are much positive pore pressure below the plastic drains setting area. This phenomenon shows that the soil layer below the plastic drains setting area is under-consolidated.

Figure 6 shows the dissipation of pore pressure of soil layer under the plastic drains setting area (-23 m below the ground surface).

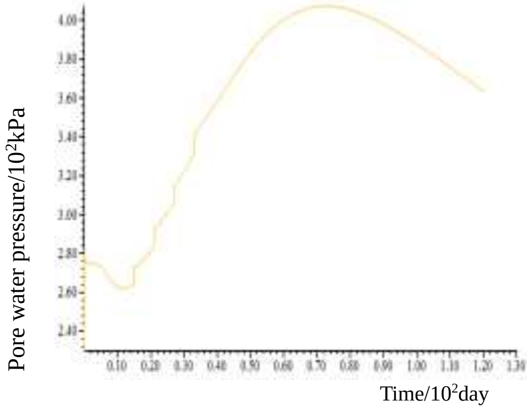

Fig. 6 Dissipation of pore pressure in soil layer below plastic drains setting area

As shown in Figure 6, the dissipation of pore pressure in soil layer below plastic drains setting area is slow. The soil layer below plastic drains setting area has no fast drainage channels, and the pore pressure cannot dissipate quickly. This soil layer is effected little by negative pressure load, therefore the pore pressure increases linearly with the increasing depth. The pore pressure reaches the peak value 70 days after applying negative pressure load then decreases to 362 kPa. The excess pore pressure is 132 kPa, and the soil layer is in unconsolidated state. The excess pore pressure distributes in the low permeability silty clay layer (as shown in Figure 7). Therefore, the settlement after foundation reinforcing treatment mainly is caused by consolidation of this layer.

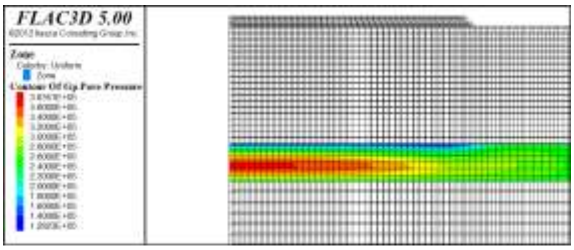

Fig. 7 The excess pore pressure distribution when reinforcing treatment finished

Figure 8 shows the comparison results between FEA calculation result and the in-site testing settlement curve.

Figure 8 shows that the FEA result is different with the in-site test value in some degrees. The different between values calculated by two methods in early stage of post-treatment is caused by the unable to loading simulation exactly. The finite element method cannot consider the soil creep and therefore the in-site testing settlement is larger than the FEA result.

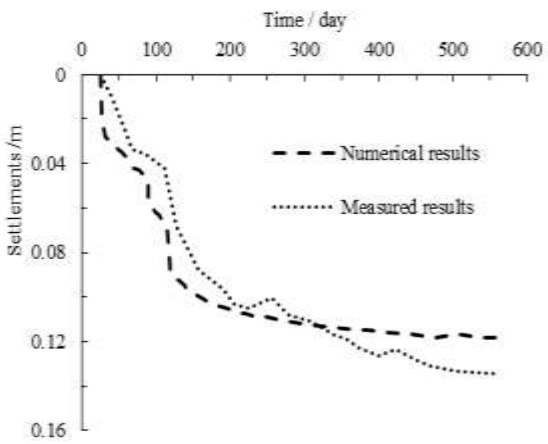

Fig. 8 Comparison between FEA result and the in-site test settlement

In order to analyze the causing of settlement in post-treatment period, the pore pressure dissipation for soil in different depths within the plastic drains setting area is gathered. And Figure 9 shows these pore pressure dissipation curves.

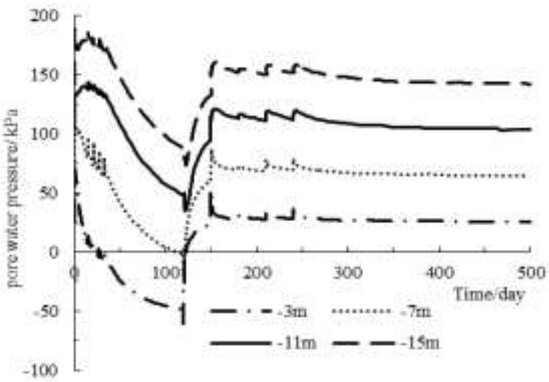

Fig. 9 The pore pressure dissipation curves for different depth soil

Figure 9 shows that the pore pressure is almost equal to the hydrostatic pressure after the negative pressure load is just unloaded. Then the pore pressure increases with the increment in construction and road loading. While the excess pore pressure dissipate quickly because of the fast drainage channels provided by the plastic drains. The plastic drains setting area still consolidates quickly in post-treatment period.

Figure 10 shows the pore pressure dissipation for soil layer under plastic drains setting area.

As shown in Figure 10, the excess pore pressure is still large when foundation reinforcing treatment finished, and the soil under plastic drains is unconsolidated at the starting phase of post-treatment period. The construction and vehicle loads causes the pore pressure rising again. The pore pressure dissipation slowly, and it will takes almost 1 year for the excess pore pressure dissipated completely.

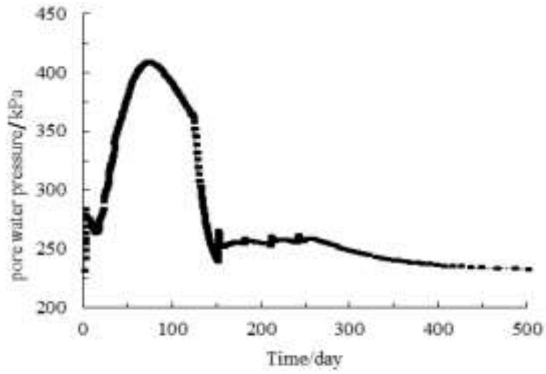

Fig. 10 Pore pressure dissipation curves for soil under plastic drains

5 CONCLUSION

This paper analyzed the settlement of an engineering case in Tianjin Port. The finite element method and in-site test are both proposed to calculate the settlement development. The main conclusions are as followed.

(1) The finite element simulation model established in this paper is calibrated with the in-site data, and the model can be used to predict the long-term settlement.

(2) The plastic drains can improve the foundation reinforcing treatment effect.

(3) The main long-term settlement comes from the consolidation of soil under plastic drains.

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