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Research paper

Soft soil foundation treatment of hydraulic fill site based on vibration boosting drainage consolidation method

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Abstract: Reclamation from the sea is a method of expanding urban area, but it also faces the problem of difficult treatment of soft soil foundation by hydraulic reclamation. Therefore, a soft soil consolidation method that combines vibration pressure boosting drainage and piled-load static pressure stacking is now proposed. To verify the effectiveness of this method, a consolidation test based on soft soil samples was designed and conducted in the study. The test results showed that when the sampling height was 240mm, the overall moisture content of the consolidated soil sample was the highest, 44.3%, and the consolidation effect was the worst. When the sampling height was 140mm, the overall moisture content obtained from the test was the lowest, 43.1%, and the consolidation effect was the best. The displacement of corner 2 and center point at the intersection of the preceding and following periods was greater, with values of 37.1 mm and 39.2 mm, respectively. At this point, the displacement of corner 1 was significantly smaller, at 30.9 mm. In the later loading stage, the slope of the vertical displacement curve significantly increased. When the experimental time reached 7000 min, the mixed method designed in this study had a drainage rate of 0.53 ml/min, which was significantly higher than other traditional methods. The experiment outcomes indicated that the method designed in this study had certain application potential for improving the consolidation effect of soft soil foundation in hydraulic fill sites.

Keywords: drainage consolidation, moisture content, soft soil foundation, vibration boosting

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1. Introduction

There are many technology roadmap for consolidation treatment of soft soil foundations (SSFs) in hydraulic fill site (HFS). Pre-compaction method is a method of pre-compacting SSF by applying loads [1,2]. The main principle is to increase the bearing capacity and stability of the soil by applying external forces to cause compaction and consolidation [3,4]. The advantages of pre-compacting method are low cost and easy construction, but the disadvantage is that it requires a longer time for pre-compacting and a longer construction period. The advantages of microbial consolidation method are environmental friendliness and good soil modification effect, but the disadvantages are long construction period and high technical requirements. The dry vibration method has the advantages of short construction period and obvious effect, but its disadvantage is that it has high requirements for vibration equipment and may cause vibration and noise pollution to the surrounding environment. Using these methods alone has certain limitations. To improve the level of SSF treatment in HFSs, this study attempts to design a hybrid treatment method.

This study consists of four parts. The first part mainly analyzes the advantages and disadvantages of current SSF treatment methods. The core content of the second part is to design a soft soil consolidation method that combines vibration boosting drainage consolidation (VBDC) and piled-load static pressure methods (PLSP), which is also the innovation of this study. The third step is to use the designed method to conduct consolidation tests on soft soil samples such as HFSs, and compare the test results with the results of common treatment methods. The fourth part analyzes the results obtained from the experiment and points out future research directions.

The geological engineering problems such as ground settlement and insufficient bearing capacity of soft soil foundation greatly restrict urban expansion and sustainable development. This study proposes and validates an advanced soft soil treatment method that combines vibration boosting and static loading. This method not only greatly improves the drainage rate and shortens the construction period, but also helps to improve the consolidation quality, thereby ensuring the stability and safety of the building. The experimental results strongly indicate that the theoretical and practical exploration of this study has high academic and practical value in solving the international problems of hydraulic fill foundation treatment, which is in line with the urgent needs of modern urban construction.

