Finite element analysis of soft ground improvement by vacuum preloading combined with surcharge preloading

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ABSTRACT

Based on the soil-water coupled finite element analysis incorporated the modified macro-element method, the improvement of soft ground by the vacuum and surcharge preloading method is investigated systematically. SYS Cam-clay model is employed for the constitutive model of soft soils and the soil parameters are determined by the curve fitting of the one-dimensional compression result. The results show that: 1) the settlement at the ground surface is as large as 3.5m which is very close to the design value; 2) the long-term settlement is also predicted and the degree of consolidation at 180d is over 98%; 3) Negative and positive horizontal displacement appears due to the vacuum preloading and surcharge preloading respectively and it is necessary to control the rate of surcharge to avoid the instability of the ground; 4) There is significant oscillation in the pore pressure inside the ground due to the construction of embankment and the following consolidation under vacuum pressure.

Keywords: finite element analysis, vacuum preloading, surcharge preloading, soft soil

1 INTRODUCTION

In China, there is about over 1.0×10^8 m^2 reclaimed ground and in most of these areas the vacuum consolidation with plastic vertical drain (noted as PVD in the following) is employed due to its easier equipment and shorter consolidation time. Binhai New Area, which is located in the west of Tianjin City, possesses extensive reclaimed grounds that are made of soft dredged soils from Bohai Sea. The typical characteristics of soft soil is of very high water content (120%–130%), low bearing capacity (1~5 kPa) and small permeability (<10^-7 cm/s), which is impossible to use surcharge preloading for consolidation. In order to understand the physical and mechanical properties of the soft soil, plenty of scholars have devoted their efforts to analyze the ground improvement by vacuum consolidation. Ye and Zhang (2004) pointed out that the after-improvement strength of soft soil is not necessary to be very high because there is no plan to build large-scale projects in the site and two field-experiments were carried out to investigate the optimum drain space ratio for soft soils. Ying and Chen (2011) proposed a two-stage vacuum consolidation method for the soft ground treatment, namely first very short PVD is used for the surface layer of the soft ground and after there is certain bearing capacity in the surface layer then put longer PVD for the consolidation of deeper layers. Dong, Chen and Mo (2010) analyzed the variation of the permeability coefficient with the void ratio and presented a single-well calculation with Abaqus. Qiu, Yan, Sun and Ji (2013) believed that the permeability coefficient of soft soil is changeable accompanying the progress of ground consolidation and put emphasis upon the influence of variable effective stresses on the permeability. However, there are not systematic numerical analyses on the consolidation of soft soils due to the limitation of constitutive models or numerical methods. In this paper, the reinforcement of the soft ground by vacuum and surcharge preloading is investigated in detail by a soil-water coupled finite element analysis (Asaoka et al., 2007) incorporating the modified macro-element method (Yamada et al., 2013). In chapter 1, the analysis background is briefly introduced and previous researches about the vacuum consolidation of the soft soil are also reviewed; The calculation conditions such as mesh partitions, soil parameters are presented in chapter 2; In chapter 3, the calculation results including the settlement, horizontal displacement, pore water pressure etc. are given in detail; The conclusions are presented in chapter 4.
2 ANALYSIS CONDITIONS

2.1 Engineering background and mesh partition
The soft ground is reinforced for a road subgrade by vacuum and surcharge preloading. However, another road that is perpendicular to this road has already been treated by the vacuum preloading. In order to evaluate the influence of consolidation of the new road on the treated road, it is necessary to carry out a detailed analysis. According to the practical engineering, the width and depth of the soft ground is taken as 222m and 40m considering the plane strain condition and the symmetry, in which the width and depth of the reinforced area improved by the PVD are 68m and 25 respectively, as shown in Fig.1. According to the field survey, the soil in the ground along the depth can be divided into two categories, silt and silty clay. Based on the curve fitting result of one-dimensional compression test as shown in Fig. 2, the determined soil parameters and initial values are presented in Table. 1. As can be seen, there is a sudden compression around 70kPa in the experimental results, which can be precisely reproduced by the constitutive model by assigning appropriate degree of structure and overconsolidation.

