Field test study on deep soft soil reinforcement by vacuum preloading without sand cushion

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Abstract. To evaluate the difference in reinforcement effect between vacuum preloading without sand cushion and conventional vacuum preloading for deep soft foundation, field comparative tests are carried out. The results show that the surface settlement during vacuum preloading without sand cushion is about 17% higher than that of conventional vacuum preloading, and the strength growth after vacuum preloading without sand cushion is about 26% higher than that of conventional vacuum preloading. The study also reveals that the reinforcement uniformity of the sand-free cushion method is weaker than that of the conventional vacuum preloading method. The research results will provide data support for the design and scheme comparison of soft foundation reinforcement by drainage consolidation method in the future.

Keywords: vacuum preloading; no-sand cushion; surface settlement; shear strength.

1 Introduction

Deep soft soil is widely distributed in coastal areas of China, including many silts and muddy soil. It has low bearing capacity and high compressibility. It cannot directly build roads, houses, wharf yards, and other building structures in the upper part, so it needs to be treated. Vacuum preloading is one of the most used methods in the reinforcement of large-area deep soft foundations. It has the advantages of a wide reinforcement range, simple construction, and high economy. In the construction of traditional vacuum preloading, it is necessary to lay a medium coarse sand cushion on the surface as a vacuum transfer medium in the drainage pipeline. However, in recent years, with the improvement of environmental protection requirements, sand resources are increasingly scarce, and many soft foundation reinforcement projects using traditional vacuum preloading methods are facing the dilemma of no sand available or a substantial increase in construction costs.

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In this background, the vacuum preloading technology without sand cushion is proposed. In the construction, the vacuum tube is directly connected to the plastic drainage plate, the laying of the sand cushion is canceled, or only a thin layer of sand is laid on the surface to meet the operation requirements of the construction machinery. Compared with the conventional vacuum preloading method, the sand-free cushion vacuum preloading method significantly saves sand resources, reduces energy loss during the vacuum degree transfer process, and improves reinforcement efficiency [1-3]. At present, domestic, and foreign scholars have done a lot of research on the calculation theory, reinforcement mechanism, and construction technology of vacuum preloading without sand cushion. Based on the assumption that the vacuum negative pressure in the shaft is linearly distributed along the depth direction, Guo et al. (2018) used the nonlinear infiltration and compression model to derive the general solution of the consolidation of the shaft foundation without the sand cushion vacuum preloading method [4]. Based on the consolidation equation and the original assumption of equal strain, Jiang et al. (2016) added the unique highly under-consolidated characteristics of dredger fill and the obvious vacuum loss of sand-free vacuum preloading to the definite solution conditions and re-derived a new analytical solution of equal strain with complete coordination between radial and vertical directions. In terms of mechanism research [5], Wang et al. (2014) and Zhang (2018) studied the transfer path of vacuum degree and the clogging behavior of plastic drainage plate in the vacuum preloading method without sand cushion using laboratory tests and numerical simulation [6-7]. Wu and Li (2017), Liu et al. (2020), and Zhou and Zhu (2021) carried out field tests to study the field construction technology of vacuum preloading without sand cushion [8-10]. The above research has laid a good foundation for the engineering application of the sand-free cushion vacuum preloading method.

However, for the conventional vacuum preloading method and the vacuum preloading method without sand cushion, due to the change of boundary conditions, the change from a uniform distribution of negative pressure boundary conditions to point source negative pressure boundary conditions will inevitably affect the settlement and reinforcement strength of the foundation. At present, there is still a lack of field test research on the difference between the settlement and reinforcement strength of the traditional preloading method and the vacuum preloading method without sand cushion. In the stage of comparison and selection of foundation treatment schemes, quantitative evaluation cannot be provided. Therefore, it is necessary to carry out further research.

