Rock and Soil Mechanics

Volume 41 | Issue 10 Article 5

3-10-2021

Physical modeling study on treatment of waste slurry with vacuum preloading at bottom combined with upper surcharge loading

Liang-tong ZHAN
Institute of Geotechnical Engineering, Zhejiang University, Hangzhou, Zhejiang 310058, China

Bin ZHANG
Institute of Geotechnical Engineering, Zhejiang University, Hangzhou, Zhejiang 310058, China

Xiao-gang GUO
Institute of Geotechnical Engineering, Zhejiang University, Hangzhou, Zhejiang 310058, China

Wen-hao JIANG
Institute of Geotechnical Engineering, Zhejiang University, Hangzhou, Zhejiang 310058, China

Custom Citation

ZHAN Liang-tong, ZHANG Bin, GUO Xiao-gang, JIANG Wen-hao, . Physical modeling study on treatment of waste slurry with vacuum preloading at bottom combined with upper surcharge loading[J]. Rock and Soil Mechanics, 2020, 41(10): 3245-3254.

Rock and Soil Mechanics 2020 41(10): 3245−3254
https: //doi.org/10.16285/j.rsm.2020.5026

ISSN 1000−7598
rocksoilmech.researchcommons.org/journal

Physical modeling study on treatment of waste slurry with vacuum preloading at bottom combined with upper surcharge loading

ZHAN Liang-tong[1, 2], ZHANG Bin[1, 2], GUO Xiao-gang[1, 2], JIANG Wen-hao[1, 2]

1. Key Laboratory of Soft Soils and Geoenvironmental Engineering of Ministry of Education, Zhejiang University, Hangzhou, Zhejiang 310058, China
2. Institute of Geotechnical Engineering, Zhejiang University, Hangzhou, Zhejiang 310058, China

Abstract: To solve the safety problem of using waste slurry to backfill discarded open pit mine, the treatment method of vacuum preloading at bottom combined with upper surcharge loading is implemented in the model test. The feasibility of using this method in the backfilling of discarded open pit mine is discussed. The test results show that the proposed method can significantly reduce the water content of the slurry and increase the shear strength of the soil. The water content of the slurry reduces from 450% to 95%–105%, and the reduction of volume reaches 73.4%. The undrained shear strength increases from zero to 9.8–13.4 kPa. In the initial self-weight consolidation stage, there is gravitational separation in the deposition of particles, and the deposition of coarse particles at the bottom is helpful to alleviate the clogging problem of vacuum preloading. During the stage of vacuum preloading, seepage direction of pore water in the slurry is not completely one-dimensional downward, and there is a hydraulic gradient in the radial direction. After the treatment, the compressibility of the soil is close to that of soft clay, while the permeability is greater than that of soft clay. Based on the experimental results and the large-strain consolidation theory, the effects of slurry thickness of a single disposal cycle on volume reduction and treatment time are analyzed using the finite difference method with consideration of the self-weight, nonlinear change of compressibility and permeability of the slurry. The process parameters for operation in site are recommended based on the results of numerical analysis.

Keywords: construction waste slurry; vacuum preloading at bottom; model test; consolidation; volume reduction of slurry

1 Introduction

With the accelerating urbanization process in China, large volumes of construction wastes are generated during the construction of high-rise buildings, underground tunnels, subways and others, and improper proposal of these construction wastes will pose a serious threat to the environment[1−2]. Waste slurry that generated from the construction process of bored pile foundation, underground diaphragm wall, shield, drilling and capping is one of the construction wastes with large output volume and difficulty in disposal[3−4]. It is a suspended turbidity system composed of water, bentonite particles, clayey particles and admixtures (e.g., adhesives and dispersants)[5−6], and characterized by complex composition[7], small particle size (mainly between 0.1−100 μm)[8], time consuming in sedimentation, high water content, very low strength and fluid state.

How to dispose of the construction waste slurry safely and environmental-friendly is a difficult problem faced by all cities of China because of its large volume. Using the mechanical filter press dehydration method can significantly reduce the water content of slurry[9−10], but this method has low efficiency and high cost in treating large amounts of slurry. At present, the main disposal method of waste slurry is dredging and backfilling. Large amounts of slurry are transported to the depressions around the city or the abandoned mine pits for backfill. And this method wastes a lot of land resources, even makes the disposal site a swamp, which is not only difficult to reuse but also poses a safety hazard to the environment. Due to the difficult problem of slurry disposal, the phenomenon of unauthorized dredging is not stopped, causing the pollution of groundwater and has a negative effect on the ecological environment.

