Element analysys of consolidation of soil under surcharge and vacuum preloading

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Abstract. As an under-consolidated soil, the reclaimed soil consolidation with vacuum preloading is very complex, so are the boundary and initial conditions. Through the analysis of the formation of the reclaimed soil foundation and its consolidation process, the initial pore pressure and the delivery of negative vacuum pressure in the PVDs herein were studied. The negative vacuum pressure was applied in the sand layer and the PVDs elements. The nonlinearity constitutive relation (Duncan-Chang's model) was employed into the Biot's consolidation theory, and a plain strain FEM program was coded considering different load conditions, initial conditions and boundary conditions. The behavior of the soft clay consolidation was also analyzed with the program. The surcharge was put into effect in the program. As a result, the program can be used to analyze the reclaimed soil consolidation with pure vacuum preloading method and also vacuum combined with surcharge preloading method. Comparing the calculating results with the observed data, it is confirmed that the developing trend of settlement and pore pressure agree very well with the field result.

Introduction

With advantage of good consolidation effects and economical efficiency, vacuum preloading method for reinforcing the soft soil foundation is popularly used in the express highway, port and land reclamation engineering. As an effective strengthening method especially for the reclaimed soil foundation, its design theory was improved continuously. However, it is confirmed in the practice that there is a significant difference between the calculation results and the field measurement. Therefore the calculation method needs to be perfected further.

The reclaimed soil foundation is newly formed with high water content, there is excessive pore pressure in the native foundation and reclaimed soil layer.The PVDs increase the vertical drainage channels and shorten the drainage path significantly when it is installed in the foundation. Therefore the excessive pore water pressure dissipates quickly and soil layer settles a lot during PVDs installation. The settlement is called PVDs installation duration settlement (General the installation time is 15-20days). According to the observed data, the PVDs installation duration settlement can reach 1/3-1/2 of the total settlement. After the vacuum loading applied, the soil consolidated continually. So the settlement of the reclaimed soil foundation includes PVDs installation duration settlement and the preloading settlement.

Yan[2004] used elasticity constitutive equations and applied negative vacuum pressure on the soil surface to calculate the consolidation basing on the biot's consolidation theory. Yu[2002] used viscoelasticity constitutive equations to calculate the consolidation process of soil layer improved by vacuum preloading by using finite element method, the negative pressure is applied in the sand bedding course and other nodes applied with zero pressure. Wei[2005] introduced the nonlinear constitutive equations to the Biot'S consolidation theory and applied surcharge load on the

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foundation. Lei[2007] used linear constitutive equations and applied the vacuum preloading through setting the pore pressure on the boundary element.

There are still some limitations in the former analysis of vacuum preloading. The distribution of vacuum pressure along the PVDs was summed up herein, negative vacuum pressure was applied on the PVDs elements.The effective self-weight of the reclaimed soil was applied on the foundation nodes in this paper. On the base of biot's consolidation theory, a finite element program was compiled using Duncan-Chang's constitutive model and field projects were analyzed. The analysis result was compared with the field data.

Finite element models

Plain strain biot's consolidation formula

According to the vacuum preloading mechanics and Biot's consolidation theory, the finite element general equation can be expressed as:

$$\begin{bmatrix} \bar{k} & k' \\ k'^T & \tilde{k} \end{bmatrix} \begin{Bmatrix} \Delta\delta \\ \beta \end{Bmatrix} = \begin{Bmatrix} \Delta R \\ 0 \end{Bmatrix} . \tag{1}$$

Where:

$$\Delta R = R - R_t . \tag{2}$$

$\bar{k}$ k' k'^T $\tilde{k}$ —stiffness coefficient matrix; $\Delta\delta$, β ——settlement increment and exceeded pore pressure; R ——external load; R_t ——the load that balance the displacement generated before $t-\Delta t$.

Constitutive model

The Duncan-chang's model was employed to model the stress strain relationship of soil layer, E_t defined as the follow formula:

$$E_t = \left[1 - \frac{R_f(1-\sin\varphi)(\sigma_1-\sigma_3)}{2c\cos\varphi + 2\sigma_3\sin\varphi}\right]^2 K_i p_a (\frac{\sigma_3}{p_a})^n . \tag{3}$$

Where: σ_1 —max primary stress; $\sigma3$ —min primary stress; c —cohesive strength; φ —internal friction angle; R_f —failure ratio; K_i —loading module; n —loading module exponential; p_a — barometric pressure.

Loads

The reclaimed soil foundation is under-consolidated. In this paper the excessive pore pressure was equated to load applied on the soil layer. Assuming the value of excessive pore pressure is $\{\beta_0\}$. The load $\{R_0\}$ need to be calculated.($\{R_0\}$was calculated by the self-weight of reclaimed soil and the filled layer, show as fig.1). The whole analysis of reclaimed soil foundation with vacuum preloading method can be equivalent to the surcharged preloading combined with vacuum preloading.

