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# Shallow ground treatment by a combined air booster and straight-line vacuum preloading method: A case study

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**Abstract.** The vacuum preloading method has been used in many countries for soil improvement and land reclamation. However, the treatment time is long and the improvement effect is poor for the straight-line vacuum preloading method. To alleviate such problems, a novel combined air booster and straight-line vacuum preloading method for shallow ground treatment is proposed in this study. Two types of traditional vacuum preloading and combined air booster and straight-line vacuum preloading tests were conducted and monitored in the field. In both tests, the depth of prefabricated vertical drains (PVDs) is 4.5m, the distance between PVDs is 0.8m, and the vacuum preloading time is 60 days. The prominent difference between the two methods is when the preloading time is 45 days, the injection pressure of 250 kPa is adopted for combined air booster and straight-line vacuum preloading test to inject air into the ground. Based on the monitoring data, this paper systematically studied the mechanical parameters, hydraulic conductivity, pore water pressure, settlement and subsoil bearing capacity, as determined by the vane shear strength, to demonstrate that the air-pressurizing system can improve the consolidation. The consolidation time decreased by 15 days, the pore water pressure decreased to 60.49%, and the settlement and vane shear strengths increased by 45.31% and 6.29%, respectively, at the surface. These results demonstrate the validity of the combined air booster and straight-line vacuum preloading method. Compared with the traditional vacuum preloading, the combined air booster and straight-line vacuum preloading method has better reinforcement effect. In addition, an estimation method for evaluating the average degree of consolidation and an empirical formula for evaluating the subsoil bearing capacity are proposed to assist in engineering decision making.

**Keywords:** land reclamation; ground treatment; vacuum preloading; air booster; consolidation

## 1. Introduction

The vacuum preloading method, which is an effective, conventional and practical soft soil ground treatment method, has been widely used to construct ports, highways, airport runways and power plants worldwide because of its low unit cost and convenience of construction (Mesri and Khan 2012, Lam *et al.* 2015, Lei *et al*. 2019, Wu *et al*. 2021). With the rapid development and opening of the Tianjin Binhai New Area, large-scale, high-speed land reclamation has begun. According to incomplete statistics, more than 4000 square kilometers of land has been reclaimed across all of China, with more than 500 square kilometers of reclamation area in the Tianjin Port area. The vacuum preloading method is a mature method for strengthening soft soil and an irreplaceable technique for improving dredged fill ground of the sea reclamation projects in the Tianjin area, more than 90% of sites use the vacuum preloading technique for soft soil ground improvement.

The conventional vacuum preloading method consists of prefabricated vertical drains (PVDs), horizontal pipes embedded in a sand blanket layer, membranes, and vacuum pumps (Basu *et al.* 2014, Khan and Mesri 2014, Mahfouz *et al*. 2016, Yanez and Massad 2018, Gouw 2019, Lu *et al*.2019). This method can generate a negative pressure under the ground surface to create a pressure gradient between the soil and a drainage channel. As a result of the pressure difference, the water in the porous soil is continuously discharged from the drainage channel, thus promoting soil consolidation (Indraratna *et al*. 2011). Kjellman (1952) first proposed this technique to improve the properties of the subsoil at the Philadelphia International Airport, USA. Since that time, a significant number of researchers have investigated mechanisms for improving the effectiveness of treatment methods for soft ground soils. However, because of environmental protection policies in the coastal areas in China, the price of sand has increased

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sharply in recent years, resulting in extremely high construction costs for practical engineering applications. To solve the sand resource problem, a straight-line vacuum preloading method was proposed. This mechanism of improvement is consistent with conventional vacuum preloading, but the sand cushion is omitted, and the horizontal drainage system is replaced by a drainage pipe. However, research shows that the conventional vacuum preloading method and the straight-line vacuum preloading method can bring undesirable results in practical applications (Kumar *et al.* 2015). For example, the clogging and bending of the PVDs decrease the vacuum pressure in the PVDs, and the preloading time is long.

In addition, the newly dredged fill ground, which has not yet been subjected to the recommended one or two years of self-weight consolidation or sun-drying, must be directly reinforced because the time horizon for a project is short. To save time, the shallow ground, i.e., depths of 3-5 m, is primarily treated, providing a platform for the construction machinery (Mahfouz *et al.* 2016). Conversely, the deep ground, i.e., depths of 5-20 m, is treated afterwards and must meet the consolidation degree and time limit requirements of engineering practice (Bhosle and Deshmukh 2018). For example, with respect to the shallow ground treatment, many experts focus on the ground bearing capacity and the degree of consolidation. Chen *et al.* (2011) stated that the depth of the PVD should be 3-5 m for the shallow ground treatment in Xiamen, Tianjin, Wenzhou and Lianyungang in China and demonstrated that the subsoil bearing capacity can reach 50 kPa at a preloading time of 100 days. Saowapakpiboon *et al.* (2018) carried out field tests in the coastal city of Bangkok, Thailand, with a shallow treatment depth of 4 m; the degree of consolidation can reach 85% when the preloading time is 120 days. In terms of deep ground treatment, based on field tests, Rujikiatkamjorn *et al.* (2008) suggested that the average land subsidence rate over 5 consecutive days is 1.97 mm/d to 2 mm/d at a treatment depth of 18 m and a preloading time of 120 days. Sun *et al.* (2018) conducted field tests and studied the vacuum preloading method using short and long PVDs with a treatment depth of 19.5 m when the preloading time is 110 days; the degree of consolidation can increase to 86.4%.

However, improving the bearing capacity of shallow ground as quickly as possible to meet the needs of follow-up engineering construction is a key problem in the improvement of soft soils. Shallow ground treatment by vacuum preloading promotes the smooth progress of the subsequent deep ground treatment and greatly influences the cost, construction time and quality of the project. To improve the ground treatment effect for shallow ground, quicken the soil consolidation and relieve the problem of sand resources, a new technique of combined air booster and straight-line vacuum preloading has been suggested by some researchers (Chai *et al*. 2013, Shibata *et al*. 2014, Krishnapriya *et al.* 2016, Griffin and O'Kelly 2017). Shen *et al.* (2015) employed the combined air booster and straight-line vacuum preloading technique to improve the soft soil subgrade and proved its effectiveness in reinforcing soft soil ground. They demonstrated that the shear strength and compression modulus of the vane increased significantly, with the maximum increase degree of 239.7% and 46.7%. Lin *et al.* (2016) demonstrated that combined air booster and straight-line vacuum preloading can improve the treatment effect, shorten the construction time. They proposed that the vane shear strength increased from 20.3 kPa to 36 kPa. The preloading time saved about half a month.

The combined air booster and straight-line vacuum preloading technique applies an additional pressure difference between the air injection boosting pipe and the PVDs. The additional pressure difference can lead to the flow of water from the pores in the soil to the PVDs, thereby accelerating the consolidation of the soil. To quantify the mechanisms underlying this consolidation and the effects of the treatment, researchers have investigated the effectiveness of the method using field tests. For example, Wang *et al.* (2016) demonstrated that air booster vacuum preloading leads to a greater consolidation than conventional vacuum preloading. They found that the surface consolidation settlement had been improved by 30%. For deep-ground soil treatments, Cai *et al.* (2018) suggested that the air booster vacuum preloading technique is more effective than the conventional vacuum preloading techniques for improving the ground quality in deep marine clay layers. The research results showed that the dissipation rate of pore water pressure at depth of 20 m increased by 20%-30%.