Therefore, based on a foundation treatment project in Nansha, Guangzhou, this paper divides the test area on the field and simultaneously carries out the field test of traditional vacuum preloading and sand-free cushion vacuum preloading. Through the analysis of soil vacuum degree and shear strength in construction, the reinforcement effect of the two methods is compared and analyzed. The research results can provide data support for the comparison and selection of drainage consolidation methods in the future.

2 Materials and methods

2.1 Site Layout

The test site is located on a wharf in Nansha, Guangzhou. The site is divided into five areas, A1 ~ A5. The layout of the test site is shown in Figure 1. Among them, the area of A3 and A5 is 42247 m^2, which is treated by conventional vacuum preloading method. The area of A1, A2, and A4 is 69034 m^2, which is treated by vacuum preloading without sand cushion.

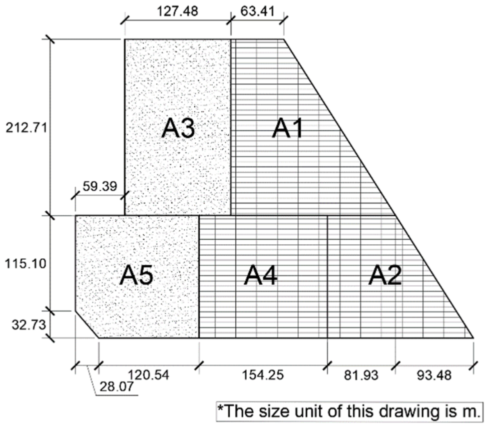


Fig. 1. The layout of the test site.

2.2 Engineering Geological Conditions

According to the survey report of the project, the soil layers of the site from top to bottom are plain fill, silt, muddy silty clay, silty clay, muddy silty clay, silt, medium coarse sand, silty clay, fully weathered argillaceous siltstone, and strongly weathered argillaceous siltstone.

The silt layer is distributed in the site, and the thickness is uneven. The maximum thickness of the layer is 10.70 m, the minimum value is 4.00 m, the average thickness is 7.00 m, and the highest value of the bottom elevation is -2.84 m. The lowest value is-9.41 m.

The distribution of muddy silty clay in the site is discontinuous. The maximum thickness is 4.20 m, the minimum is 1.60 m, the average thickness is 2.55 m, the maximum value of the bottom elevation is -4.44 m, the minimum value is -8.82 m, and the average value is -7.20 m. The standard penetration test was carried out 6 times, with an average value of N = 3.2 hits (3 ~ 4 hits).

The silty clay is distributed in the site, and the thickness is not uniform. The maximum thickness of the layer is 8.70 m, the minimum value is 0.70 m, the average thickness is 2.58 m, the highest value of the bottom elevation is −6.84 m, the lowest value is −15.73 m, the average value is −9.50 m, and the standard penetration test is 18 times. The average is N = 8.9 (3 ~ 27).

The muddy silty clay is only distributed in a small amount, with a layer thickness of 1.00 m ~ 3.30 m and a layer bottom elevation of −8.84 m ~ −13.15 m.

The silt is widely distributed on the site. The maximum thickness of the layer is 4.70 m, the minimum value is 1.25 m, the average layer thickness is 2.42 m, the highest value of the bottom elevation is -9.15 m, the lowest value is -14.62 m, and the average value is -11.57 m.

The medium-coarse sand is widely distributed on the site. The maximum layer thickness is 6.10 m, the minimum value is 2.60 m, the average layer thickness is 4.56 m, the highest value of the bottom elevation is −10.84 m, the lowest value is −15.99 m, and the average value is −14.20 m.

2.3 Test Scheme

The main technical requirements of foundation treatment in this project are as follows: vacuum pressure under membrane ≥ 86.7 kPa, dead load time ≥ 90 d, residual settlement ≤ 30 cm 25 years after construction; the bearing capacity of the foundation of the construction site is ≥ 100 kPa; the consolidation degree calculated by the measured settlement curve is ≥ 80%.

