Numerical analysis on ground improvement of vacuum preloading with prefabricated radiant drain

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ABSTRACT

A new technology of vacuum preloading with prefabricated radiant drain (PRD), including prefabricated vertical drain (PVD) and prefabricated horizontal drains (PHD), was proposed in this paper. The validity of numerical model parameter was verified by comparative analysis of deformation development of numerical simulation results and field tests. In addition, two influence factors of PHD spacing and PHD length for vacuum preloading with PRD technique were systematically studied by finite element method. The results show that vacuum preloading with PRD can obviously improve the reinforcement effect of dredged fill ground. Compared with the conventional vacuum preloading, the maximum settlement of vacuum preloading with PRD respectively is increased by 88.94 % and the maximum lateral displacement is 110.4 % at the PHD spacing of 0.5 m. Moreover, reducing the PHD spacing can improve the ground treatment effect. Compared with the PHD spacing of 1.5 m, the maximum settlement respectively is enlarged by 39.93 % and the maximum lateral displacement is increased by 49.4 % for the PHD spacing of 0.5 m. Increasing the PHD length can boost settlement and lateral displacement for the PHD length range of 0.2 m–0.4 m. The settlement and lateral displacement are 38.98 % and 50.3 % higher for the PHD length of 0.4 m than those for a PHD length of 0.2 m.

Keywords: ground treatment, vacuum preloading, prefabricated radiant drain; improvement effect, numerical simulation.

1 INTRODUCTION

Vacuum preloading with prefabricated vertical drains (PVD) have been extensively used to improve large area soft soil ground in land reclamation engineering. However, the filler material used in the land reclamation project is high plastic clay, which has the characteristics of high plastic index, fine clay particle and low shear strength and poor permeability (Lei et al. 2018; Sandeep and Vivek 2018). The conventional vacuum preloading often causes the bending and clogging of PVD, forming "soil column", resulting in poor ground reinforcement effect (Chai et al. 2014; Cai et al. 2016). The conventional vacuum preloading often causes the bending and clogging of PVD, forming "soil column", resulting in poor ground reinforcement effect (Chai et al. 2014; Cai et al. 2016). The conventional vacuum preloading often causes the bending and clogging of PVD, forming "soil column", resulting in poor ground reinforcement effect (Chai et al. 2014; Cai et al. 2016). The conventional vacuum preloading often causes the bending and clogging of PVD, forming "soil column", resulting in poor ground reinforcement effect (Chai et al. 2014; Cai et al. 2016). Therefore, it is urgent to develop a new vacuum preloading technology to solve the above problems and provide technical support for preventing engineering accidents and ensuring the normal use of buildings.

Some new vacuum preloading technologies have been extensively studied, such as vacuum preloading combined with surcharge preloading (Ye et al. 2018), air booster vacuum preloading (Cai et al. 2018), straight-line vacuum preloading without sand cushion (Miao et al. 2015), electroosmosis vacuum preloading (Wang et al. 2016), pharmaceutical vacuum preloading (Wu et al. 2017). The main improvement mechanisms are summarized as follows: (1) drainage pipeline is used as horizontal drainage system to replace sand cushion (Shi et al. 2018); (2) pressure difference around PVD is increased to accelerate soil consolidation (Xie et al. 2019); (3) directional movement law of particles is changed to prevent PVD from silting up (Chai and Rondonuwu 2015); (4) particle size distribution is changed to boost soil drainage capacity (Shen et al. 2017).

At present, with respect to the new vacuum preloading technology, lots of research results have been achieved, the new vacuum preloading method cannot be popularized since there is no corresponding specification in China. In addition, the combined effect of PVD and prefabricated horizontal drain (PHD) on ground reinforcement has not been taken into account in the new vacuum preloading. Few experts have systematically studied the effect of PHD on ground reinforcement.

Therefore, a new technology of vacuum preloading...
with prefabricated radiant drain (PRD) is proposed. The finite element numerical model of conventional vacuum preloading is established, and the rationality of model parameters is verified by comparative analysis of the settlement development for field tests and numerical simulation results. To explain the improvement effect of ground by vacuum preloading with PRD, the influence factors of PHD spacing and PHD length are considered to analyse the settlement and lateral deformation evolution of ground by numerical simulation. The research results can provide a reference for vacuum preloading with PRD to reinforce soft soil ground.