Although results from various studies have been presented in the literature, the combined air booster and straight-line vacuum preloading technique is only in the exploration phase, and China does not have a national code or industry standard for this technique. As a result, the new technique is not widely used for large areas of dredged fill ground. Therefore, based on the engineering geological conditions of the Tianjin Binhai Area, this study introduces the vacuum preloading system and the air-pressurizing system. To accumulate engineering data, the mechanical parameters, hydraulic conductivity, pore water pressure and settlement are systematically evaluated to explain the consolidation behaviors of soft soil grounds. An estimation method that evaluates the average degree of consolidation is suggested. Furthermore, the vane shear strength and the bearing capacity are determined to evaluate the effect of the ground treatment. Finally, an empirical formula to evaluate the subgrade bearing capacity is proposed to assist in engineering decision making.

## 2. Site conditions

The field test for the shallow ground treatment via straight-line vacuum preloading without sand was conducted in the Lin Gang area of Tianjin, China, as shown in Fig. 1. The entire ground treatment area for the field test is approximately 100 square kilometers. The ground elevation was surveyed before and after the vacuum preloading, with the datum being taken as the mean sea level of the Yellow Sea in China. According to the survey, the initial ground surface was at an elevation of +5.5 m. To evaluate the effect of the shallow ground treatment by combined air booster and straight-line vacuum preloading, two sections of the field test are chosen for a comparison of the improvement effects. The total area of the selective


Fig. 1 Location of field tests (map adapted from Google)

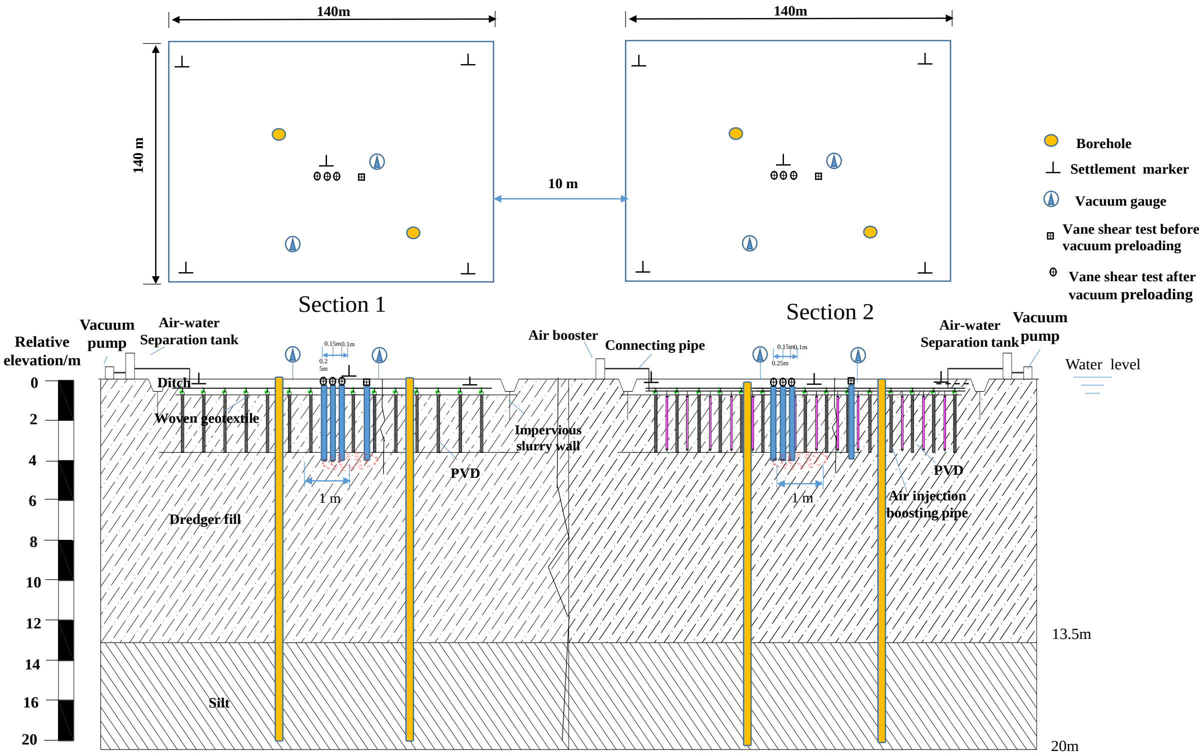



Fig. 2 Plan view of the treatment areas and the instrumentation

ground treatment is 39,200 m$^2$, of which the treatment areas of Section 1 (S1) and Section 2 (S2) are each 19,600 m$^2$, as shown in Fig. 2.

To obtain accurate data and reasonably evaluate this vacuum preloading method, pore water pressure gauges were situated at depths of 1.0 m, 2.5 m, and 4 m. Settlement marks were placed in the four corners and in the central location of each section, and the average value of the 2 sections was obtained. Vacuum gauges were used to monitor and control the vacuum pressure under the vacuum sheet. The vane shear strengths were measured in the vane shear test to assess the subsoil bearing capacity. The placement of the monitoring devices is shown in Fig. 2. Samples were obtained from a depth of 20 m below the ground surface at the construction site. Shelby tubes with an internal diameter of 9.8 cm and a 6-degree tapered end were used to take soil samples to reduce the sampling disturbance. The length of the tube was 50 cm, and the wall

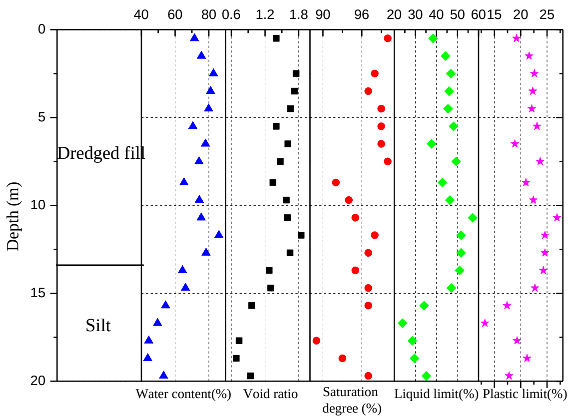



Fig. 3 Geotechnical property indices with depth

thickness was 0.2 cm, according to the local standard "*Specification of soil test*" (GB/T 50123-2019) (Ministry of Water Resources of the People's Republic of China 2019).

