# Numerical simulation of combined vacuum loading soft foundation treatment considering time effect and well resistance effect

Xionghui Zhang*, Jianfeng Peng, Xiaofu Huang, Guanghui Lin, Fagui Liu

Guangzhou Salvation Bureau, Guangzhou, 510260, China

*E-mail: 154997320@qq.com

**Abstract.** Since the existing numerical simulation calculation methods of vacuum stacking combined with precompression soft base treatment are mostly applied according to the vacuum degree unchanged or linearly decreasing along the depth, in fact, with the passage of time, due to the cracking of the surrounding soil, the vacuum degree will also show an overall downward trend over time. In this paper, the MIDAS GTS finite element software is used to consider the influence of well resistance effect and time effect on vacuum, and the numerical simulation and comparison study of vacuum combined with stacked soft base treatment are carried out, and the results show that the loss of vacuum degree due to depth and time will have a certain impact on the final soft base treatment effect.

**Keywords:** Soft base reinforcement; vacuum-stacking combined preloading; Numerical simulation.

## 1 Introduction

The vacuum-stack combined preloading method combines the advantages of vacuum preloading to strengthen the soft foundation on the basis of the stacking preload. Professor Jellman[1] first proposed the concept of vacuum preloading in 1952 .Its working mechanism[2] is as follows: a certain vacuum degree is applied in the soil, so that the pore water is gradually discharged from the drainage board under the action of vacuum negative pressure, and the pore water pressure gradually dissipates and is converted into effective stress, so that the soil is consolidated; The vacuum combined stacking preloading method combines the vacuum load with the reactor load, which has a good reinforcement effect, which greatly shortens the construction period and is suitable for large-area soft foundation reinforcement treatment projects.

However, many problems will also be encountered when using the vacuum-stacking combined preloading method to reinforce the soft foundation, such as the vacuum degree in the soil will gradually decrease with the increase of the depth of the drainage plate due to the well resistance effect [3], and the vacuum degree will also be lost with the cracking of the soil with the reinforcement process[4]. The finite element numerical


A. M. Zende et al. (eds.), *Proceedings of the 2024 3rd International Conference on Structural Seismic Resistance, Monitoring and Detection (SSRMD 2024)*, Atlantis Highlights in Engineering 27,
https://doi.org/10.2991/978-94-6463-404-4_19

calculation method can be applied to the study of foundation consolidation treatment because it can take into account the characteristics of soil. Based on the three-dimensional Biot consolidation theory, Chen Xi [5] used the equivalence principle of the drainage plate to equivalence the drainage plate to a sand well, and then simplified the sand well foundation to a sand wall foundation for simulation calculation. Peng Jie, Liu Hanlong, Chen Yonghui et al. [6] (2002) used the finite element analysis method to combine the numerical simulation with the soft foundation engineering practice of vacuum stacking combined preloading method in the Louxiachen section of the Hangjinya Expressway in Zhejiang Province to simulate the measured reinforcement effect and the surrounding environmental impact. Liu Yong[7] established a mathematical model of variable well resistance, simplified the smearing area, and considered the three-dimensional finite element analysis of vacuum preloading under variable well resistance and smearing effect. Chen Huan[8] explained the internal seepage of soil under vacuum state through theoretical analysis. At the same time, she established two consolidation models to reveal the reasons for negative pressure formation and reinforcement mechanism. She discussed the one-dimensional and two-dimensional stress states of soil under negative pressure and extended them to three-dimensional and axisymmetric problems. She also obtained effective stress variation laws by changing boundary conditions.[9]

In this paper, combined with the practical engineering, according to the Biot consolidation theory, it is simplified into a two-dimensional plane strain problem, and the vacuum combined stack preloading model is established by MIDAS finite element, and the influence of the change of vacuum degree under the influence of well resistance effect and time effect on soil settlement and horizontal displacement is studied. It provides strong theoretical guidance for the development of practical projects.