2. Related works

Related works serve as the theoretical foundation and technical support for this study. By comprehensively evaluating existing soft soil foundation treatment technologies, not only can the advantages and disadvantages of each method be more deeply identified, but also applicability issues can be identified for specific geological environments. Especially under the special conditions of hydraulic fill soil foundation, the analysis of previous work not only provides inspiration for the treatment methods and ideas of this study, but also helps to construct a new framework for design methods. SSF is a hot research topic in the engineering community due to its high moisture content (MC), low bearing capacity, and susceptibility to significant settlement. Studying the treatment methods and mechanical and physical properties of SSF can help find better methods for SSF treatment in this study, or provide some inspiration for the research. Therefore, it is necessary to analyze previous literature on this type [5]. Yu et al. found that excavation near existing tunnels during underground construction could have adverse effects on the tunnel, especially when there was a large amount of soft soil in the underground construction environment. Therefore, the author designed a finite element model (FEM) based on simulation analysis software. The FEM analysis findings denoted that nearby excavation could reduce the bearing capacity of soft soil in the surrounding rock of the tunnel. Therefore, more protective measures were needed during the construction of such projects, and if necessary, soft soil that had significant adverse effects on construction needed to be replaced [6]. Bai et al. believed that when constructing ship lock heads on SSFs, the problem of uneven settlement of the structure and foundation would be more prominent. This deformation posed a threat to the safety of the lock head during construction. Therefore, the author proposed a comprehensive time-varying analysis method for ship lock heads on SSFs. In addition, an optimization method of hybrid particle swarm optimization, enhanced whale optimization algorithm and differential evolution (PSO-EWOA-DE) was proposed to optimize 34 design variables of the lock head. In the study, the optimization objective was to minimize the volume of the ship lock head, and a FEM was established. The outcomes indicated that optimized design could reduce the structural volume by 10.45%. The optimization program proposed in this study provided a new perspective for the structural optimization of hydraulic structures on SSFs [7]. The study by Chandran et al. aimed to analyze the impact of typical soft and hard soil foundation types on seismic response in the Indian Peninsula. The parameter study findings showed that the heterogeneity of underground media was very sensitive to low amplitude ground motion input, especially in hard soil foundation, while the bearing capacity of SSF was less affected by seismic wave [8].

Wu et al. studied the seismic performance of typical cross interchange station in SSF by combining shaking table test and numerical modeling. Through combining experimental and numerical research, it has been found that in the case of sudden stiffness changes in the connection area, SSF could lead to concentrated shear deformation in the bottom layer. This would lead to significant stress concentration on the side walls of the station in the same area. Earthquake damage could be avoided by increasing the reinforcement ratio at key locations or introducing deformable joints [9]. Chooosrithong et al. found that in difficult geological conditions such as abundant soft soil, the structural support system was a key element in the design of any deep foundation pit, and sufficient safety margin was required to cover the inherent uncertainties in civil engineering. A parameterized three-dimensional FEM was run in the study to demonstrate the consequences of single support failure by analyzing a 30 meter deep foundation pit in marine soft soil supported by template walls and multi-layer supports. The research outcomes indicated that for SSFs, a robust design could provide significant stress redistribution ability to avoid catastrophic failure of the foundation pit when a single supporting element failed [10].

In summary, although previous studies have conducted extensive research to improve the quality of SSF treatment, most of them have adopted methods such as adding support structures and avoiding them in advance. However, some SSFs, such as those in HFSs, cannot be effectively treated using these two methods. Therefore, it is necessary to conduct this study.

3. Experiment of VBDC method in soft soil treatment of HFS

The treatment of SSF in HFSs has always been a key and difficult issue in the industry, and the traditional dynamic and energy drainage consolidation methods have different drawbacks [11]. Therefore, this study combines the VBDC method with the PLSP method, and applies it to the consolidation treatment of a certain SSF soil sample.

3.1. Selection of soft soil properties and consolidation methods for HFSs

The VBDC method is a comprehensive SSF treatment technology. Therefore, in this test, the vibrator is used to apply vibration load in the SSF [12, 13]. Combined with the advantages of the vibrator penetrating into the soft soil and the vane vibration wing with adjustable frequency, it directly acts on the reinforced soil layer to improve the soft soil mechanics characteristics [14]. The vibration load generates excessive static pore water pressure, which combined with upper static pressure stacking and vertical drainage channels, to accelerate the dissipation of pore water pressure and achieve rapid consolidation of soft soil. Considering the applicability of the experiment and construction, the experiment adopts a combination of vibration boosting and stacking for consolidation treatment. A frequency adjustable vibrator is used to place it in the target soil layer, and the vibration frequency is adjusted to change the loading method. The vibrator transmits energy deep into the soil layer, increases pore water pressure, and accelerates drainage and consolidation speed [15, 16].