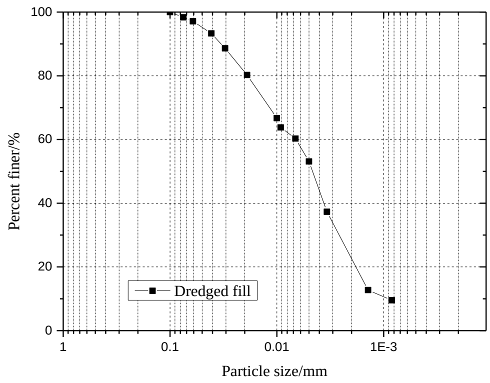
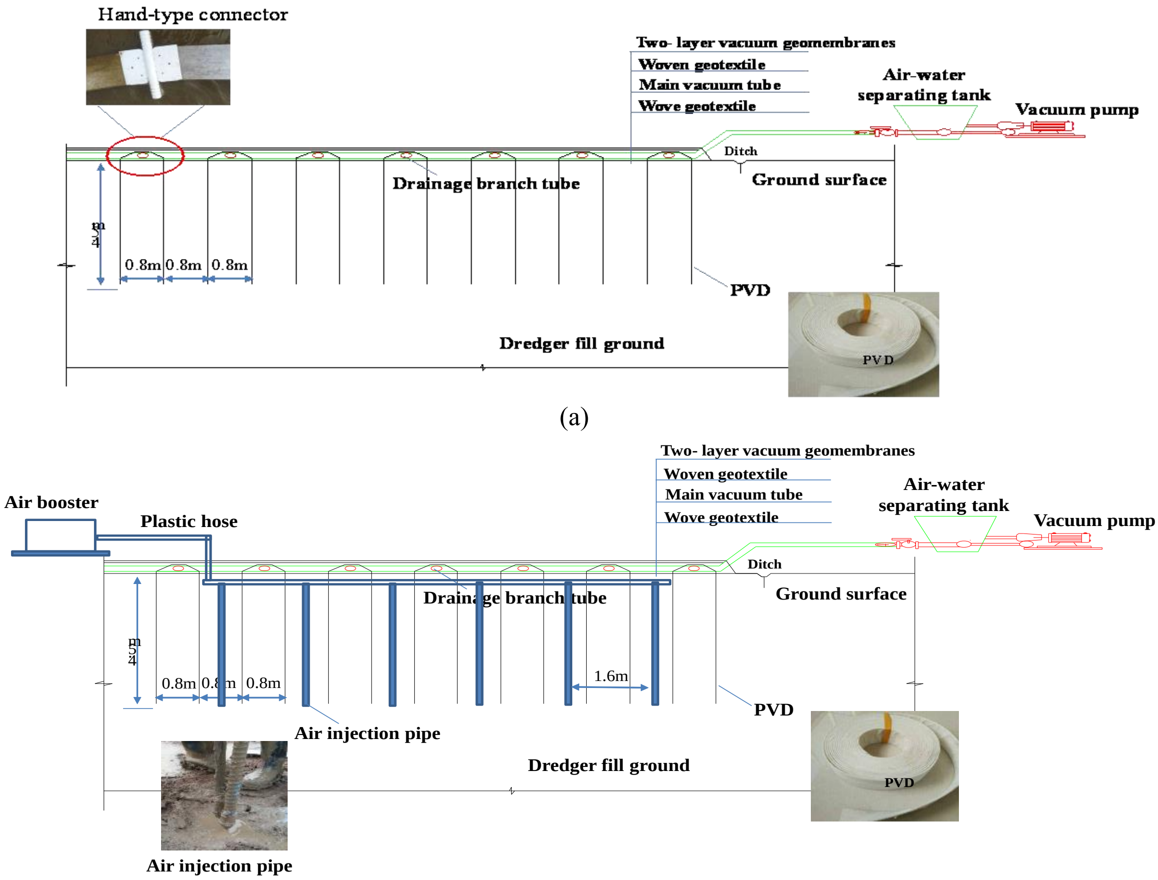



Fig. 4 Particle size distribution curve of typical Tianjin clay




(a)

(b)

Fig. 5 Construction procedure and connection mode; (a) straight-line vacuum preloading method and (b) combined air booster and straight-line vacuum preloading method

A series of laboratory tests was conducted in the Underground Engineering Laboratory of Tianjin University to obtain the basic physical indices, as shown in Fig. 3. The water content was approximately 60-85% at a depth of 15 m. The saturated soil, which had a 90-100% degree of saturation, showed a high void ratio greater than 1.0. The liquid limit was 31-65%, and the plastic limit was 15-30%.

To evaluate the clay content of the dredged fill, a hydrometer test was performed in a sedimentation cylinder with 50 g of oven-dried sample. The height of the cylinder was 457 mm, and the diameter was 63.5 mm. Sodium hexametaphosphate was used as the dispersing agent, and the volume of the dispersed soil suspension was filled to 1,000 mL by adding distilled water. From the beginning of the sedimentation, a hydrometer was placed in the soil suspension at time $t$ to measure the suspension density near its bulb at depth $L$. Then, the percent passing particle size was calculated according to Stokes' law, as shown in Fig. 4. The test results show that the clay content (< 5 μm) was approximately 53.32%.

## 3. Test plans

The combined air booster and straight-line vacuum

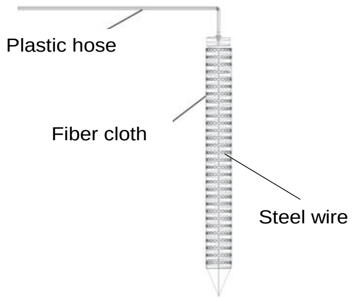



Fig. 6 The structure of the air injection boosting pipe

Table 1 Cases tested

| Subarea | Treatment by vacuum method | | | | Vacuum pumping method |
|---|---|---|---|---|---|
| | Area ($m^2$) | Design parameter | PVD layout | Air injection boosting pipe layout | |
| Section 1 | 19,600 | Spacing (m) | 0.8 (Square configuration) | / | Water and air separating tank |
| | | Depth (m) | 4.5 | / | |
| | | Air pressure (kPa) | / | / | |
| | Preloading time (days) | | | 60 | |
| Section 2 | 19,600 | Spacing (m) | 0.8 (Square configuration) | 1.5 (Square configuration) | Water and air separating tank |
| | | Depth (m) | 4.5 | 4.5 | |
| | | Air pressure (kPa) | / | 250 | |
| | Preloading time (days) | | | 60 | |

preloading method includes an air-pressurizing system and a straight-line vacuum preloading system. The straight-line vacuum preloading system consists of different components, whose installation at the test site followed several steps: (1) the woven geotextile was laid down to separate the drainage system from the dredged soil and to provide a platform for mobilizing construction equipment; (2) the PVDs were manually rooted to a depth of 4.5 m in a square pattern with spacing of 0.8 m at both S1 and S2; (3) the PVDs were extended 0.5 m above the ground and then tied to drainage branch tubes via hand-type connectors, and the other end of drainage branch tubes were connected to main vacuum tubes through four-way (or three-way) joints; (4) the main vacuum tubes were joined to larger collecting pipes, through which pumped water was sent to an air-water separating tank by a vacuum pump; (5) a peripheral ditch was dug around the test sections to contain the outflow, and a layer of geomembrane was placed over the ditch to prevent the water from seeping back into the ground; and (6) the wire hose was installed, above which two layers of vacuum geomembranes were placed. Between the wire hose and the lower layer of the geomembrane was inserted a layer of the needle-punched geotextile to prevent breakage of the vacuum geomembranes. The air-pressurizing system consists of an air injection boosting pipe, a booster pump and a plastic hose. These injection pipes were inserted midway between the PVDs, and the injection spacing is 1.5 m to the same depth as the PVDs, as shown in Fig. 5.

The core of the air-pressurizing system is the design of the air injection boosting pipe. The Underground Engineering Laboratory at Tianjin University has independently developed an air injection boosting pipe with a length of 4.5 m. Steel wire wrapped in fibrous cloth is used to form the skeleton to bear the construction load. The structure of the air injection boosting pipe is shown in Fig. 6.