## 2 Project Overview

Shenzhen Marine Emerging Industry Base is located in the Dakong Peninsula District, covering an area of about 7.44 square kilometers. The total area of land formation in Lot 3B is about 1,121,800 $m^2$, considering the formation of zonal land area, the filler is backfilled with urban spoil, and the foundation treatment area is about 1,067,400 $m^2$. As shown in Figure 1, the land formation mainly adopts the spoil backfill method, and the foundation treatment adopts the in-line vacuum combined stacking preloading scheme. This section is divided into four fills, T1-T4, and the T3 fills are taken to carry out finite element simulation calculation. According to the preliminary survey results of the nearby site, the stratigraphic distribution of the site is: silt, clay, coarse sand, silty clay, fully weathered gneiss, strongly weathered gneiss, and the silt soft soil layer in the current site is thicker. Table 1 shows the basic physical properties of the soil layer.

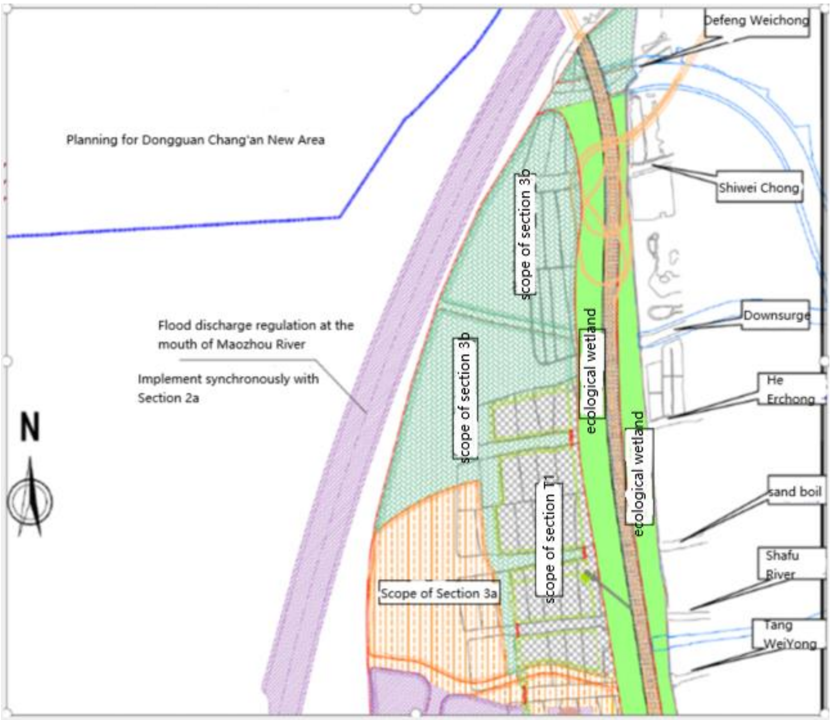



**Fig. 1.** Project Location Diagram

**Table 1.** Parameters for calculating soil layers

| | Sand cushion | Silt | Clay | Silty clay | Medium coarse sand | Fill soil |
|---|---|---|---|---|---|---|
| Soil layer thickness (m) | 0.5 | 6.4 | 10.5 | 4.4 | 7.2 | 5 |
| Constitutive model | Molar Coulomb | Revised Cam-bridge | Revised Cam-bridge | Revised Cam-bridge | Molar Coulomb | Molar Coulomb |
| Elasticity modulus （kPa) | 18000 | 2900 | 3000 | 2950 | 20000 | 12000 |
| Possion ratio | 0.32 | 0.49 | 0.35 | 0.37 | 0.3 | 0.37 |
| Cohesion (c) | 20 | 9 | 34 | 16 | 0 | 12 |
| Internal friction angle (°) | 15 | 6 | 10 | 6 | 36 | 9 |
| Weight (kN/m$^2$) | 18 | 14.6 | 18.1 | 16.5 | 18.8 | 18.7 |
| Horizontal permeability coefficient (cm/s) | $9.1\times10^{-3}$ | $4.5\times10^{7}$ | $4.9\times10^{6}$ | $1.5\times10^{6}$ | $9.3\times10^{3}$ | $3.7\times10^{-6}$ |