2 MODEL VALIDATION FOR NUMERICAL SIMULATION

2.1 Soil property and field test

The field test for the conventional vacuum preloading was conducted in the Lin Gang area of Tianjin, China. To better understand the stratigraphic sequence, boreholes were created in the test field. In accordance with the Chinese local standard for the “Specification of soil test” (GBT 50123-2019; Ministry of Water Resources of the People’s Republic of China, 2019), a series of laboratory tests were conducted to obtain basic physical indices for dredger-fill shown in Table 1. The ground treatment area for the field test is approximately 225 m², and preloading time is 60 days. PVDs are arranged in square grids with a spacing of 1.0 m and the insertion depth is 4.5 m, and the vacuum pressure should remain 90 kPa.

![Model schematic with triangular mesh elements](image)

A triangular element is used in the model, and the mesh density is set to “fine”, with 3,765 units and 31,987 nodes for the conventional vacuum preloading model. The normally fixed constraint condition is applied to the maximum boundary (top boundary) and the free boundary (bottom boundary), and the free constraint condition is then applied to the maximum boundary (right boundary). The full constraint condition is applied to the minimum boundary (left boundary). Three construction phases are created for the conventional vacuum preloading, as shown in Table 3.

| Soil descriptions | Particle composition (%) | Elastic modulus (kN/m²) | Poisson ratio | Cohesive force (kN/m²) |
|--------------------|--------------------------|-------------------------|----------------|------------------------|
| Dredged fill       | Fine sand (particle size >0.075 mm) | 25.1                    | 1500           | 0.35                   | 6                       |
|                    | Silt (particle size of 0.075 mm ~ 0.005 mm) |                         |                |                        |                         |
|                    | Clay (particle size <0.005 mm)          |                         |                |                        |                         |
| Physical indices   | Size                        | 56.7                    | 1.36           | 19.7                   |
|                    | Water content w (%)         |                         |                |                        |                         |
|                    | Void ratio e               |                         |                |                        |                         |
|                    | Plasticity index Ip         |                         |                |                        |                         |
| Physical indices   | Liquid index I_L           | 1.36                    | 0.796          | 3.21                   |
|                    | Coefficient of compressibility d1-2 |                       |                |                        |                         |
| Physical indices   | Hydraulic conductivity k   |                         |                |                        |                         |
|                    | (MPa⁻¹)                    |                         |                |                        |                         |
| Physical indices   | Hydraulic conductivity k   |                         |                |                        |                         |
|                    | (cm.s⁻¹) ×10⁻²             |                         |                |                        |                         |

2.2 Establishment and validation of conventional vacuum preloading numerical model

A conventional vacuum preloading model is established by the commercial finite element method (FEM) software Plaxis-2D, developed at Delft University of Technology in the Netherlands. The model size is 64 m × 16.6 m, and the PVDs are simulated by line elements, which are rooted at a depth of 4.5 m, as shown in Fig.1. The behaviors of the soil are assumed to obey the constitutive theory of “Hardening soil” model (Indraratna et al. 2016). To determine parameters for the model, laboratory tests were conducted in the Underground Engineering Laboratory at Tianjin University, China. The material parameters for the unit cell model are summarized in Table 2.

Fig. 2 shows that ground settlement increases with time. The field monitoring results are consistent with the numerical simulation results. When the preloading time is 10 days, the field monitoring settlement is 74.5 mm and the numerical simulation settlement is 84.8 mm.
mm, the difference between them is 10.3 mm. When the preloading time is 45 days, the field monitoring settlement is 202.5 mm and the numerical simulation settlement is 187.4 mm, the maximum settlement difference is 15.1 mm. When the preloading time is 60 days, the monitoring settlement is 221.25 mm, the numerical simulation settlement is 216.5 mm, and the settlement difference is 4.75 mm. The numerical simulation results are consistent with the settlement monitoring data, which demonstrates that the model parameters are reasonable and the model is correct.