During the field test, Section 1 and Section 2 are used to analyze the improvement effect. The straight-line vacuum preloading method is applied in Section 1, and the combined air booster and straight-line vacuum preloading method is adopted in Section 2. In both sections, the PVDs were manually set on a 0.8-m square grid to a depth of 4.5 m. The vacuum tubes and the PVDs are linked by hand-type connectors. In addition, an air-water separation tank, which is used to separate water and air, is used to connect the pipes and the vacuum pumps. However, the air-pressurizing system is additionally applied in Section 2. The air injection boosting pipes should be rooted at a depth of 4.5 m and manually set on a 1.5 m square grid, which is connected with the booster pump and a plastic hose. At present, there is no consensus on the selection of a proper range of air injection pressures. Some researchers recommend that the injection pressure be no more than 100 kPa, while others suggest the pressure be in excess of 100 kPa. Based on the monitoring data, Wang *et al*. (2016) found that air-boosted vacuum preloading was most effective when the injection pressure was 80 kPa, while Hu *et al*. (2018) indicated that a lower range of the injection pressure, i.e., 0-20 kPa, was preferable. Based on field tests, Shen *et al*. (2015) observed that the preferable air injection pressure was 400 kPa. Xie *et al.* (2009) found that when the injection pressure ranged between 60 kPa and 200 kPa, the drainage efficiency was improved as the air injection pressure increased. The air pressure of 250 kPa was selected in this work. When the preloading time reached 45 days, air was injected in Section 2 for 1 hour every 3 hours. The detailed experimental plan is presented in Table 1.

The spile machine (Hercules-35, made by Xuzhou Hercules Machinery Manufacturing Co., Ltd, China.) is commonly used in engineering practice in China. There are three types of spile machine, GJL-20, GJL-25 and GJL-30, weighing 15 t, 18 t and 20 t, respectively. Generally, the outline dimensions of a spile machine are 26.7 m × 10 m × 6 m (height × length × width). In engineering practice, to prevent the spile machine from sinking into the ground, equidistant rootstocks should be set at the bottom of the mechanical equipment to reduce the pressure. Five rootstocks with cross sections of 10 m × 0.2 m are commonly used at construction sites. In addition, it is necessary to consider the influence of the impact load on the soft soil pressure when inserting PVDs, as the pressure caused by static loads is multiplied by a factor of 1.5, which is referenced in the construction contract. From calculation, the subsoil bearing capacity ranges from 22.5 kPa to 30 kPa. Therefore, shallow subsoil treatment by combined air booster and straight-line vacuum preloading is required to withstand the weight of the mechanical equipment; the characteristic values of the subsoil bearing capacity at the

Table 2 Mechanical parameters before and after treatment

| Section | Before or after treatment | Water content $W$ (%) | Specific gravity (kN/m$^3$) | Void ratio $e$ | Direct shear test $c$ (kPa) | Direct shear test $\varphi$(°) | Compression coefficient $a_{1\text{-}2}$(MPa$^{-1}$) | Compression index $C_c$ |
|---|---|---|---|---|---|---|---|---|
| S1 | Before treatment | 76.5 | 15.09 | 1.91 | 4.5 | 1.7 | 1.69 | 0.52 |
| | After treatment | 55.0 | 16.25 | 1.56 | 17.0 | 2.3 | 1.41 | 0.49 |
| | Difference value | -21.5 | 1.16 | -0.35 | 12.5 | 0.6 | -0.28 | -0.03 |
| S2 | Before treatment | 76.5 | 15.09 | 1.91 | 4.5 | 1.7 | 1.69 | 0.52 |
| | After treatment | 51.3 | 16.62 | 1.45 | 19.8 | 1.8 | 1.23 | 0.48 |
| | Difference value | -25.2 | 1.53 | -0.46 | 15.3 | 0.1 | -0.46 | -0.04 |

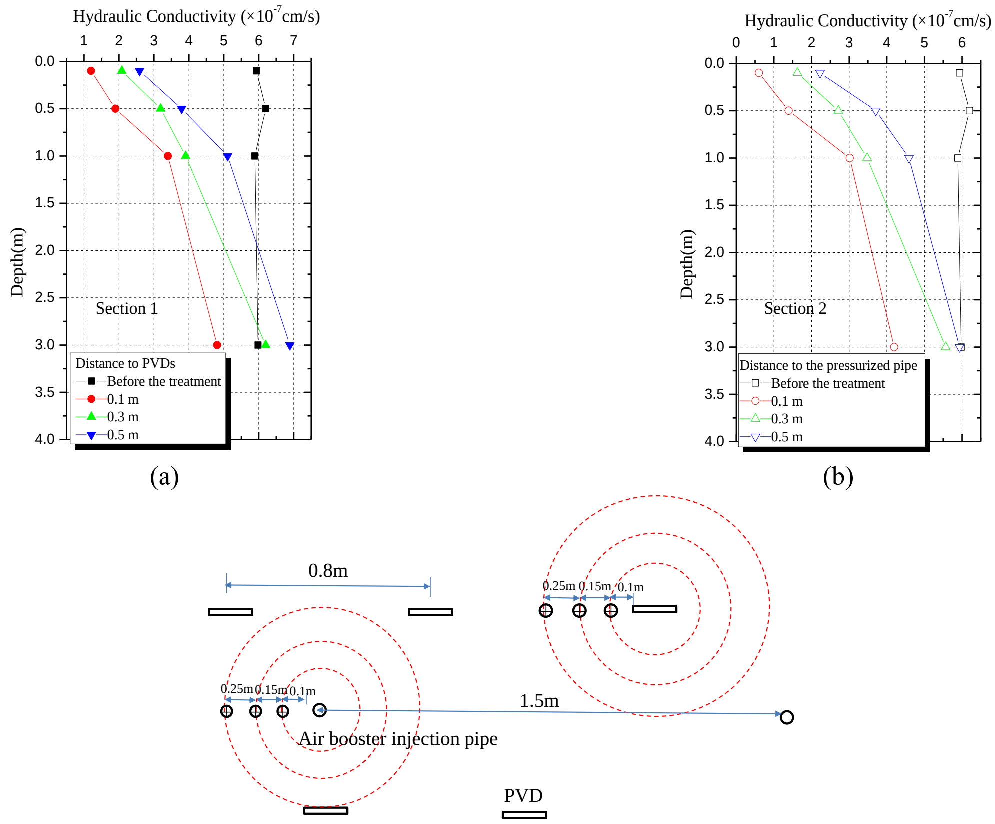



Fig. 7 Relationship between hydraulic conductivity and depth before and after the vacuum preloading; (a) different distances to the PVDs in Section 1, (b) different distances to the air injection boosting pipe in Section 2 and (c) position relationship of PVD and air booster injection pipe

surface of the ground must exceed 30 kPa at a preloading time of 60 days to ensure construction safety. In addition, treatment by the vacuum preloading method should ensure that the degree of consolidation is more than 60%, according to the construction contract requirements and the local standard "*Technical specification for vacuum preloading technique to improve soft soil*" (JTS_147-2-2009) (Ministry of Transport of the People's Republic of China, 2009). If the requirements of settlement and strength are not met, vacuuming is continued, with the settlement monitored every day and vane shear strength tested every 10 days, until the ground strength and settlement meet the requirements of the construction contract.