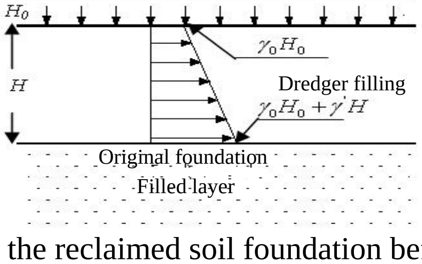


Fig.1. The surcharge of the reclaimed soil foundation before the PDVs installing

The distribution of the vacuum load along PVDs

Because of the well block, the vacuum load will be reduced along the PVDs. Zhao Chang-Zhou did an experiment to study the distribution law, the result shows as fig.2.

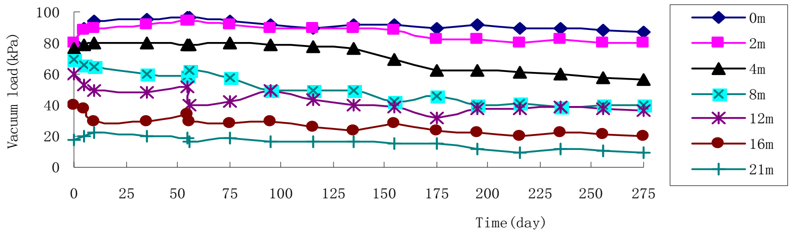


Fig.2. The delivery of the vacuum degree in the PVDs

In the base of the vacuum load analysis on the project of Tianjin port, the distribution of negative pressure in PVDs is presented and shows as fig.3.

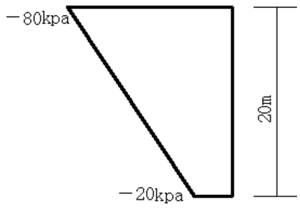


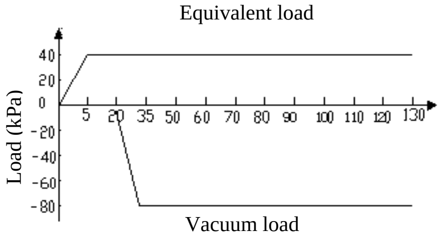
Fig.3. The negative pressure distribution along the PDVs of Tianjin port vacuum preloading

Case 1

This project was a general bulk cargo berths yard located at southern border of Tianjin Port. The improving region is 94m×311m rectangular. The PVDs were installed in1m×1m square pattern and 20m in depth. According to the field measurements and laboratorial experiment, the parameters of the soil and Duncan-chang's Model are known.

Modeling. Because the cross section of this area is symmetric, half region is selected with width equals to 47m and length equals to 30m. The width of effected region was 106m from the edge of the improving zone to study the influencing area. Because the depth of four soil layers under the ground was 17m and the depth of PVDs was 20m, the fifth layer was divided into two parts to input the initial data easily. PVDs were installed at 1m spacing in a square pattern and the equivalent drain diameter was 60mm. The smear diameter was 100mm.

The FEM analysis of reclaimed soil foundation include two phase: the first phase is PVDs installment in first 20 days, in this course, the self-weight of reclaimed soil and filling layers are applied on the foundation nodes (the load is showed as fig.1), and the soil consolidated under this load. The second phase is the vacuum preloading, in this course, the soil consolidated under the self-weight and vacuum load. The loading applying process is showed as fig.6.



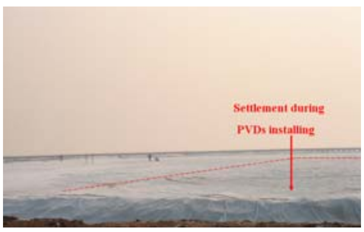


Fig.6. Load applying process   Fig.7. Settlement during the PVDs installing

Settlement Calculation. Fig.8 shows the comparison between the FEM result of surface and the field data at the centre of improving region. The settlement includes two parts, one part is the settlement during the PVDs installation(fig.7) and the other part is the settlement during the vacuum preloading. Compared with the field measurement data, the result analyzed using Duncan-Chang's model is better than using the linearity constitutive relation. It can be seen from Fig.8 that calculated results which used the Duncan-Chang's model agree well with the field test.

Pore water pressure calculation. According the FEM results, the pore pressure-time relationship in the depth of -8m, -17m are shown in Fig.9-Fig.10.