| | Sand cushion | Silt | Clay | Silty clay | Medium coarse sand | Fill soil |
|---|---|---|---|---|---|---|
| Vertical permeability coefficient (cm/s) | $9.1\times10^{3}$ | $4.3\times10^{7}$ | $1.2\times10^{6}$ | $1.9\times10^{-6}$ | $9.3\times10^{3}$ | $3.7\times10^{-6}$ |
| Initial void ratio (eo) | 0.66 | 2.28 | 0.97 | 1.4 | | |
| Overconsolidation ratio (OCR) | | 1 | 1 | 1 | 0.68 | 0.89 |
| Normal consolidation line slope (λ) | | 0.18 | 0.23 | 0.31 | | |
| Normal consolidation line slope (k) | | 0.081 | 0.042 | 0.097 | | |
| Normal consolidation line slope (M) | | 0.92 | 0.8 | 0.68 | | |

# 3 Establishment of the MIDAS finite element model

## 3.1 Establishment of finite element modeling

Based on the Biot consolidation theory, we simplify the three-dimensional space problem to a two-dimensional plane strain problem and use MIDAS.GTS for finite element simulation analysis. The width of the reinforcement area of the finite element model is set to 30m, the width of the influence zone is 30m, and the length of the drainage plate is set to 16m, so the width × height of the whole 2D model is b×h=60×28.5m, the middle is the reinforcement area, and the two sides are the influence area. The constitutive model of soil parameters and materials is shown in Table 1, and the finite element model is established according to the thickness of the soil layer, the height of the pile, the depth and spacing of the drainage plate, as shown in Figure 2.

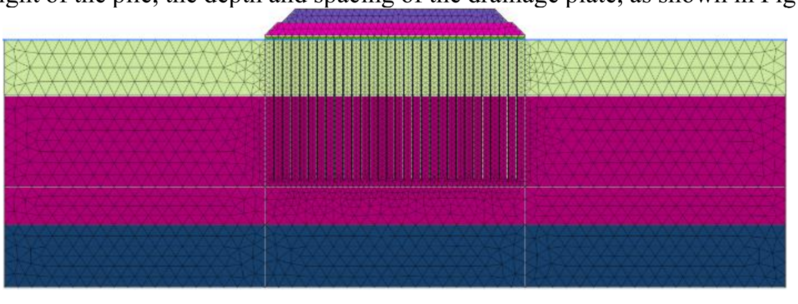


**Fig. 2.** Schematic diagram of the finite element model

### 3.2 Equivalent calculation of vertical drainage panels

In this simulation experiment, the method of laying a vertical drainage plate in the soft foundation is used to strengthen the foundation, so as to play its role in transmitting vacuum negative pressure and drainage. In this project, a C-shaped plastic drainage board with a cross-sectional size of 100 mm × 4 mm is used, and according to the principle of plane strain equivalence, the plastic drainage plate is converted into a sand well, and then the axisymmetric sand well foundation is converted into a sand wall, so that the two-dimensional finite element model can be used for calculation [10].

The drainage plate is equivalent to the sand well, and the equivalent sand well and the plastic drainage plate are required to have comparable drainage capacity, and the cross-sectional size of the drainage plate is converted into the equivalent diameter of the sand well dw.

$$d_w = \alpha \frac{2(a+b)}{\Pi} \tag{1}$$

where a and b are the cross-sectional width and thickness of the drainage board, respectively; α is the conversion factor, which is 0.9 in this project.

The key to equivalence of three-dimensional sand well to two-dimensional plane sand wall lies in the adjustment of the permeability coefficient, and the equivalent calculation formula of the converted sand wall is as follows:

$$k_{xp} = D_x k_{ra} \tag{2}$$

$$k_{zp} = D_z k_{za} \tag{3}$$

where $k_{xp}$ and $k_{zp}$ are the horizontal and vertical permeability coefficients of the sand wall, respectively. $K_{ra}$ and $K_{za}$ were the horizontal and vertical permeability coefficients of sand wells, respectively. Dx and Dz are adjustment coefficients for horizontal and vertical permeability, respectively.

According to the above formula, the equivalent diameter and equivalent permeability coefficient of the drainage plate are obtained as shown in Table 2 below.