3 VACUUM PRELOADING MODEL WITH PREFABRICATED RADIANT DRAIN ESTABLISHMENT AND NUMERICAL SIMULATION SCHEME

3.1 Introduction of vacuum preloading with prefabricated radiant drain

The key of PRD vacuum preloading is the design of PHD, as shown in Fig. 3. PRD is connected with PHD on the basis of PVD. PHD and PVD work together during the ground treatment by vacuum preloading. Water and air in soil are collected into PVD through PHD, and water and air are transported to drainage branch pipe through single-handed connector. It is noted that PRDs are rooted into dredged fill ground by manual power before the ground treatment by vacuum preloading, it is necessary to assemble PVDs and PHDs. The branch pipe is connected with the PRD through the single-handed connector. The layout of PRD is shown in Fig. 4.

3.2 Model establishment

The size, parameters, constitutive model and boundary conditions of the vacuum preloading with PRD model are consistent with those of the conventional vacuum preloading model. However, the vacuum preloading with PRD model assumes that the vacuum negative pressure can be completely transferred to the PHD. Both PVD and PHD are simulated by drainage lines, and the water head is set at - 9.0 m to ensure that the horizontal and vertical vacuum pressure is maintained at 90 kPa along the PHD and PVD. 15 nodes are selected for element, and the density of mesh generation is set to "fine", as shown in Fig. 5. There are 3,798-4,234 units and 32,573-33,654 nodes in the model.

3.3 Numerical simulation scheme

To evaluate the reinforcement effect of the vacuum preloading with PRD, numerical simulation was carried out from two aspects of different PHD spacings and PHD lengths. A total of 9 models were simulated, the PHD spacing of 0.5 m, 1 m and 2 m and the PHD length of 0.2 m, 0.3 m and 0.4 m were studied. The simulation scheme is shown in Table 4.

![Fig. 3 Prefabricated radiant drain structure](image)

![Fig. 4 Layout of prefabricated radiant drain](image)

![Fig. 5 Model establishment of prefabricated radiant drain vacuum preloading](image)

| Case number | PVD spacing (m) | PHD length (m) | PHD spacing (m) |
|-------------|-----------------|----------------|-----------------|
| 1           |                 |                | 0.5             |
| 2           | 1.0             | 0.3            | 1               |
| 3           | 0.2             |                | 2               |
| 4           |                 |                | 0.5             |
| 5           | 1.0             | 0.3            | 1               |
| 6           |                 |                | 2               |
| 7           |                 |                | 0.5             |
| 8           |                 |                | 1               |
| 9           |                 |                | 2               |

Fig. 2 Development of settlement by comparative analysis of monitoring data and numerical simulation

![Fig. 2 Development of settlement by comparative analysis of monitoring data and numerical simulation](image)
4 SIMULATION RESULTS

4.1 PHD spacing

Fig. 6 shows that settlement increases with time, and the settlement of ground treated by vacuum preloading with PRD is more than that by convention vacuum preloading. When the PHD length is 0.2 m, 0.3 m and 0.4 m, settlement for conventional vacuum preloading is 0.217 m at the preloading time of 60 days. By contrast, settlement for PRD vacuum preloading is 0.249 m, 0.265 m, 0.295 m, and 0.276 m, 0.306 m, 0.360 m, and 0.293 m, 0.334 m, 0.410 m at the preloading time of 60 days regarding to the PHD spacing of 1.5 m, 1.0 m and 0.5 m, respectively.

Compared with the conventional vacuum preloading, the maximum settlement respectively is increased by 39.94 %, 65.89 % and 88.94 % for the PHD spacing of 1.5 m, 1.0 m and 0.5 m. Obviously, the ground treatment effect of PRD vacuum preloading is better than that of conventional vacuum preloading. The main reason is that both PHD and PVD play a role in accelerating the consolidation of dredged fill ground, resulting in the settlement of vacuum preloading with PRD is larger than that of the conventional vacuum preloading. In addition, the smaller the PHD spacing is, the larger the settlement presents. When the PHD length is 0.2 m, 0.3 m and 0.4 m, the maximum settlement difference is 0.046 m, 0.084 m and 0.117 m. Compared with the PHD spacing of 1.5 m, the maximum settlement respectively is enlarged by 18.47 %, 30.43 % and 39.93 % at the PHD spacing of 0.5 m.