Table 1. Comparison of SSF treatment methods in the consolidation zone

Technical method	**Comprehensive construction unit price (¥/m^2)**	**Duration/day**	**Advantages and disadvantages**	**Applicability**
Powder spraying pile and cement mixing pile	296–331	Around 120	High bearing capacity, but treatment depth less than 15 m; The difference in soil settlement between piles is significant, making it difficult to control the quality of the pile body.	Suitable for treating subgrades with a depth of less than 15 m, not suitable for treating large areas of ground
Vacuum preloading method (VPM)	192–209	About 210	Mature and simple; The treatment depth is generally less than 15 m, with a bearing capacity of about 80 kPa, and a sealed wall is required.	The bearing capacity is too low and requires joint dynamic compaction treatment, which is not suitable

Continued on next page

Table 1 – *Continued from previous page*

Technical method	**Comprehensive construction unit price (¥/m^2)**	**Duration/day**	**Advantages and disadvantages**	**Applicability**
Stacking preloading method (PM) + precipitation dynamic compaction	231–248	Around 180	The treatment depth is large and the settlement after construction is small; Loading and unloading of fill soil are required, and sealing walls are required.	Need for precipitation and strong compaction, which may form “rubber soil” and is not suitable
PM	212–234	Around 300	Mature and simple; A large amount of stacked fill material needs to be transported.	The construction period is too long and not suitable
Rapid pressurization and PM	98–107	About 100 days	Short processing time; Capable of handling deep soil layers with minimal impact on the environment	Appropriate

The test soil sample comes from a clay mixed with sandy soft soil from a coastal reclamation site in China, which contains sea sand and forms a heterogeneous reclamation site [17]. The distribution of water content in soft soil is as follows: 51.97% to 106.88% of the soil sample MC is divided at a depth of 3.0–3.5 m, with an average of 79.15%. The average MC at a depth of 3.5 m is 95.8%. The Ps value at 3 m of the static penetration test hole is 0.06–2.0 MPa, and 50% of the survey hole samples are less than 0.15 MPa. The average Ps value of flowing mud to sludge is 0.128 MPa. The predicted MC of the upper layer of flowing mud (with a thickness of 8.0 m to 11.0 m) in the center of the site and under the water body is 109% to 118%, and the Ps value is less than 0.03 MPa. The lower silt (thickness 3.0–8.0 m) has a water content of 60–80%, and a void ratio of 2.8–3.0 and 1.65–2.0. The soft soil within the site has a high MC and low bearing capacity. Based on the on-site particularity analysis of this engineering case, the combination of VBDC method and PLSP is more reasonable.

3.2. Design of experiments of hydraulic fill soft soil treatment by VBDC method

In the experiment, a 24 V DC motor is used as the vibration equipment, and lead eccentric blocks with masses of 40 g, 60 g, and 80 g are driven by the shaft to generate regular vibration and form a vibration module [18]. The vibration unit is sealed in an organic glass cylinder with a diameter of 40 mm and a height of 80 mm, respectively. The top of the plexiglass cylinder is connected to a universal joint to make the vibration unit vibrate freely and transmit the vibration energy to the test soil sample during the vibration of the plexiglass cylinder [19]. The eccentric block of the vibrator moves according to the circular motion track, and the corresponding centrifugal force generated is calculated according to Eq. (3.1).

$$F = r \cdot m \cdot \omega^2 \tag{3.1}$$

In Eq. (3.1), m, r, and ω respectively indicate the mass of the eccentric block, the distance from the center of gravity of the eccentric block to the shaft, and the angular velocity of the eccentric block, with corresponding units being g, mm, and rad/s. The diameter of the vibrator is 40 mm, and the outer part of the vibrator is a seamless cylinder made of organic glass. The top and bottom of the vibrator are all waterproof and sealed. The vibrator is equipped with a DC motor inside, which is equipped with a frequency adjustable eccentric block. The motor has a diameter of 24.4 mm and a height of 38 mm. The motor body is bonded and fixed to the organic glass cylinder. After starting the motor, the eccentric block rotates to generate vibration force, and the vibrator begins to vibrate. Adjusting the vibration frequency of the motor can change the centrifugal force generated by the vibrator, and the vibration load gears that can be selected are 5 N, 7.5 N, and 10 N, respectively.