The soft foundation treatment scheme in A3 and A5 areas adopts the conventional vacuum preloading method. The foundation treatment scheme is: dredged soil to +4.95 m → one layer of geotextile plus one layer of geogrid → 0.8 m medium coarse sand cushion to +5.75 m → vacuum filter tube → two layers of sealing film → sealing water thickness of 30 ~ 50 cm.

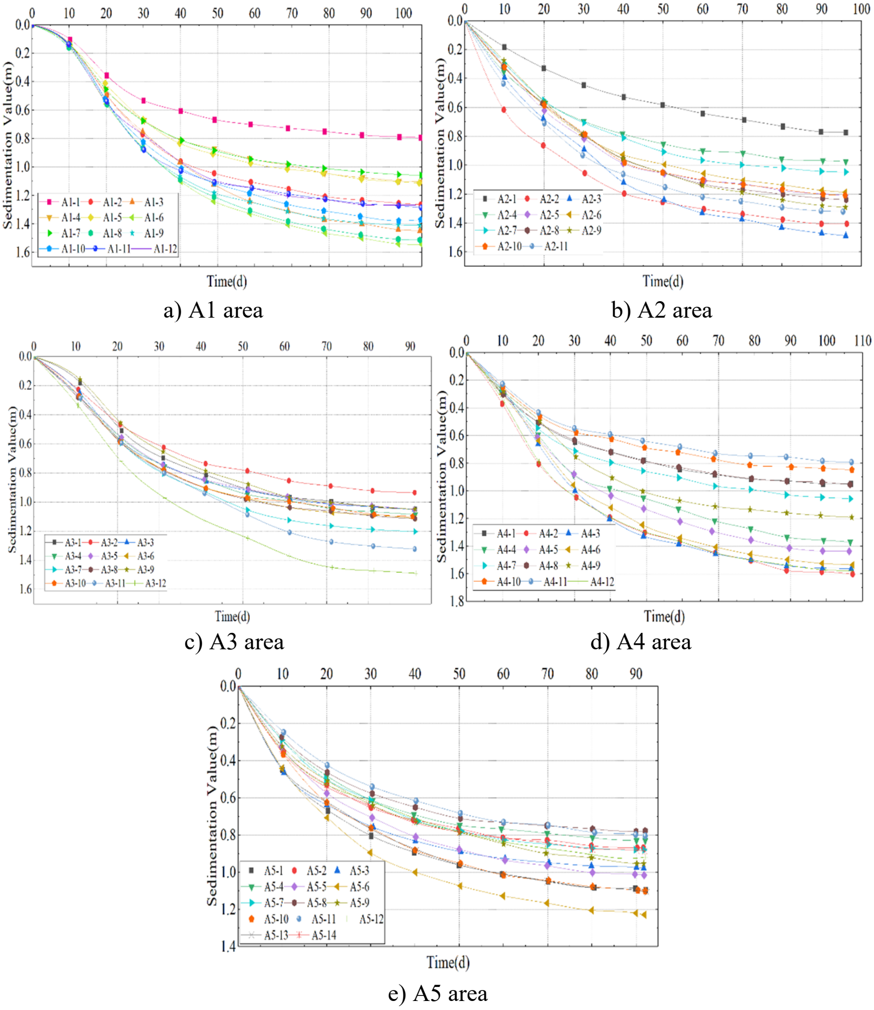
The soft foundation treatment scheme in A1, A2, and A4 areas adopts sand-free vacuum preloading. There is no need to set a medium-coarse sand cushion, and it is replaced by a medium-fine sand cushion to improve the existing soft reclaimed soil layer and the plastic drainage plate. The thickness of the medium-fine sand cushion is set to 1.5 meters, and the spacing of the vacuum filter tube is adjusted from about 6 meters to 2.4 meters. The drainage plate and the filter tube are connected by a plate-tube connector. In addition, a layer of geotextile is added to the upper part of the filter tube for protection. The construction steps are as follows: fill the dredged soil to +4.95 m → two layers of geotextile with a layer of bamboo → lay 1.5 m fine sand cushion to +6.45 m → vacuum filter pipe (buried in 0.25 m fine sand cushion) → one layer of geotextile → two layers of sealing film → sealing water thickness of 30 ~ 50 cm.