## 4. Test results

### *4.1 Consolidation properties*

#### *4.1.1 Comparative analysis of mechanical parameters before and after treatment*

A series of laboratory tests were conducted to determine the soft clay properties before and after the vacuum preloading treatment. For example, the water content, specific gravity, void ratio, cohesive force, internal friction angle, compression coefficient and compression index were obtained at the end of the 60-day preloading time; these data are summarized in Table 2.

The data in Table 2 show that the average value of the water content is approximately 76.5% before treatment, while the average value is approximately 55% after treatment in Section 1 and 51.3% after treatment in Section

2. This result illustrates that the air-pressurizing system can accelerate the discharge of water from the soil. The void ratio, soil compression coefficient and soil compression index in Section 2 are similarly smaller than those in Section 1. Additionally, the cohesive force of the soil in Section 2 is greater than that in Section 1, which demonstrates that the shear strength is somewhat increased by the air-pressurizing system.

#### *4.1.2 Hydraulic conductivity*

The hydraulic conductivity is an important index for evaluating the soil permeability, compaction and the smearing effect of the PVDs. In addition, the hydraulic conductivity is related to the void ratio of the soil. The relationship between the hydraulic conductivity and void ratio of clay can be obtained as follows:

$$k = c\frac{e^{4.03}}{1+e} \tag{1}$$

where $e$ is the void ratio and $c$ is a test constant of $6.16\times10^{-7}$ cm/s (Artidteang *et al.* 2011). Based on the change in the void ratio, engineers can judge the compaction indirectly according to the change in the hydraulic conductivity.

The soil samples before and after vacuum preloading were obtained at different depths. The sample hydraulic conductivity is studied at distances of 0.1 m, 0.3 m and 0.5 m from the air injection boosting pipe in Section 2, while the same distances from the PVDs are used in Section 1. The relationship between the hydraulic conductivity and depth is shown in Fig. 7(a) and Fig. 7(b). In addition, the position relationship between the injection pipe and PVD and the permeability coefficient monitoring was given in Fig. 7(c)

The data in Fig. 7 show that the hydraulic conductivity increases with the depth, and the closer the sample is to the air injection boosting pipe, the smaller the hydraulic conductivity in Section 2. As the distance to the PVDs decreases, the hydraulic conductivity in Section 1 also decreases.

In general, the hydraulic conductivity of the soil samples before vacuum preloading is approximately $6.1\times10^{-7}$ cm/s at the end of the 60 day preloading time. However, at a depth of 0.1 m, the hydraulic conductivities are $0.603\times10^{-7}$ cm/s, $1.623\times10^{-7}$ cm/s and $2.226\times10^{-7}$ cm/s at distances to the air injection boosting pipe of 0.1 m, 0.3 m, and 0.5 m, respectively, in Section 2. According to Eq. (1), the corresponding void ratios are 0.63, 0.83 and 0.91, respectively. This phenomenon demonstrates that closer to the air injection boosting pipe, the hydraulic conductivity is smaller. The void ratio decreases closer to the air injection boosting pipe, which indicates the compaction of the soil. Thus, the improved air booster and straight-line vacuum preloading technology helps the soil around the air injection boosting pipe become denser. However, when the depth is 3.0 m, the variation range of the hydraulic conductivity is $4.2\times10^{-7}$-$5.9\times10^{-7}$ cm/s in Section 2. Compared with the depth of 0.1 m, the hydraulic conductivity increases by a factor of 5.96-8.78. Obviously, the hydraulic conductivity increases with the depth within the range of 3 meters, which shows that at deeper depths, the soil layer is less compact, and improvement effect of the soil is less. Fig. 7 reveals that the air injection pressure has a great influence on the soil in the depth range of 0-0.1 m; the void ratio can be calculated from Eq. (1) to be approximately 0.81-1.05 at depth of 0.1 m, while it is 1.13-1.21 at a depth of 3.0 m.

A similar relationship exists in Section 1. When the depth is 0.1 m, the hydraulic conductivities are $1.20\times10^{-7}$ cm/s, $2.08\times10^{-7}$ cm/s and $2.58\times10^{-7}$ cm/s at distances to the PVDs of 0.1 m, 0.3 m, and 0.5 m, respectively, which are larger values than those in Section 2. The corresponding void ratios are 0.765, 0.89 and 0.95, respectively. Compared with the values in Section 2, the void ratio decreases by 0.135, 0.06, 0.04, which shows that air injection boosting can accelerate the consolidation of the soil and reduce the hydraulic conductivity and the void ratio, indicating denser soil. When the depth is 3.0 m, the variation range of the hydraulic conductivity is $4.8\times10^{-7}$-$6.9\times10^{-7}$ cm/s, and the corresponding void ratio range is 1.13-1.26. Compared with the value at a depth of 0.1 m, the void ratio increased by 0.31-0.356 at a depth of 3.0 m, which demonstrates that the ground improvement effect at a depth of 3.0 m is less than that at a depth of 0.1 m in Section 1.

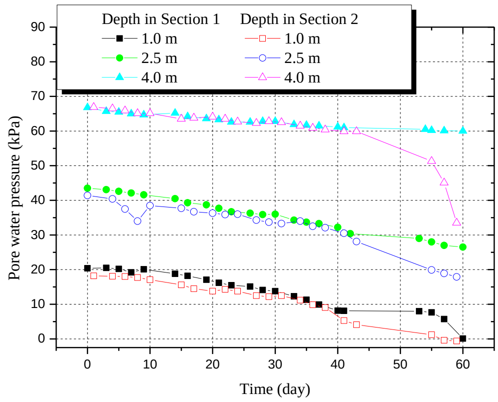


Fig. 8 Relationship between pore water pressure and time under the different depths in the Section 1 and Section 2

#### *4.1.3 Analysis of pore water pressure*

The pore water pressure characterizes the consolidation behaviors of the dredged fill, as shown in Fig. 8. The data in Fig. 8 show that the pore pressure dissipates with time and that the dissipation of the pore pressure decreases with the depth in both Sections 1 and 2. However, the pore water pressure dissipates slowly from the beginning to the preloading time of 40 days. The pore pressure dissipation is 12.25 kPa, 11.3 kPa, and 5.1 kPa at depths of 1.0 m, 2.5 m and 4.0 m in Section 1, while in Section 2, the dissipation is 10.16 kPa, 9.32 kPa, and 5.5 kPa during the whole preloading time of 40 days. Clearly, the pore pressure dissipation in the first 40 days is basically consistent in the two sections. In contrast, when the preloading time is from 40 to 60 days, the pore water pressure dissipates more significantly. When the preloading time is 40 days, the pore water pressures are 10.2 kPa, 36.8 kPa and 62.8 kPa at depths of 1.0 m, 2.5 m, and 4.0 m, respectively, in Section 1, and they are 7.9 kPa, 30.5 kPa and 60.2 kPa in Section 2. In contrast, when the preloading time is 60 days, the pore

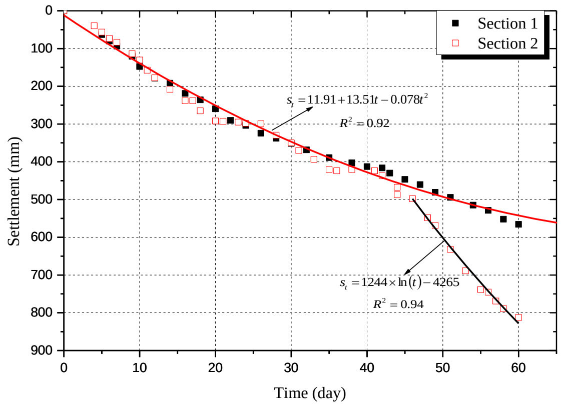



Fig. 9 Empirical formula fitting of settlement and preloading time in Section 1 and Section 2

water pressures are 0.1 kPa, 26.5 kPa and 60.1 kPa, respectively, in Section 1 and 0.01 kPa, 17.9 kPa and 36.5 kPa in Section 2. The pore water pressure dissipation degree is respectively 99.1%, 30%, and 4.23% at depths of 1.0 m, 2.5 m and 4.0 m in Section 1 and 99.8%, 41.3%, and 39.3% in Section 2.