The stepless speed regulation equipment of the vibration unit and the pulse frequency tachometer of the Extensible Memory Specification (XMS) are connected to the brushless motor through four wire flat wires. The speed control unit outputs a speed pulse signal through a Pulse Width Modulation (PWM) hall sensor to display the vibration frequency of the vibration unit. After the assembly of the vibration unit is completed, it is calibrated using a calibration bucket and vibration acquisition equipment. The hydraulic fill soft soil used for the bucket filling test is installed with a horizontal acceleration sensor. The acceleration sensor and vibration measurement acquisition system are provided by the vibration test and monitoring system of the Applied-mechanics Research Institute of the National Seismological Bureau. In conclusion, the vibration load response of the vibrator and the corresponding main frequency of Fast Fourier Transform (FFT) analysis can be obtained, as shown in Fig. 1. Where, when the rotational speed of the vibration unit is 480 r/min, the corresponding theoretical vibration frequency and vibration main frequency values are 8 Hz and 7.95 Hz, respectively. This is

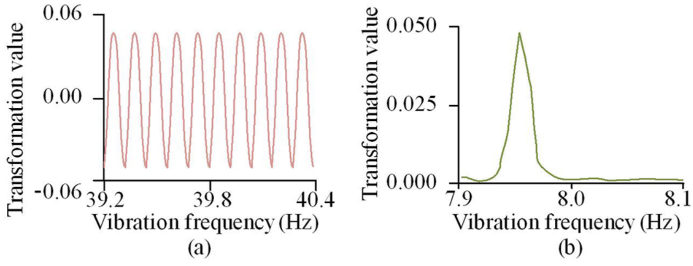


Fig. 1. Vibration load response and FFT analysis main frequency at a speed of 480 r/min; (a) Load response, (b) FFT analysis main frequency

basically consistent with the rotational frequency of the vibration unit motor of 8 Hz, indicating that the rotational speed frequency of the DC motor is the same as the corresponding vibration frequency of the vibration unit.

The experiment is completed in a cube tempered glass box, with each side length of 500 mm and thickness of 10 mm, which can be regarded as a smooth rigid boundary. Vertical plastic drainage boards are used to realize two-way drainage, and geotextile is set between the upper and lower sand cushions for isolation. The thickness of the bottom sand layer, the middle test soil sample, and the top sand layer are 50 mm, 300 mm, and 120 mm, respectively. The top sand layer of the cube tempered glass box is equipped with a loading plate for applying preloading. There are four vibrators inside the model box, with a vibration speed range of 0–1200 r/min. The quality and size of the four vibrators are identical, and they are all fixed on the loading plate by vertical smooth circular threaded rod parts. The vibrator will not slide in soft soil and is fixed at the design height. The main monitoring indicators during the experiment are the settlement of the model, drainage rate, pore water pressure inside the soft soil, and the vibration response of the vibrator to the soil. The overall experimental process is shown in Fig. 2.

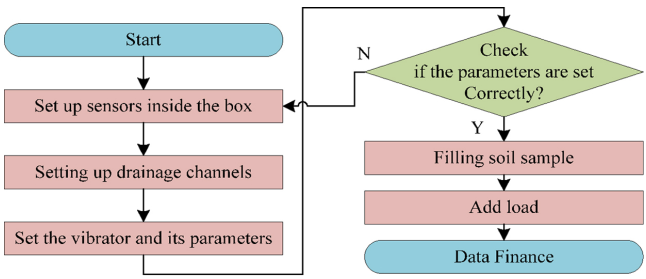


Fig. 2. Test procedure flowchart

The arrangement of four vibrators connected to the tachometer to display the rotational speed is shown in Fig. 3.

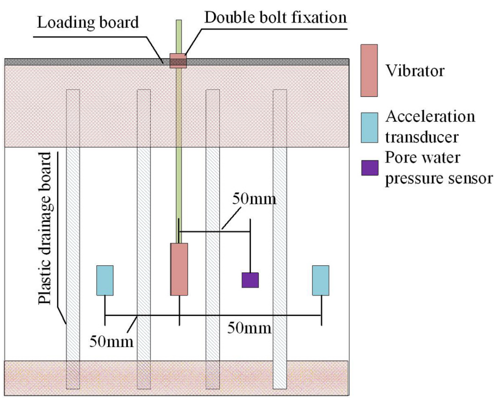


Fig. 3. Vertical layout of model vibrator

The vibration load is divided into two stages: the first stage is double vibrator vibration, and the second stage is four vibrator vibration. The vibrator is connected to a stainless steel threaded rod and fixed on a loading plate on the upper part of the sand layer, controlling the depth of the vibrator's burial and allowing it to move horizontally along the chute. The layout of the model is shown in Fig. 4.