To monitor the construction quality of vacuum preloading and evaluate the reinforcement effect, the following observation items were designed in this project: surface settlement monitoring, pore water pressure monitoring, layered settlement monitoring, water level monitoring, borehole sampling geotechnical test before and after reinforcement, standard penetration test before and after reinforcement, vane shear test before and after reinforcement, static cone penetration test after reinforcement and plate load test after reinforcement.

3 Results and analysis

3.1 Ground Surface Settlement

The surface settlement is a reference for evaluating whether the consolidation degree meets the design requirements before unloading. The surface settlement observation results of each area are shown in Figure 2.



a) A1 area b) A2 area c) A3 area d) A4 area e) A5 area

Fig. 2. Surface settlement curve during the construction period.

The average settlement of the reinforced area in A1, A2, and A4 areas with vacuum preloading without sand is 1.273 m, 1.178 m, and 1.244 m respectively. The minimum settlement of each partition during the vacuum period is 0.802 m, 0.773 m, and 0.790 m respectively. The maximum settlement of each partition during the vacuum period is

1.550 m, 1.479 m, and 1.616 m respectively. The consolidation degree of the foundation in each partition is calculated by the logarithmic curve method. The consolidation degree of each partition before unloading is 94.1%, 92.7%, and 89.6% respectively. The average main residual settlement of each partition is 0.078 m, 0.086 m, and 0.128 m respectively.

The average settlement of A3 and A5 areas reinforced by the conventional vacuum preloading method is 1.134 m and 0.960 m respectively. The minimum settlement of each partition during the vacuum period is 0.941 m and 0.782 m respectively. The maximum settlement of each partition during the vacuum period is 1.484 m and 1.220 m respectively. The consolidation degree of the foundation in each partition is calculated by the logarithmic curve method. The consolidation degree of each partition before unloading is 92.1% and 96.5% respectively. The average main residual settlement of each partition is 0.099 m and 0.035 m respectively.

From the surface settlement data, the consolidation degree of each zone foundation reinforced by sand-free vacuum preloading or conventional vacuum preloading method is more than 85% before unloading, and the average main residual settlement is less than 0.25 m, which meets the design requirements. It effectively eliminates the main consolidation settlement and reduces the post-construction settlement.

It can be seen from the above comparison that the surface settlement during vacuum preloading without sand cushion is about 17% higher than that of conventional vacuum preloading. The above reasons show that during the vacuum preloading reinforcement without sand cushion, the transmission efficiency of vacuum degree is higher and the drainage rate is faster, which leads to the surface settlement of the surface is greater than that of the conventional vacuum preloading method.

3.2 Strength of foundation before and after reinforcement

In the same area of each reinforcement area, the cross-plate shear test before and after reinforcement is carried out, and the test results are shown in Table 1. From the vane shear test data, the shear strength of the vane in each reinforcement area is improved after vacuum preloading.

Table 1. Comparison of cross plate shear test before and after reinforcement in each area

Area	Before reinforcement		After reinforcement	
	Shear strength (kPa)	Average value (kPa)	Shear strength (kPa)	Average value (kPa)
A1	14.3~35.8	19.5	30.7~74.1	43.1
A2	16.3~27.1	21.1	30.0~64.9	37.8
A4	14.8~27.6	19.0	28.6~78.5	45.3
A3	14.7~33.7	21.2	28.8~65.8	39.1
A5	17.7~29.2	23.3	29.8~71.9	40.5

The minimum values of vane strength of foundation soil before reinforcement in A1, A2, and A4 areas reinforced by sand-free vacuum preloading are 14.3 kPa, 16.3 kPa, and 14.8 kPa. After vacuum preloading, the minimum values of vane strength of foundation soil after reinforcement increase to 30.7 kPa, 30.0 kPa, and 28.6 kPa, and the average values of vane strength increase from 19.5 kPa, 21.1 kPa, and 19.0 kPa to 43.1 kPa, 27.8 kPa, and 45.3 kPa.