Note that the pore water pressure dissipation degree at a depth of 1.0 m is larger than those at depths of 2.5 m and 4.0 m. In addition, the dissipation of the pore water pressure is related to the air pressurization injection; compared with Section 1, the dissipation of pore water pressure should be increased by 22.3% and 7.78 times at depths of 2.5 m and 4.0 m in Section 2. Research has shown that the stress condition of the soil is the $k_0$ consolidation state before vacuum preloading. In contrast, the vacuum loading is considered spherical stress under vacuum preloading. However, the pressure can be added in the lateral direction and vertical direction (Cai *et al.* 2018). Therefore, the primary reason for the documented behavior is that the air extruded from the soil provides positive pressure, increasing the pressure difference between the PVDs and the vacuum geomembrane, which is equivalent to amplifying the lateral vacuum pressure and accelerating soil consolidation.

### *4.2 Analysis of settlement*

The data shown in Fig. 9 indicate that the surface settlement of the soft soil ground increases with time and that the cumulative settlements of Sections 1 and 2 are 559.2 mm and 812.6 mm, respectively, at the end of 60 days. In addition, the average settlement difference between Sections 1 and 2 is approximately 10 mm after the 45-day preloading time. The settlement difference between Sections 1 and 2 increases with the preloading, which can be attributed to the air injection pressurization. The air-pressurizing system is activated on day 45 in Section 2. From Fig. 9, the maximum settlement difference between Section 1 and Section 2 reaches 253.4 mm at a vacuum preloading time of 60 days. The settlement rate of Section 1 is approximately 8.53 mm/day during the entire 60-day preloading time, while it is approximately 8.94 mm/day in Section 2 at end of 45 days and reaches 11.8 mm/day during the last 10 days. This phenomenon demonstrates that the air-pressurizing system is useful for shallow ground treatment and can reduce construction times in engineering practice.

The average consolidation degree is important for evaluating the standard of unloading in engineering practice (Parsa-Pajouh *et al.* 2014). An empirical formula based on curve regression fitting and the principle of effective stress is provided to predict the average consolidation degree (Terzaghi 1925). When engineers lack a geological survey report or similar detailed material, this empirical formula can help engineers make timely decisions.

According to consolidation theory, the average consolidation degree can be defined as follows:

$$U_t = \frac{\int_0^H \sigma'(z,t)dz}{\int_0^H u_0(z)dz} = \frac{s_t}{s_\infty} \tag{2}$$

where σ'(*z*, *t*) is the effective stress, $u_0(z)$ is the initial pore water pressure, $s_t$ is the consolidation settlement at time *t*, and $s_\infty$ is the consolidation settlement at time of infinity.

The empirical formula is developed by quadratic polynomial fitting and a logarithmic function, where the degree of fitting is more than 90%, as follows:

$$s_t = 11.91 + 13.51t - 0.078t^2 \quad (0<t<45) \tag{3}$$

$$s_t = 1244 \times \ln(t) - 4265 \quad (45 \le t \le 60) \tag{4}$$

Eq. (3) is adopted for the straight-line vacuum preloading, and both Eqs. (3) and (4) are employed for the combined air booster and straight-line vacuum preloading.

To calculate $S_\infty$, the following equation is offered by Shen *et al.* (2015):

$$s_\infty = \sum_{i=1}^{n} \xi h_i (e_{0i} - e_{1i}) / (1 + e_{0i}) \tag{5}$$

where $e_{0i}$ is the void ratio before treatment, $e_{1i}$ is the void ratio after treatment, $h_i$ is the thickness of the soil layer in the *i* deposit or the treatment depth, and $\xi$ is an empirical coefficient. Based on engineering practice, $\xi$ is equal to 1.4, $e_{01}$ is equal to 1.91, and $e_{11}$ is equal to 1.56 for Section 1; $e_{01}$ is equal to 1.91, and $e_{11}$ is equal to 1.45 for Section 2, according to Table 2. In addition, $h_1$ is 4.5 m.

To describe the average consolidation degree and illustrate the rationality of the method, the calculated values and predicted values of the average consolidation degree for Sections 1 and 2 are presented in Table 3. The data shown in Table 3 reveal that the consolidation degree increases as the preloading time increases. When the preloading time is 45 days, the average consolidation degrees are 40.7% and 37.15% in Sections 1 and 2, respectively. However, at a preloading time of 60 days, the average consolidation degree in Section 1 is approximately 51.6%, while that in Section 2 is 61.82%. The difference in the consolidation degree is 10.22 percentage points. As the preloading time increases from 45 to 60 days, the average consolidation degree increases by approximately 10 percentage points, which demonstrates that the air-pressurizing system might reduce the preloading time by 15 days.

To verify the validity of the prediction method, a

Table 3 Calculated values and predicted values of average consolidation degree for Sections 1 and 2

| Section | Preloading time (day) | Monitoring data $s_t$ (mm) | Predicted value $s_t$ (mm) | $s_\infty$ (mm) | Calculated value $U_t$ (%) | Predicted value $U_t$ (%) | Relative error (%) |
|---|---|---|---|---|---|---|---|
| S1 | 5 | 63.2 | 77.51 | 1097.42 | 5.8 | 7.1 | 21.8 |
| | 10 | 147.8 | 139.21 | | 13.5 | 12.7 | 6.0 |
| | 15 | 200.1 | 197.01 | | 19.1 | 18.0 | 6.0 |
| | 20 | 259.7 | 250.91 | | 23.7 | 22.9 | 3.5 |
| | 25 | 312.8 | 300.91 | | 28.6 | 27.4 | 4.1 |
| | 30 | 351.5 | 347.01 | | 32.0 | 31.6 | 1.2 |
| | 35 | 388.9 | 389.21 | | 35.4 | 35.5 | 0.2 |
| | 40 | 412.8 | 427.51 | | 37.6 | 39.0 | 3.6 |
| | 45 | 446.8 | 461.91 | | 40.7 | 42.1 | 3.4 |
| | 50 | 490.4 | 492.41 | | 44.8 | 44.9 | 0.2 |
| | 55 | 520.6 | 519.01 | | 47.6 | 47.3 | 0.6 |
| | 60 | 565.8 | 541.71 | | 51.6 | 49.4 | 4.3 |
| S 2 | 5 | 56.6 | 77.51 | 1320.97 | 4.28 | 5.9 | 37.1 |
| | 10 | 130.5 | 139.21 | | 9.88 | 10.5 | 6.7 |
| | 15 | 238.1 | 197.01 | | 18.02 | 14.9 | 17.2 |
| | 20 | 292.0 | 250.91 | | 22.1 | 19.0 | 14.1 |
| | 25 | 298.5 | 300.91 | | 22.6 | 22.8 | 0.8 |
| | 30 | 349.8 | 347.01 | | 26.48 | 26.3 | 0.8 |
| | 35 | 420.4 | 389.21 | | 31.83 | 29.5 | 7.4 |
| | 40 | 422.8 | 427.51 | | 32.01 | 32.4 | 1.1 |
| | 45 | 490.8 | 470.49 | | 37.15 | 35.6 | 4.1 |
| | 50 | 597.2 | 601.56 | | 45.21 | 45.5 | 0.7 |
| | 55 | 738.7 | 720.12 | | 55.92 | 54.5 | 2.5 |
| | 60 | 812.6 | 828.36 | | 61.82 | 62.7 | 1.4 |