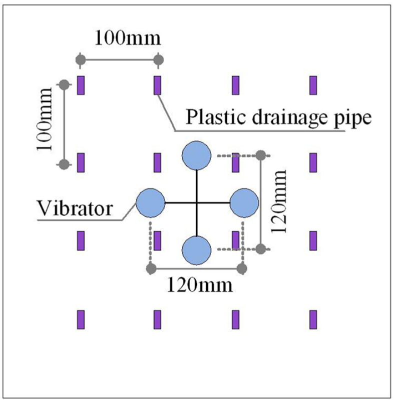


Fig. 4. Layout plan of model vibrators

The next step is to fill the soil sample. It puts the soil sample after standing into the model box. The thickness of the lower sand, soft soil and the upper sand layers are respectively 5 cm, 30 cm and 10 cm. The soil layers are separated by geotextile. Then it needs to proceed with the load application step, place the loading plate on the sand layer, ensuring complete contact between the two. It needs to fix the connecting bolts of the vibrator in the loading plate chute and apply a surcharge. Finally, data collection work is carried out. After the sensor is balanced and cleared, the vertical settlement displacement of the model box test soil sample is collected throughout the entire process. The vibrator is turned on to collect the internal vibration response and pore water pressure dissipation process of the soil under different vibration frequencies.

4. Analysis of experimental results on the treatment of hydraulic fill soft soil using VBDC method

To test the application effect of the preloading+vibration boosting drainage method (P_VBDM) designed in this study on the consolidation of SSF in HFSs, a clay mixed sand soft soil from a coastal HFS in China was obtained and consolidation tests were conducted according to this method. And the commonly used PM, vibration boosting drainage method (VBDM), and VPM in this type of engineering were selected as comparative methods.

4.1. Overview of soil samples and layout of data detection points

After completing the experiment according to the set plan, three sample layers in the depth direction needed to be tested on the soil samples in the model, with sampling depths positioned at 30 mm, 140 mm, and 240 mm. In the experiment, the diameter of the vibrator was 40 mm. If the diameter of the vibrator was D, soil samples would be sampled and tested at positions $3/4D$, $3/2D$, $9/8D$, and $3D$ away from the vibrator. The initial soil sample parameters before the consolidation test were as follows: MC of 62.1%, density of 1.701 g/cm3, void ratio of 1.620, saturation greater than 95%, liquid limit of 44.6%, and 22.5%. Strain displacement sensors were used to collect vertical displacement in the experiment, with the collection positions being bilateral corner points and center points, and the detection points were located on the rigid loading plate. The box shaped loading plate in the model was composed of three rigid strip plates, and each loading plate had monitoring points distributed on it. In the early stage of the experiment, the mode of applying dynamic load was double vibrator vibration, and in the later stage, it became all vibrators loaded together.

4.2. Analysis of test results

After the experiment was completed, the basic parameters of each soil sample were calculated as shown in Table 2. Where, as the distance between the sampling point and the vibrator increased, the water content of the sample gradually increased, but the density decreased slightly, and the void ratio increased. This was mainly because the farther away the vibrator was, the greater the drainage degree, and the more pores were left in the soil sample. For example, for a soil sample system with a sampling depth of 30 mm, the MC and density at the positions $3/4D$ and $3D$ from the vibrator were 41.1% and 45.9%, respectively, and 1.843 g/cm^3 and 1.828 g/cm^3, while the void ratio were 1.074 and 1.192, respectively.

Then it analyzed the relationship between the distance between the sampling location and the vibration center under the mixed method designed in this study and the water content, as well as the relationship between the water content and the sampling depth. The statistical results are shown in Fig. 5. It needed to note that to improve the accuracy of the statistical results, this experiment was conducted five times. Observing Fig. 5a, there was a general positive correlation between the distance from the sampling location to the vibration center and the sample MC. From the perspective of soil layer depth, there was no significant correlation between soil layer depth and water content. In the study, multiple styles of mathematical regression models were used to fit the relationship between the distance from the sampling location to the vibration center and the sample MC. Finally, it was found that the linear model had the best fitting effect, and the optimal regression Equation is shown in Eq. (4.1).