**Table 2.** Equivalent parameters of drainage boards

| Parameter | Value |
|---|---|
| Elastic modulus $E_s$/kPa | 8000 |
| spacing s/m | 1 |
| equivalent diameter $d_w$/m | 0.06 |
| Poisson's ratio ν | 0.25 |
| Permeability coefficient k/m.s$^{-1}$ | 5.8×10$^{-6}$ |
| Adjustment coefficient of horizontal permeability coefficient $D_x$ | 1.05 |
| Adjustment coefficient of vertical permeability coefficient $D_z$ | 0.83 |
| Adjusted horizontal permeability coefficient $k_x$/m.s$^{-1}$ | 6.1×10$^{-6}$ |
| Adjusted vertical permeability coefficient $k_z$/m.s$^{-1}$ | 4.8×10$^{-6}$ |

### 3.3 Programming of the program

When setting the boundary constraint, the setting of the vacuum negative pressure adopts the drainage plate as a straight line, and the vacuum negative pressure is directly applied to the soil node on the sand cushion node and the drainage plate straight line. The attenuation of vacuum along the depth direction should be considered when calculating the vacuum preload settlement, and it is suggested that the decay rate of the vacuum degree along the depth direction should be taken as 3.5~4.5kPa/m in the absence of reliable vacuum attenuation data[11]. Combined with the on-site sub-membrane vacuum detection data, the total vacuum loss is 10-12kPa from the application of vacuum preload to the completion of the stack preload stage, which can be approximately regarded as a linear decrease over time, and four simulation schemes are set as follows:

(1) The vacuum degree does not change with depth and time, and the initial vacuum degree is applied to all nodes of the sand cushion and all soil nodes in the straight line of the drainage plate -85kPa.

(2) With the increase of depth, the vacuum negative pressure in the soil will gradually decrease due to the well resistance effect, and the loss along the way is set to 3.5kPa/m applied to the soil node.

(3) With the passage of time after applying vacuum negative pressure, the vacuum degree is lost due to the loss of vacuum degree in the soil, and the loss is about 12kPa, which can be approximately regarded as a total loss of 12kPa on each soil node.

(4) Considering that the vacuum degree is lost with depth and time, there is a loss of 3.5 kPa/m along the depth and a loss of 12 kPa over time, which is applied to each soil node at the same time. Definition of construction phases

In MIDAS, the vacuum negative pressure is applied by changing the nodal head, and the nodal hole pressure of the plastic drainage board is changed according to different schemes, so as to simulate the change of vacuum degree with depth and time.

(1) Initial Stress Analysis Phase: Activate all soil layers, boundary constraints, surface water, and self-weight of the model, and select Displacement Zero in the Define Construction Stages dialog box.

(2) Vacuum preloading phase: The vacuum load is applied as an instantaneous load, the nodal head of the vacuum negative pressure is activated, and since the vacuum pump cannot be simulated, the bedding drainage conditions and the drainage plate drainage conditions are also activated, and the duration is set to 30 days in the user-defined stage.

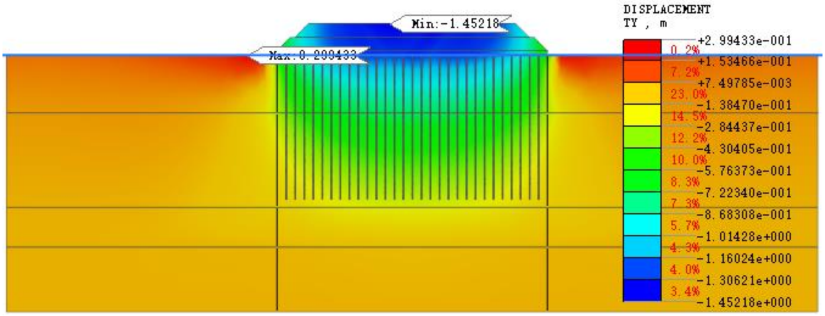
(3) Vacuum combined stacking preloading stage: apply the corresponding vacuum negative pressure according to different schemes, carry out hierarchical stacking preloading in the reinforcement area, activate the stacking soil and the stacking non-consolidation conditions; The stacking is carried out in two stages, and the construction time of each stage is 2 days, and it is allowed to stand for 10 days after stacking, and this stage lasts for 20 days.

(4) Static phase: Keep the above operations unchanged and end the calculation after 60 days of standing.