The minimum value of the vane strength of the foundation soil before the reinforcement of the A3 and A5 zones reinforced by the conventional vacuum preloading method is 14.7 kPa and 17.7 kPa. After the vacuum preloading treatment, the minimum value of the vane strength of the reinforced foundation soil is increased to 28.8 kPa and 29.8 kPa, and the average value of the vane strength is increased from 21.2 kPa and 23.3 kPa to 39.1 kPa and 40.5 kPa.

The above strength test results show that the strength of the soil has been greatly improved after sand-free vacuum preloading or conventional vacuum preloading. Among them, after vacuum preloading without sand cushion, the shear strength of soil increases by 16.7 ~ 26.3 kPa, while after conventional vacuum preloading, the shear strength of soil increases by 17.2 ~ 17.9 kPa. The strength growth of sand-free cushion is about 26% higher than that of conventional vacuum preloading. It is further explained that the sand-free cushion method is better than the conventional vacuum preloading method in improving the strength of the soil. The possible reason is that the vacuum in the sand-free cushion vacuum preloading can reach the deep soil directly, reducing the redistribution process in the transfer process. However, it should also be noted that the uniformity of sand-free cushion reinforcement is significantly lower than that of the conventional vacuum preloading method, which is mainly caused by the superposition of uneven boundary conditions and geological conditions of the site.

3.3 Pour Water Pressure

The observation results of pore water pressure in each area are shown in Table 2.

Table 2. Pore water pressure in each area

Area	Depth (m)	Pore-water pressure difference (kPa)
A1	4	-79.7
	8	-80.3
A2	4	-79.5
	8	-80.1
A4	4	-78.5
	8	-79.9
A3	3	-82.8
	7	-82.3
	10	-81.8
	13	-77.1
A5	4	-85.4
	8	-85.2
	12	-84.5

It can be seen from the pore water pressure data of each zone that the pore water pressure dissipation law of the two vacuum preloading methods is the same. In the initial stage of vacuum pumping, the pore water pressure of the sandy soil layer decreases rapidly, and the pore water pressure dissipation is consistent with the increase of the vacuum degree under the membrane, while the pore water pressure dissipation of the deep muddy soil layer lags the increase of the vacuum degree under the membrane. During the preloading period of some partitions, there is either long or short pump-stopping maintenance (such as A3 area and A4 areas). The pore pressure curve increases significantly after the pump stops, indicating that the pore water pressure in the soil increases, and the pore pressure curve decreases after the dead load again. The pore pressure began to rise after vacuum unloading.

4 Conclusions

In this paper, the field test and corresponding monitoring test are carried out for the reinforcement effect of conventional vacuum preloading and sand-free cushion vacuum preloading, and a comparative analysis is carried out. The main conclusions of this paper are:

(1) The settlement and consolidation degree of the foundation treated by the two methods can meet the requirements, but the surface settlement during vacuum preloading without sand cushion is about 17% higher than that of conventional vacuum preloading.

(2) After sand-free vacuum preloading or conventional vacuum preloading, the strength of the soil has been greatly improved, but the strength growth after sand-free cushion reinforcement is about 26% higher than that of conventional vacuum preloading.

(3) Although the reinforcement effect of the sand-free cushion is better than that of the traditional vacuum preloading method due to its high vacuum transfer efficiency, the uniformity of its reinforcement effect is often lower than that of the conventional vacuum preloading method due to the superposition of point source boundary conditions and uneven engineering geological conditions.

Although this paper makes a comprehensive comparative analysis of the reinforcement effect of the vacuum preloading method without sand cushion and the conventional vacuum preloading method through field tests, the uniformity of the two methods and their influence on the normal operation of the superstructure after construction have not been analyzed. Further analysis and evaluation will be carried out to support engineering design.

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