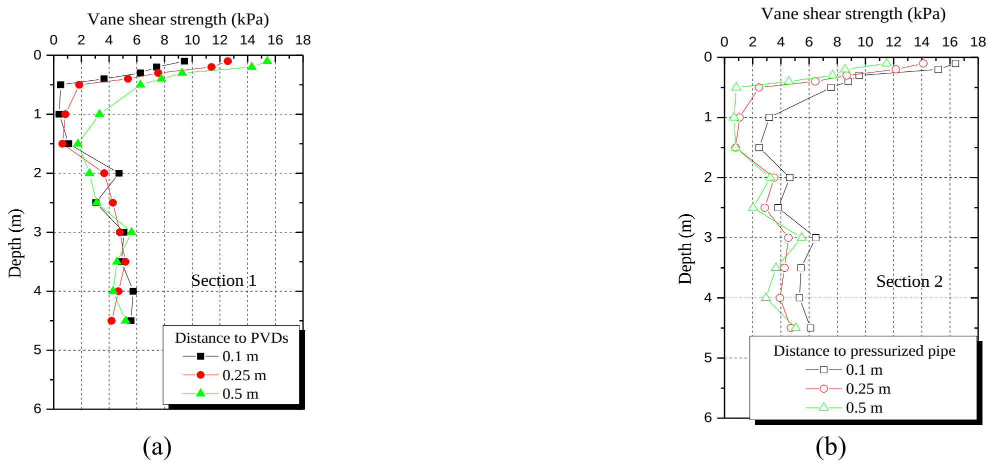



Fig. 10 Relationship between vane shear strength and depth; (a) different distances to the PVDs in Section 1 and (b) different distances to the air injection boosting pipe in Section 2

relative error analysis is carried out. The relative error is the ratio of the difference between the predicted value sequence and the original value sequence to the original value sequence (Sahu *et al*. 2017). The original value sequence is $X=(x_1, x_2,\ldots, x_n)^T$, and the predicted value sequence is $Y=(y_1, y_2,\ldots, y_n)^T$; therefore, the relative error equation is defined as follows:

$$E=(e_1,e_2,\ldots,e_n)^T \quad (n=1,2,3,\ldots n) \tag{6}$$

$$e_j=\frac{|y_j-x_j|}{|x_j|} \quad (i=1,2,3,\ldots i;\ j=1,2,3..j) \tag{7}$$

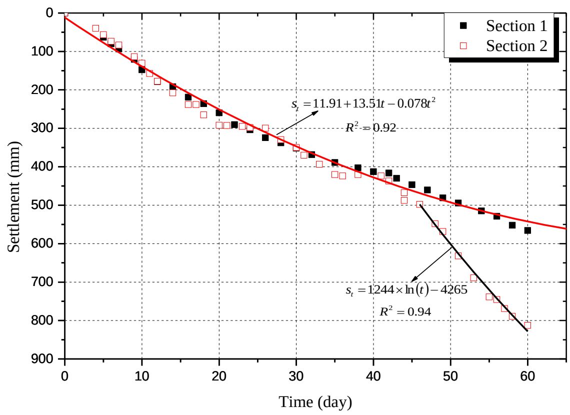



Fig. 11 Empirical formula fitting of subsoil bearing capacity and preloading time

Table 4 Monitoring data and predicted values of subsoil bearing capacity for Sections 1 and 2

| Preloading time (days) | Monitoring data (kPa) | | | Predicted value (kPa) | | | Relative error range (%) |
|---|---|---|---|---|---|---|---|
| | *d*=0.2 m | *d*=0.3 m | *d*=0.4 m | *d*=0.2 m | *d*=0.3 m | *d*=0.4 m | |
| 5 | 3.13 | 3.12 | 3.11 | 4.48 | 4.12 | 3.75 | 20.5-43.2 |
| 10 | 4.97 | 4.94 | 4.94 | 4.25 | 4.24 | 4.23 | 14.1-14.5 |
| 15 | 5.80 | 5.56 | 5.51 | 4.64 | 4.89 | 5.13 | 0.14-11.6 |
| 20 | 6.43 | 6.43 | 6.43 | 5.68 | 6.06 | 6.44 | 1.09-11.6 |
| 25 | 8.01 | 8.15 | 8.25 | 7.35 | 7.76 | 8.16 | 1.08-8.18 |
| 30 | 10.08 | 10.08 | 10.08 | 9.67 | 9.98 | 10.29 | 1.12-5.05 |
| 35 | 13.21 | 13.21 | 13.21 | 12.84 | 12.73 | 12.61 | 2.81-4.51 |
| 40 | 16.22 | 16.22 | 16.22 | 16.20 | 16.00 | 15.80 | 0.12-2.6 |
| 45 | 20.01 | 19.51 | 19.31 | 20.42 | 19.80 | 19.17 | 0.724-2.07 |
| 50 | 25.14 | 24.62 | 23.75 | 25.29 | 24.12 | 22.95 | 0.58-3.33 |
| 55 | 30.52 | 28.43 | 27.32 | 30.78 | 28.97 | 27.15 | 0.61-1.91 |
| 60 | 37.98 | 33.07 | 30.82 | 36.92 | 34.34 | 31.76 | 2.79-3.83 |

The data shown in Table 3 demonstrate that when the preloading time is from 25 days to 60 days, the relative error is less than 5%, and as the vacuum preloading time decreases, the relative error increases, especially in the first five days. The primary reasons for these changes are that the monitoring data are relatively few and the different types of curve fitting likely introduce large errors. Therefore, the results of this study suggest that the method for the prediction of the average consolidation degree could be adopted for a preloading time of 25-60 days.

### *4.3 Evaluation of the treatment effect*

In engineering practice, considering the reasons for PVD clogging and bending, the improvement effects at different locations and depths of the improvement area are inconsistent. For example, in the same improvement area, different positions and depths can be monitored to obtain different vane shear strengths and subsoil bearing capacities.