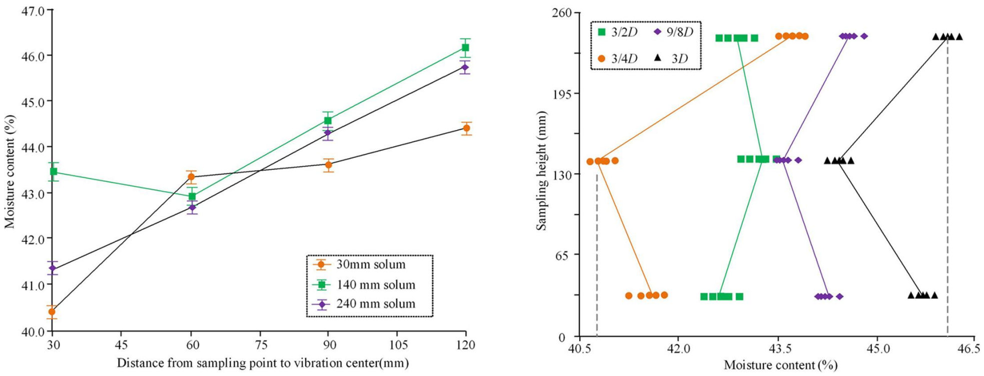
$$y = 25.7x + 42.6 \tag{4.1}$$

In Eq. (4.1), x and y respectively represent the distance from the sampling position to the vibration center (in mm) and the sample MC (in %).

Observing Fig. 5b, when the sampling depth was 240 mm, the overall water content obtained from the experiment was the highest, at 44.3%. When the sampling depth was 140 mm, the overall water content obtained from the experiment was the lowest, at 43.1%.

Table 2. Basic parameters of soil samples after testing

Borrow layer depth (mm)	Distance from vibrator (mm)	MC (%)	Density (g/cm^3)	Void ratio
30	3/4*D*	41.1	1.843	1.074
30	3/2*D*	42.8	1.838	1.103
30	9/8*D*	44.5	1.832	1.125
30	3*D*	45.9	1.828	1.192
140	3/4*D*	40.6	1.865	1.008
140	3/2*D*	43.5	1.824	1.126
140	9/8*D*	43.8	1.823	1.130
140	3*D*	44.6	1.797	1.174
240	3/4*D*	43.5	1.827	1.115
240	3/2*D*	43.0	1.835	1.126
240	9/8*D*	44.8	1.812	1.174
240	3*D*	46.3	1.795	1.209



(a) (b)

Fig. 5. Relationship between water content and sampling location and depth of soil samples; (a) Vibration position and moisture content, (b) Moisture content and sampling height

The statistical results of the numerical displacement curve of the mixed consolidation method proposed in this study are shown in Fig. 6. Where, during the loading stage of the dual vibrator stage, the loading position was relatively close to the loading plate at corner 2 and center point, so the displacement at the intersection of the front and rear stages was greater at corner 2 and center point, which were 37.1 mm and 39.2 mm, respectively. At this point, the displacement of corner 1 was significantly smaller, at 30.9 mm. During the loading stage of four vibrators, due to the doubling of the number of vibrators involved in vibration consolidation, the slope of the curve significantly increased after more than 4000 minutes.

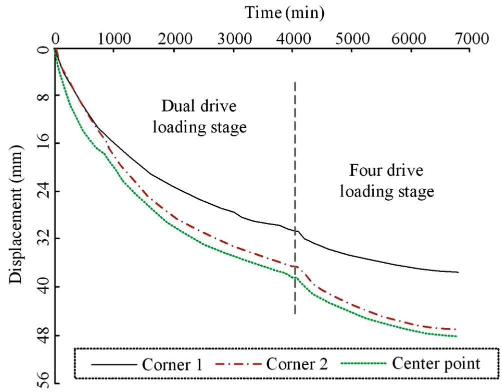


Fig. 6. Numerical displacement curve of mixed consolidation method

Because there were horizontal drainage channels and holes at the bottom of the experimental model box, it was possible to record the drainage velocity during the consolidation. Therefore, by comparing the changes in the total amount of experimental drainage in the model, the statistical results are shown in Fig. 7. Observing Fig. 7, the P_VBDM method designed in this study had a total drainage of 8622 ml during the experiment, which was significantly greater than the other consolidation drainage methods.