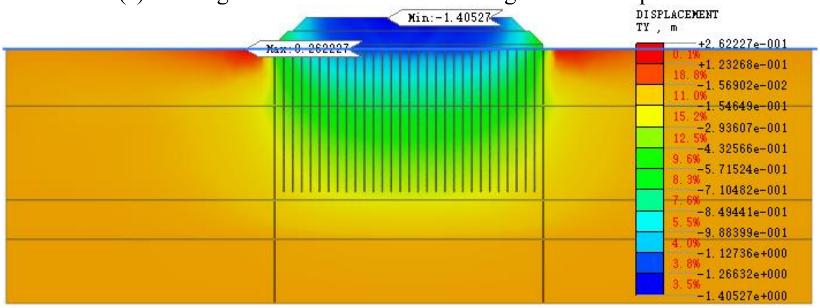
# 4 Analysis of results

## 4.1 Calculation and analysis of vertical settlement

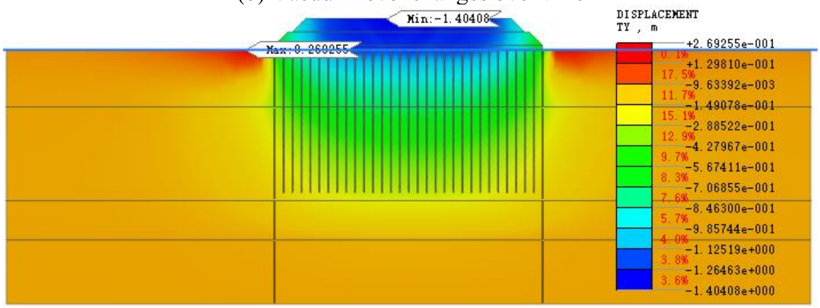
Fig. 3 shows the finite element calculation contour and final settlement for the four vacuum laying conditions. In the reinforcement area, the soil layer is degraded from top to bottom and deformed in a concave shape, and the settlement of the soil becomes smaller and smaller as the soil becomes farther and farther away from the center of the reinforcement area. The soil settlement in the center of the reinforcement zone is the largest, and there is obvious uneven settlement, and the soil settlement gradually decreases with the increase of depth.



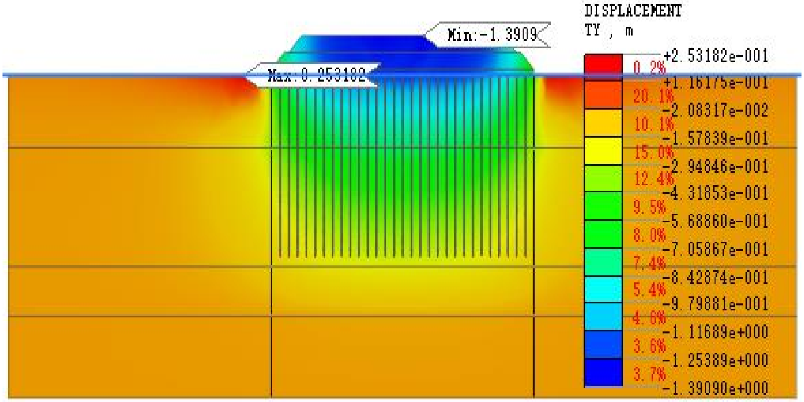

(a) The degree of vacuum does not change with the depth of time




(b) Vacuum level changes over time




(c)The degree of vacuum varies with depth




(d) The degree of vacuum varies with the depth and time

**Fig. 3.** Vertical settlement calculation contour

Fig. 4 shows the relationship curve between the depth and the final settlement under different vacuum degree laying conditions, and the final settlement amount is the vacuum degree with time depth change (1.3909m), vacuum degree with depth (1.40408m), vacuum degree with time (1.40527m), and vacuum degree unchanged (1.45218m) from small to large under vacuum combined stacking preload. The difference in the settlement of surface soil under the four working conditions is the largest, and the difference between the four gradually decreases with the increase of depth, which is due to the poor drainage effect of deep soil and the small consolidation settlement. In addition, the difference in settlement under the four working conditions is mainly due to the loss of vacuum degree caused by the time effect and the well resistance effect, which reduces the ultra-static pore water pressure, and the change of pore water pressure in the soil causes the change of effective stress, which leads to the difference of settlement of different vacuum degrees.