In this study, the shear strength of the soil after the vacuum preloading was systematically analyzed. The data in Fig. 10 show that the vane shear strength of the soil decreases as the depth increases in Sections 1 and 2. For example, in Section 2, when the distance from the air injection boosting pipe is 0.1 m, the vane shear strengths are 16.39 kPa, 7.56 kPa, 3.17 kPa, 4.63 kPa, 6.47 kPa, and 5.32 kPa at depths of 0.1 m, 0.5 m, 1.0 m, 2.0 m, 3.0 m and 4 m, respectively. By contrast, in Section 1, when the distance from the PVDs is 0.5 m, the vane shear strengths are 15.42 kPa, 6.26 kPa, 3.37 kPa, 2.59 kPa, 5.62 kPa and 4.29 kPa at depths of 0.1 m, 0.5 m, 1.0 m, 2.0 m, 3.0 m and 4.0 m, respectively. The primary reason for this phenomenon is that the consolidation effect is lower at a depth of 4.0 m since the pore water pressure dissipation degree is 4.23% for the straight-line vacuum preloading and 39.3% for the combined air booster and straight-line vacuum preloading. In addition, although the vane shear strength in Section 2 is greater than that in Section 1, the improvement effect is still poor at a depth of 4.0 m.

At a depth of 0.1 m, the vane shear strengths are 11.5 kPa, 14.11 kPa and 16.27 kPa at distances from the air injection boosting pipe of 0.5 m, 0.25 m and 0.1 m, respectively, in Section 2. This trend demonstrates that the closer the air injection boosting pipe is, the higher the shear strength. However, the same trends are evidenced in Section 1. At a depth of 0.1 m, the vane shear strengths are 9.44 kPa, 12.57 kPa and 15.42 kPa at distances from the PVDs of 0.5 m, 0.25 m and 0.1 m, respectively, in Section 1. Obviously, the combined air booster and straight-line vacuum preloading can improve the vane shear strength of the ground, with an increase of 6.29% at a depth of 0.1 m. In addition, this trend illustrates that the closer the PVDs are, the larger the resulting shear strength. The analysis results indicated that a hardshell layer is formed within 0.1 m of the ground in both Section 1 and Section 2 after the vacuum preloading. According to the construction contract requirements, the vane shear strength of the hardshell layer must be greater than 10 kPa, which is 11.5-16.27 kPa for Section 2 instead of 9.44-15.42 kPa for Section 1. In addition, according to the reinforcing range of the air injection boosting, it is suggested that the optimum air injection spacing is 1.0 m in this field test, as the vane shear strength is greater than 10 kPa. Engineers can reasonably determine the air injection spacing according to the requirements of the construction contract.

The vane shear strength reflects the subsoil bearing capacity. According to the local code "*Technical specification for vacuum preloading technique to improve soft soils*" (JTS_147-2-2009) (Ministry of Transport of the People's Republic of China, 2009), the Eq. (8) is as follows:

$$f_{ak}=M_cC_u \tag{8}$$

where $f_{ak}$ is the characteristic value of the subsoil bearing capacity; $M_c$ is a coefficient of the bearing capacity, which is recommended to be $(\pi+2)/2$ or monitored by the loading plate test; and $C_u$ is the average vane shear strength.

In Section 2, according to Eq. (8), the characteristic values of the subsoil bearing capacity at the surface are 42.12 kPa, 36.27 kPa, and 29.56 kPa at distances from the air injection boosting pipe of 0.5 m, 0.25 m and 0.1 m, respectively. Similarly, the characteristic values 39.63 kPa, 32.31 kPa, and 24.27 kPa at distances from the PVDs of 0.1 m, 0.25 m and 0.5 m, respectively, in Section 1. The characteristic value of the subsoil bearing capacity at the ground surface is greater than 30 kPa in all cases, meeting the construction contract requirement. Therefore, this result demonstrates that the combined air booster and straight-line vacuum preloading method is likely to meet the construction requirements.

To help engineers estimate the bearing capacity of a foundation treated by combined air booster and straight-line vacuum preloading, a method for estimation the subsoil bearing capacity is proposed in this paper. The monitoring data from the vane shear strength of the surface at distances of 0.5 m and 0.1 m from the pressurized pipe are collected to illustrate the relation between the preloading time and the characteristic value of the subsoil bearing capacity. The data in Fig. 11 show that the monitoring data can be fitted by a quadratic polynomial with a degree of fitting greater than 90%.

When the monitoring point is 0.5 m from the pressurized pipe, the characteristic value of the subsoil bearing capacity is predicted by the Eq. (9) as follows:

$$f_{ak}=M_cC_u \tag{9}$$

When the monitoring point is 0.1 m from the pressurized pipe, the characteristic value of the subsoil bearing capacity is predicted by the Eq. (10) as follows:

$$f_{ak}^{0.1}=0.015t^2-0.345t+6.202 \quad (5\leq t\leq 60) \tag{10}$$

When the distance ($d$) is 0.1 m to 0.5 m, the characteristic value of the subsoil bearing capacity is obtained by linear interpolation, using the Eq (11) as follows:

$$f_{ak}^{d}=2.5\left(f_{ak}^{0.1}-f_{ak}^{0.5}\right)\left(0.5-d\right)+f_{ak}^{0.5} \quad (0.1\leq d\leq 0.5) \tag{11}$$

To verify the validity of the prediction method of the subsoil bearing capacity, the soil vane shear strengths at distances of 0.2 m, 0.3 m and 0.4 m to the air injection boosting pipe are measured. According Eq. (8), the subsoil bearing capacity is calculated. The predicted value of the subsoil bearing capacity is calculated by Eqs. (9)-(11), as shown in Table 4. The data shown in Table 4 illustrate that the relative error of the subsoil bearing capacity is greater than 5% before the vacuum preloading time of 30 days. In contrast, when vacuum preloading time is from 35 to 60 days, the relative error is less than 5%. The reason for this phenomenon is when the vacuum preloading time is 10 to 30 days, and the predicted bearing capacity of foundation does not satisfy the trend that the nearer the air injection boosting pipe is, the higher the subsoil bearing capacity. Therefore, this study suggests that the prediction method for the subsoil bearing capacity could be applied for a preloading time of 35-60 days.

## 5. Conclusions

This paper adopts a novel combined air booster and straight-line vacuum preloading technique with an air injection pressure of 250 kPa for 1 hour every 3 hours. The improvement effect is higher than that of the straight-line vacuum preloading technique. The ground treatment effect, mechanical parameters, hydraulic conductivity, pore water pressure and settlement are systematically tested to describe the consolidation properties. In addition, a prediction method for the average consolidation degree and an estimation method for evaluating the subsoil bearing capacity are also discussed. The following conclusions are drawn:

(1) The air-pressurizing system can reduce the consolidation time by 15 days and improve the consolidation degree to 10.22%. The air booster vacuum preloading can improve the shear strength and subsoil bearing capacity, which increases by 6.29% at the surface when the preloading time is 60 days. And the air-pressurizing system can accelerate the pore water pressure dissipation to 2.29-60.94%. It also influences the consolidation process, increasing the settlement by 45.31% and improving the settlement rate from approximately 8.94 mm/day after 45 days to 11.8 mm/day after 60 days.

(2) It is suggested that the maximum influencing distance from the air injection boosting pipe is 1.0 m, as the vane shear strength of ground is greater than 10 kPa at depth of 0.1 m. In addition, the thickness of the hardshell layer, supporting layer for the construction machine, is

approximately 0.1 m, and its vane shear strength range is 11.5 kPa-16.27 kPa.

(3) A method for estimating the average consolidation degree and the subsoil bearing capacity is proposed for engineering practice when engineers do not have a geological survey report or other detailed material, thus helping engineers make timely decisions. In the case of 5% relative error, the prediction method for the average consolidation degree can be adopted for preloading times of 25-60 days, while the prediction method of the subsoil bearing capacity can be used for preloading times of 35-60 days.

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