For the hydraulic boundaries of the ground, the undrained condition is employed at the right side and the bottom. At the top surface, it is the atmosphere boundary and considering the symmetry of the mesh, the undrained boundary is used at the left side. As for the boundary of the improved area by the PVD, at the bottom undrained condition is used and at the top vacuum boundary, namely about -80kPa is applied at the top of the PVD. At the right side of the improved area, the undrained condition is applied from the top surface until 1.5m underground to act as the clay sealing wall.

For the displacement boundary, all the nodes at the bottom are fixed in both horizontal and vertical directions and the nodes at the top are free in both directions. At the two side surfaces, only the horizontal direction is fixed.

2.2 Soil parameters
SYS Cam-clay model (Asaoka et al. 1998, 2000, 2002), which is able to describe the different disturbance of clay by introducing the concept of structure, overconsolidation and anisotropy based on the Cam-clay model, is employed to describe the mechanical response of the soft soil. There are two groups of parameters for SYS Cam-clay model: one is called elasto-plastic parameters that are exactly same as that in Cam-clay model; the other one is evolutional parameters which control the degradation of structure and the loss of overconsolidation.

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Fig. 2. Curve fitting of experimental and calculation results of silt soil by constitutive model test.
Table 1. Soil parameters and initial values of soft soil.

|                      | silt | silty | clay | sand |
|----------------------|------|-------|------|------|
| Elasto-plastic parameters |      |       |      |      |
| Compression index $\lambda$ | 0.291 | 0.190 | 0.05 |      |
| Swelling index $k$ | 0.036 | 0.0179 | 0.012 |      |
| Critical state constant $M$ | 1.02 | 1.12 | 1.0 |      |
| Intercept of NCL $N$ | 2.445 | 1.93 | 1.98 |      |
| Poisson’s ratio $\nu$ | 0.3 | 0.3 | 0.3 |      |
| Evolutional parameters |      |       |      |      |
| Degradation index of structure $\gamma$ | 0.2 | 1.2 | 0.22 |      |
| Degradation index of OC $m$ | 0.6 | 3.2 | 0.06 |      |
| Initial values |      |       |      |      |
| Specific volume $v_0$ | 3.099 | 2.385 | 1.62 |      |
| Stress ratio $\eta_0$ | 0.375 | 0.375 | 0.545 |      |
| Degree of structure $1/R_0$ | 18.5 | 12.2 | 79.0 |      |
| Degree of OCR $1/R_0$ | 5.0 | 4.0 | 1.2 |      |
| Degree of anisotropy $\varphi_0$ | 0.0 | 0.0 | 0.0 |      |
| Soil density $\rho_s$ (g/cm$^3$) | 2.63 | 2.60 | 2.41 |      |
| Permeability $k$ (cm/s) | $2 \times 10^{-7}$ | $2 \times 10^{-7}$ | $1 \times 10^{-4}$ |      |

*) Specific volume on NCL of fully remolded soil when $p' = 98.1$ kPa, $q = 0$

3.1 Settlement

Fig. 4 shows the settlement at the ground surface and at the middle of PVD respectively. As can be seen, the numerical settlement at the ground surface is as large as 3.5m, which is very close to the design settlement. The settlement at the middle of PVD is around 1.2m, which means there is around 2.3m settlement within the depth of -12.5m to 0. It can also be known that even there is an embankment with the height of 4m, the final ground level would only increase about 0.5m due to the significant settlement.

Fig. 4. Numerical settlements at the ground surface and the middle of PVD.

Fig. 5. Prediction of long-term settlement at the ground surface.

Fig. 6. Settlement and uplift of the ground surface at different distances from the improved area.
In order to estimate the degree of consolidation at 180d, the consolidation calculation is kept until 300d and the final settlement is shown in Fig. 5. Therefore, the degree of consolidation is around 98.6%, which means that it is enough for the improved period about 180d.