Fig. 6 settlement evolution under the different the PHD spacings

Fig. 7 presents the lateral displacement at the edge of the improvement area. It can be seen that lateral displacement increases with time and lateral displacement of vacuum preloading with PRD is larger than that of conventional vacuum preloading. When the PHD length is 0.2 m, 0.3 m, and 0.4 m, the lateral displacement is 0.115 m, 0.131 m, 0.142 m, 0.161 m, and 0.115 m, 0.148 m, 0.167 m, 0.205 m, and 0.115 m, 0.162 m, 0.190 m, 0.242 m, respectively, for none spacing (conventional vacuum preloading), spacing of 1.5 m, 1.0 m and 0.5 m. Compared with the conventional vacuum preloading, the maximum of lateral displacement is increased by 40 %, 78.3 %, 110.4 %. Moreover, the minor the PHD spacing is, the larger the lateral displacement performs. Compared with the PHD spacing of 1.5 m, the maximum lateral displacement is increased by 22.9 %, 38.5 %, 49.4 %, respectively.
the PHD length have a significant effect on the soft soil ground. This is mainly because the longer the horizontal length is, the wider the reinforcement range will be, which is beneficial to consolidate the soil.

Fig. 8 shows that settlement increases with time and the longer the PHD length is, the larger the settlement will be. When the vacuum preloading time is 60 days, the settlement can respectively reach 0.295 m, 0.360 m and 0.410 m for the PHD length of 0.2 m, 0.3 m and 0.4 m, and the maximum settlement difference is 0.115 m, which is increased by 38.98%. This demonstrates that

Fig. 9 presents that lateral displacement increases with time and the longer the PHD length is, the larger the lateral displacement will show. The lateral displacement is 0.161 m, 0.205 m, and 0.242 m for the PHD length of 0.2 m, 0.3 m and 0.4 m at the preloading time of 60 days, which implies that the maximum lateral displacement difference is 0.081 m. Compared with PHD length of 0.2 m, lateral displacement is enlarged by 50.3%.

5 CONCLUSIONS
To solve the engineering problems of conventional vacuum preloading in the process of ground treatment, a new technology vacuum preloading with prefabricated radiant drain is proposed. Combined with Tianjin project, the conventional vacuum preloading field test and numerical simulation are carried out to verify the correctness of parameter of numerical model. Based on it, the influence of different prefabricated
horizontal drain spacings and prefabricated horizontal drain lengths on the improvement effect of soft soil ground are studied by numerical simulation, and the following conclusions are obtained:

1) The improvement effect of vacuum preloading with PRD is better than the conventional vacuum preloading. Compared with the conventional vacuum preloading, the maximum settlement of vacuum preloading with PRD respectively is increased by 39.94 %, 65.89 % and 88.94 % and the maximum increase of lateral displacement is 40 %, 78.3 %, 110.4 % for the PHD spacing of 1.5 m, 1.0 m and 0.5 m.

2) Reducing the PHD spacing can improve the effect of ground reinforcement. When the PHD length is 0.2 m, 0.3 m and 0.4 m, compared with the PHD spacing of 1.5 m, the maximum settlement respectively is enlarged by 18.47 %, 30.43 % and 39.93 % at the preloading time of 60 days. By contrast, the maximum lateral displacement is increased respectively by 22.9 %, 38.5 %, 49.4 %, respectively.

3) Increasing the PHD length can boost the soft soil consolidation to obtain the large settlement and lateral displacement for the PHD length range of 0.2 m–0.4 m. Compared with PHD length of 0.2 m, settlement and lateral displacement are enlarged by 38.98 % and 50.3 %, respectively, for the PHD length of 0.4 m at PHD spacing of 0.5 m.

ACKNOWLEDGEMENTS

The authors acknowledge the National Key Research and Development Program of China (Grant No. 2017YFC0805402), the Major Projects of the National Natural Science Foundation of China (NSFC) (Grant No. 51578371), the Open Project of State Key Laboratory of Disaster Reduction in Civil Engineering (Grant No. SLDRC1E7-01), the Tianjin Construction Commission Science and Technology Project (Grant No. 2017E6-0015), Incentive Fund for Overseas Visits of Doctoral Students of Tianjin University in 2019 (070-0903077101), China Scholarship Council (CSC. 201906250153) for their financial support.

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