The surface center point of the reinforcement area was analyzed, and the surface subsidence-time relationship curve of the center point was obtained (Fig. 5). It can be seen from the figure that the soil settles after the vacuum negative pressure is applied, and the soil settlement gradually decreases and tends to stabilize after the vacuum negative pressure is applied for a period of time, and the overall settlement in the vacuum negative pressure stage accounts for about 20% of the overall settlement. This is due to the relatively large initial porosity of the soil, which causes the dissipation of ultra-static pore water after the application of vacuum negative pressure, and the effective stress of the soil increases, resulting in a certain settlement of the soil. At this stage, due to the increase of the total stress in the upper part of the soil layer, the soil body has a large settlement, accounting for about 80% of the total settlement, and the soil gradually tends to stabilize and no longer settles in the final static stage.

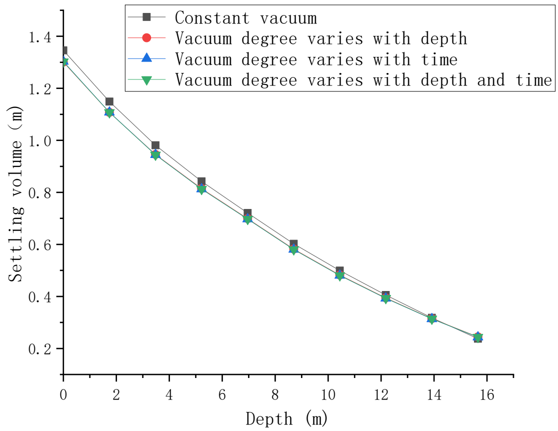



**Fig. 4.** Relationship between depth and final settlement

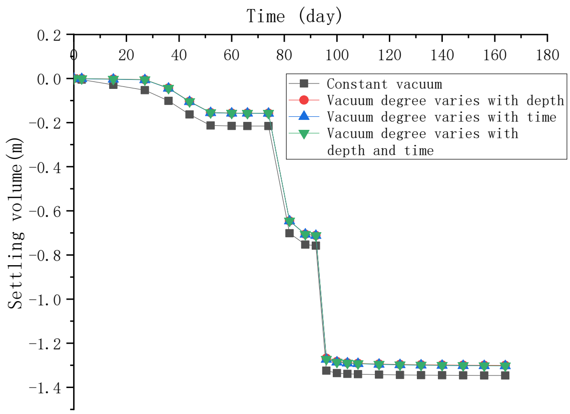
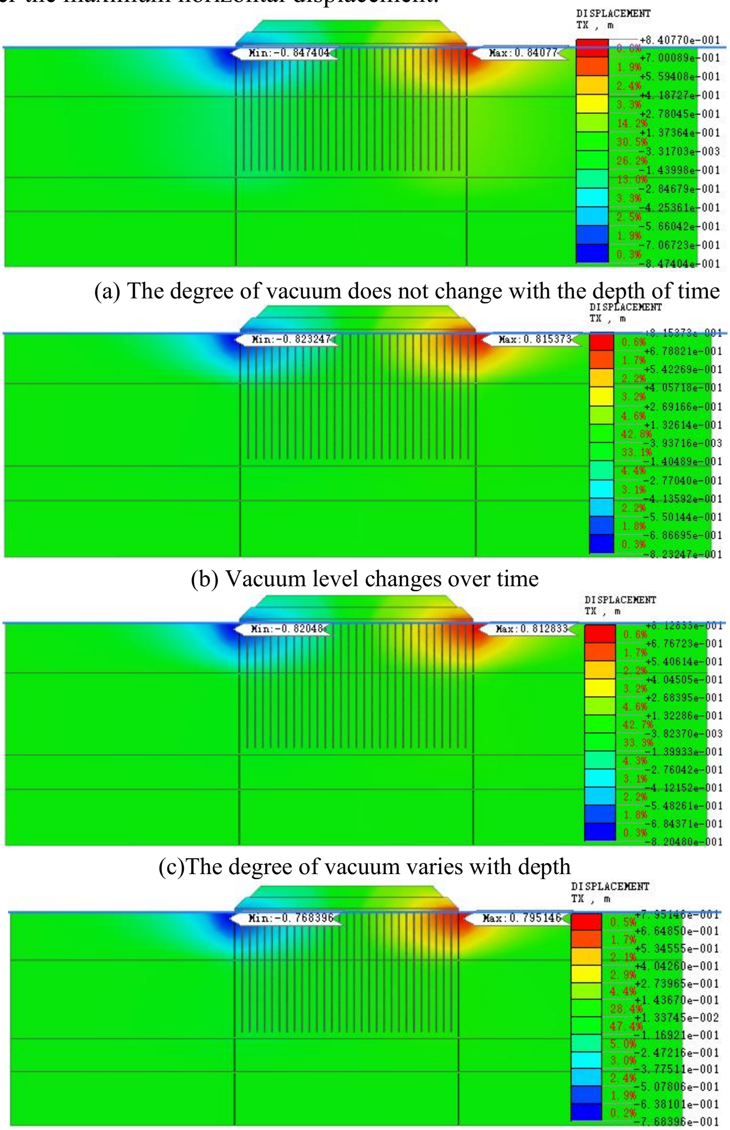