In order to see the influence of vacuum preloading and surcharge preloading on the ground surface near the improved area, the deformation of ground surface at different distances of the border of the improved area is shown in Fig. 6. At the border of the improve area, the settlement of the ground surface is around 1.2m and 0.6m can be seen at the distance of 3m. For the ground deformation at the distance of 12m, it can be seen that the settlement becomes smaller after 26d at which the surcharge loading begins to be added, which means that there is certain uplift of ground surface due to the embankment load.

3.2 Horizontal displacement

![Graph showing horizontal displacement](image)

**Fig. 7.** Horizontal displacement along the depth at the border of improved area at different stages.

The horizontal displacement along the depth at the border of improved area at different stages is shown in Fig. 7, which the negative value represents the inner displacement to the symmetric center. As can be seen, when there is only vacuum preloading until 26d, the horizontal displacement is negative from the ground surface to the bottom and gradually decreases to the bottom. The maximum horizontal displacement occurs at the ground surface and is about 946mm. It can also be seen that even though the depth of the PVD is 25m, there is still certain inner displacement below the depth of 25m. After the first embankment load is applied at 36d, there is a significant decrease of the horizontal displacement, about 116mm, which means the horizontal displacement towards the outer occurs due to the surcharge load. The red broken line beside the curve at 36d represents the horizontal displacement after 5d consolidation of the first embankment load. As can be seen, there is another slight inner displacement due to the dissipation of excess pore pressure that is caused by the embankment load under the vacuum consolidation. By that analogy, significant outer horizontal displacement occurs due to the construction of embankment and immediately after slight inner horizontal displacement appears due to the consolidation of the soft ground and finally the horizontal displacement keeps 525mm.

It should also be noticed that from the second surcharge load at 51d, the positive horizontal displacement begins to occur between the depth of 25 and 35m. The range of such kind of positive displacement gradually increases towards the ground surface until the depth of 14m at 180d and there is also an obvious increase in the magnitude until 76mm, which represents that the ground at the deeper layer gradually deforms towards the outside of the improved area due to the surcharge load. Therefore, there is a risk for the ground due to the fast surcharge and it is necessary to control the surcharge rate in the real construction.

3.3 Pore pressure

![Graph showing pore pressure variation](image)

**Fig. 8.** Variation of pore pressure in the ground at different depths.

Fig. 8 demonstrates the variation of pore pressure in the ground at depths 0.5, 4.5, 6.5 and 8.5m. As can be seen, the similar tendency can be observed in the variation of pore pressure at different depths. The pore pressure firstly decreases until 26d due to the application of vacuum pressure and there are four fluctuations in the pore pressure due to the add of embankment and the following consolidation under the vacuum pressure. Finally, the pore pressure at each depth keeps stable until the end of the combining preloading. It can also be known that the dissipation
values of the pore pressure are 46.9, 57, 37 and 64 kPa from the ground surface downward.

4 CONCLUSIONS

A soil-water coupled finite element analysis incorporated the modified macro-element method is carried out systematically to investigate ground improvement of soft ground by the vacuum preloading combined with surcharge preloading. The conclusions are as follows:

(1) The settlement at the ground surface is as large as 3.5 m which is very close to the value evaluated by the design. Also about 66% settlement at the ground surface comes from the range of the upper half part of the PVD. In order to evaluate the consolidation degree, the long-term settlement is also predicted and it can be seen that the consolidation degree is over 98%. The influence of combining preloading on the ground surface deformation can be found as far as 12 m from the border of the improved area.

(2) Negative horizontal displacement along the depth can be seen at the border of the improved area due to the vacuum preloading and positive horizontal displacement gradually increases due to the construction of embankment. Also it should be noticed that there is a risk of losing stability of the ground at the deep layer if the surcharge rate is too fast.

(3) The pore pressure in the ground is also influenced by the vacuum preloading and surcharge preloading. There are significant oscillations in the variation of pore pressure due to the construction of embankment and consolidation.

(4) As a prospective evaluation of the construction, although there is no measured datum to verify the accuracy of the calculation results, the tendency of the ground deformation and pore pressure variation can be reproduced faithfully, which can provide useful information for the future construction.

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