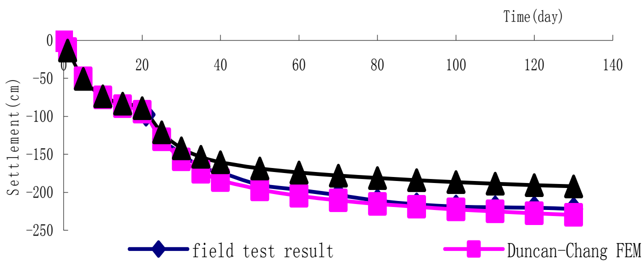
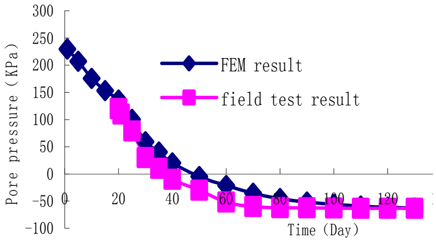


Fig.8. Settlement-time relation curve



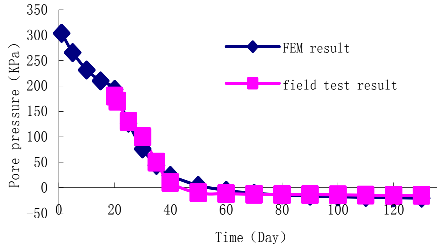


Fig.9. Pore pressure-time relation in the -8m   Fig.10. Pore pressure-time relation in the -17m

2.6 Case 2

The project located at Tianjin Port. The improving region was a 30m×80m rectangular. The PVDs were installed in1m×1m square pattern and 20m in depth. A surcharge of 40kPa was applied in 2 stages. According to the indoor triaxial test, the parameters of soil and Duncan-chang's model are known.

Load Applying. There are 3 steps in the process of load applying. Firstly, the vacuum pressure is applied; secondly, after 50 days, a surcharge load of 15kPa is applied; and thirdly, another surcharge load of 25kPa was applied after 130 days, so the total value raised to 40kPa in the final stage. The process of applying load is showed in Fig.11.

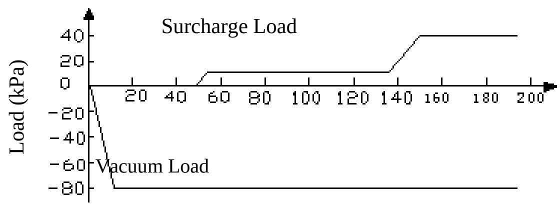


Fig.11. Load applying of the surcharge preloading combined with vacuum preloading

Results of Calculation. According to the results of FEM calculation, which had calculated the settlement in depth of 0m, 3.8m, 7.0m, 10.5m, 14.5m, the comparison of calculated settlement-time relation curve with field data in the middle point of the improving region is shown as Fig.12. The calculated results agree well with the observed data, which proves that the method proposed by this paper is feasible.

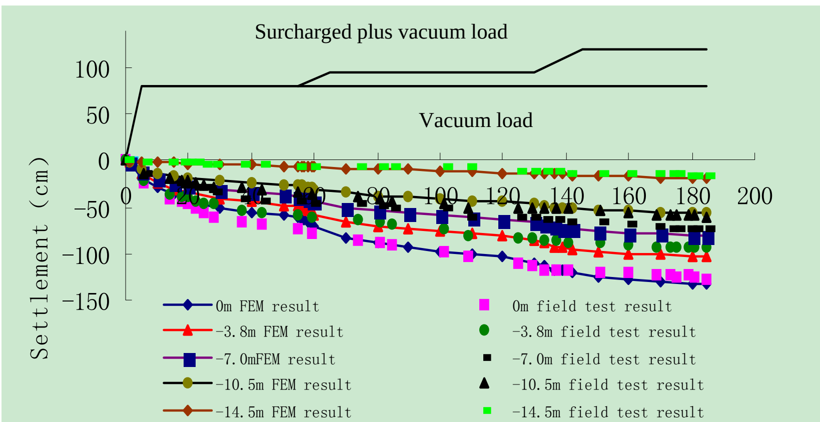


Fig.12. Settlement-time relation of the surcharge preloading combined with vacuum preloading

Conclusions

Through the analyzing of the reclaimed soil foundation and the load conditions during the foundation enforcement, a FE program was developed to simulate the whole consolidation process. Some conclusions can be made as following:

1) Comparing the FEM analysis results using linear elastic model and Duncan-Chang model with the measured data, it can be known that Duncan-Chang nonlinearity constitutive calculation results fix better.

2) The vacuum pressure is negative in the sand bedding and PVDs elements and varies linearly along the drains, which is appropriate for the practice.

3) If the soil is under-consolidated, based on the analysis method of surcharge preloading combined with vacuum preloading, add the equivalent surcharge load to soil nodes in FEM model instead the excessive pore pressure. The load value varied linearly along the depth. The calculation and the consolidation process matched well.

4) Comparing the calculation results with the measured data for the project No.2, it can be informed that the program can be used to solve the problems of surcharge combined with vacuum preloading by giving a external load vector $\{R\}$.

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