**Fig. 5.** Curve of central settlement and time at the surface level

## 4.2 Horizontal displacement calculation analysis

Fig. 6 is the horizontal displacement calculation cloud diagram of four kinds of calculation conditions, it can be seen from the figure, in the vacuum preloading stage, the horizontal displacement of the soil should have moved from outside the reinforcement area to the inside of the reinforcement area under the influence of pressure difference, but the soil body is extruded outward under the action of stacking, and the effect of vacuum negative pressure is offset with the increase of the stacking pressure, and the soil body begins to move from the reinforcement area to the influence zone. At the same time, the maximum value of horizontal displacement occurs at the boundary between the reinforcement zone and the influence zone, and the influence range in the influence zone is also larger. For the four calculated cases, the maximum horizontal displacement from large to small is the vacuum degree unchanged, the vacuum degree changes with time, the vacuum degree changes with depth, and the vacuum degree changes with time and depth, indicating that the smaller the loss of the vacuum degree, the greater the maximum horizontal displacement.




(a) The degree of vacuum does not change with the depth of time

(b) Vacuum level changes over time

(c)The degree of vacuum varies with depth

(d) The degree of vacuum varies with the depth and time

**Fig. 6.** Horizontal displacement calculation contour

Fig. 7 shows the horizontal displacement and depth relationship curves calculated for the four working conditions. As can be seen from the figure, the horizontal displacement generally shows a decreasing trend with increasing depth and reaches a maximum at the surface. The horizontal displacement has an obvious decreasing trend from the surface to 6.4m below the surface, and the decreasing trend slows down significantly after 6.4m below the surface, which is due to the fact that the soil layer is separated here, the soil changes from silt to clay, and the physical properties of the soil change greatly, resulting in a significant change in the horizontal displacement.

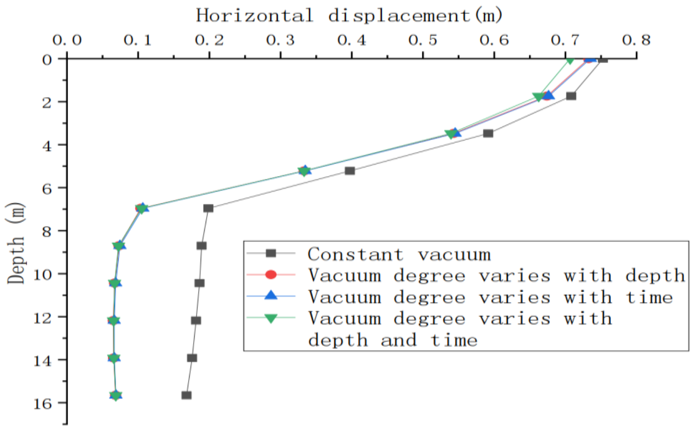



**Fig. 7.** Horizontal displacement vs. depth curve

## 5 Conclusion

In this paper, the 3b bid section of the land area formation project of the marine emerging industrial base in Shenzhen, Guangzhou is taken as the research object, and the influence of the change of vacuum degree on the treatment effect of soft foundation under the influence of well resistance effect and time effect is emphatically explored, and the following conclusions are obtained by using MIDAS.GTS.NX software, according to the actual engineering conditions, four calculation conditions are set up: the vacuum degree is unchanged, the vacuum degree changes with time, the vacuum degree changes with depth, and the vacuum degree changes with time and depth respectively, and the following conclusions are obtained:

(1) The maximum vertical settlement under vacuum combined stack preload is located in the center of the surface of the reinforcement area, and the settlement gradually decreases with the increase of depth. The vacuum degree is unchanged, which shows that under the influence of the well resistance effect and the time effect, the soft foundation treatment effect is different due to the change of vacuum degree, but the final soil settlement caused by the change of vacuum degree with time and the change of vacuum degree with depth is almost the same.

(2) In the vacuum combined stack preload under the four vacuum laying conditions, the maximum horizontal displacement values all appear at the boundary between the

reinforcement area and the influence zone, and the maximum horizontal displacement from large to small is the vacuum degree unchanged, the vacuum degree changes with time, the vacuum degree changes with depth, and the vacuum degree changes with time depth, indicating that the smaller the loss of the vacuum degree, the greater the maximum horizontal displacement, and the damage of the vacuum degree caused by the well resistance effect and the time effect affects the maximum horizontal displacement value to varying degrees.

(3) In general, the loss of vacuum degree caused by depth change and time will have a certain impact on the treatment effect of soft foundation, but the impact of the two is not much different from the perspective of well resistance effect and time effect, and can be considered as appropriate in the actual construction process.

## References

1. KJELLMAN W. Consolidation of clay soil by means of atmospheric pressure; proceedings of the Proceedings of the Conference on Soil Stabilization, Boston, F, 1952 [C]. Massachusetts Institute of Technology.
2. Peng Jie. On site experimental study and mechanism exploration of vacuum surcharge combined preloading method [J] Journal of Jiangsu University of Science and Technology (Natural Science Edition), 2006 (01): 20-26.
3. Baral P, Indraratna B, Rujikiatkamjorn C, et al. Consolidation by Vertical Drains beneath a Circular Embankment under Surcharge and Vacuum Preloading[J]. Journal of Geotechnical and Geoenvironmental Engineering,2021,147(8):05021004.
4. Zeng Fangjin, Shi Changxin, Fu Hongtao, et al. Experimental study on the engineering characteristics of hydraulic fill under vacuum combined preloading with uniform speed and equal amount of loading [J]. Science and Technology and Engineering, 2018,18 (15): 137-142.
5. Chen Xizhou, Wei Hongbao. Numerical analysis of the process of vacuum heap load combined preloading for strengthening soft foundations [J]. Journal of Nanjing University of Technology, 2000 (05): 457-461.
6. Peng Jie, Liu Hanlong, Chen Yonghui. Discussion on the reinforcement mechanism of vacuum heap load combined preloading method [J]. Journal of Hehai University (Natural Science Edition), 2003 (05): 560-563.
7. Liu Yong, Qi Lan, Li Shaoming. Three-dimensional finite element analysis of vacuum preloading considering variable well resistance and coating effects [J]. Geotechnical Mechanics, 2017,38 (05): 1517-1523.
8. Chen Huan, Bao Xiuqing. The effective consolidation stress of soil under negative pressure conditions [J] Journal of Geotechnical Engineering, 1984 (5): 39-47.
9. Chen Huan. The theory and practice of vacuum preloading for strengthening soft foundations [J] Industrial Architecture, 1984 (1): 38-43.
10. Chen Xi, Zhou Wei, Hong Baoning. Numerical analysis of vacuum-stacked combined precompression reinforcement soft base process[J]. Journal of Nanjing University of Science and Technology,2000(05):457-461.
11. LIU Zhizhong, DING Jianwen, WANG Gang, et al. Calculation method of vacuum precompression sedimentation considering vacuum degree attenuation[J]. Journal of Southeast University (Natural Science Edition),2016,46(01):191-195.