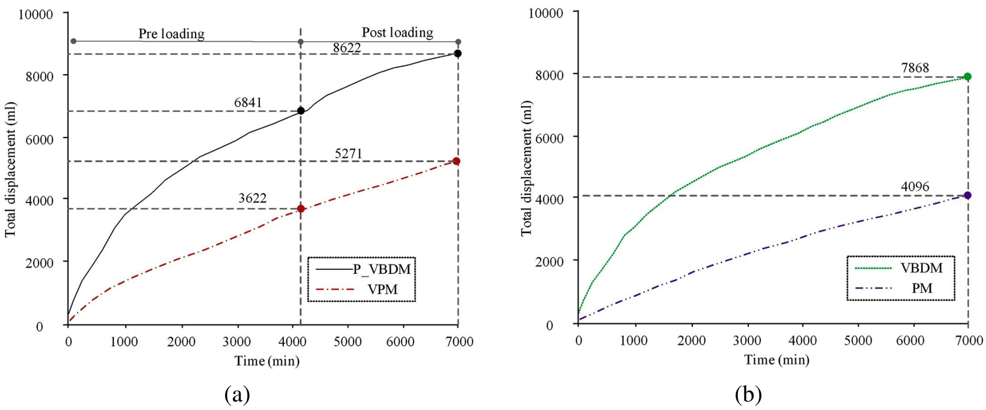


Fig. 7. Comparison of total experimental drainage amount for various consolidation methods; (a) P_VBDM and VPM, (b) VBDM and PM

The drainage rates of various consolidation methods were compared during the experiment, as shown in Fig. 8. Where, at the beginning of the experiment, the drainage speed of each method was relatively high, but as the experiment progressed, it rapidly decreased. When the test time reached 7000 min, the drainage rates of P_VBDM, VPM, VBDM, and PM were 0.53 ml/min, 0.26 ml/min, 0.32 ml/min, and 0.17 ml/min, respectively.

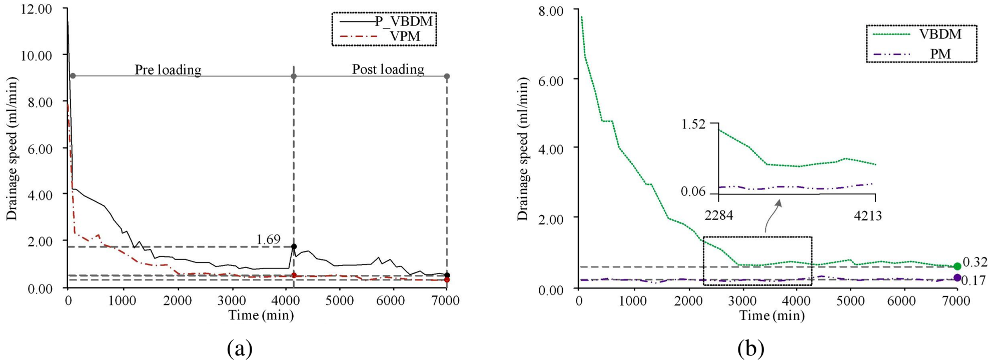


Fig. 8. Comparison of experimental drainage rates for various consolidation methods; (a) P_VBDM and VPM, (b) VBDM and PM

Finally, this method was used to treat soft soil foundation in a large-scale reclamation and road construction project in China. The test results showed that the bearing capacity of the foundation treated with this method after 10 days, 20 days, and 30 days increased by 15.8%, 8.2%, and 9.6% compared to VPM, VBDM, and PM methods, respectively. This indicates that the method still performs well in large-scale testing.

5. Conclusions

This study focused on the consolidation problem of SSF treatment in HFSs, and designed a soft soil consolidation method that combined VBDC and PLSP methods. A consolidation treatment experiment was conducted on soft soil samples. At the beginning of the experiment, the drainage speed of each method was relatively high, but as the experiment progressed, it rapidly decreased. When the test time reached 7000 min, the drainage rates of P_VBDM, VPM, VBDM, and PM were 0.53 ml/min, 0.26 ml/min, 0.32 ml/min, and 0.17 ml/min, respectively. The experimental data proved that the hybrid method designed in this study could achieve faster and greater consolidation effect of soft soil compared to traditional methods. The research results of this study are beneficial for providing potential reference for improving the quality of SSF treatment for HFSs in the civil engineering industry. The designed method can more efficiently treat the SSF formed by hydraulic fill, which can shorten the construction speed of civil engineering and save construction costs. However, due to limitations in information sources, more actual construction project soil samples were not collected for testing, which is also something to pay attention to when conducting further research in the future.

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