Based on the current states of waste slurry disposal, the development of large-capacity, low-energy-consumption disposal technology is a top priority. There are many abandoned open-pit that need to be backfilled in China. If the construction slurry can be used as backfill material, it can not only solve the problem of waste slurry disposal, but also restore the ecology of mines. Considering the physical and mechanical characteristics of the waste slurry, there are two issues to backfilling the mines with the construction slurry directly: (i) The construction slurry is fluid with a low (even no) bearing capacity; the upper backfill without sufficient drainage and consolidation can cause instability of foundation, such as piping. (ii) The self-weight consolidation of mud slurry with high water content and low solid content is time-consuming, which will affect the construction of backfill and cause significant post-construction settlement and affect the

---

Received: 10 January 2020 Revised: 11 June 2020
This work was supported by the Key R & D program of Zhejiang Province (2019C03107).

First author: ZHAN Liang-tong, male, born in 1972, PhD, Professor, mainly engaged in the teaching and scientific research of unsaturated soil mechanics and environmental geotechnical engineering. E-mail: zhanlt@zju.edu.cn topographic slope of the reclaimed land. Therefore, it is necessary to develop a new method of pit backfilling to reduce the volume of construction slurry and increase the pit capacity, and to ensure that the strength and settlement of treated mud can meet the backfilling requirements. The vacuum preloading is widely used in treatment of soft soil and dredged slurry, and has achieved good reinforcement effects[11−12]. Usually, prefabricated vertical drains or vertical sand wells are set in the soft soil and covered with a sand cushion. Geomembrane is used to seal the site. Once vacuum pressure is applied, negative pressure rapidly spreads into soils along drainage system, forming pressure difference between vertical drains and pore water in soils. This pressure difference causes the pore water to flow toward vertical drain, which means soil consolidation happens, and that can reduce the settlement of foundation after construction. Wei et al.[13] carried out an in-situ vacuum preloading test with prefabricated vertical drains, and after the treatment, the water content of mud was reduced from 65.5% to 45%, and the bearing capacity of foundation was improved. The mud used in the test had been deposited for a long time and has a low water content with a shell layer on the mud surface, which has a certain bearing capacity and can be used for installation of prefabricated vertical drains. However, this is quite different from the actual situation. The construction waste slurry is in a flowing state and has almost no bearing capacity, therefore, prefabricated vertical drains cannot be installed directly. It is also unable to allow a long-term natural sedimentation due to the need of rapid treatment. In order to solve this problem, it is necessary to improve the traditional vacuum preloading method to make it suitable for the practical engineering.

In this study, model test on the treatment of waste slurry with vacuum preloading at bottom combined surcharge preloading at top is carried out. In the model test, pore water pressure, settlement, water content and strength were monitored and measured. Then, performance of the proposed method and feasibility of the soil after treatment used as backfill material for foundation construction were discussed and the process parameters for operation in site are recommended.

2 Material and apparatus of model test

2.1 Materials of model test

The slurry used in the model test was taken from wharf of Xiecun, Hangzhou, China and produced from construction of bored pile. Its physical and chemical properties are shown in Table 1. $NaCO_3$ is usually added to the slurry as a dispersant, therefore, the slurry is generally alkaline with high Na^+ content. The test results show that the Pb^{2+} content is 0.344 mg/L, which is lower than the maximum allowable discharge concentration of class I pollutants (1.0 mg/L) in the integrated wastewater discharge standard (GB8978−1996)[14]. The particle size distribution of the slurry is shown in Fig. 1. The contents of silt (0.005−0.075 mm) and clay (<0.005 mm) are 75.87% and 22.69%, respectively.

Table 1 The physical and chemical properties of waste slurry

Density /(g • cm^{-3})	Water content /%	G_s	LL /%	PL /%	Sand /%	Slit /%	Clay /%
1.12	450	2.72	59.8	23.3	1.44	75.87	22.69

Electrical conductivity /(mS • cm^{-1})	pH	Ca^{2+} /(mg • L^{-1})	Na^+ /(mg • L^{-1})	Pb^{2+} /(mg • L^{-1})
1.456	8.9	114.3	228	0.344

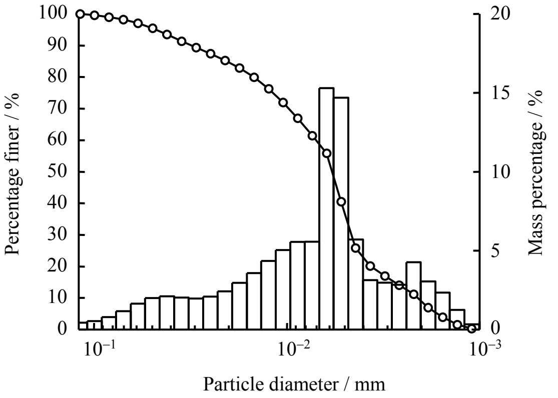


Fig. 1 Particle-size distribution curve of slurry

2.2 Apparatus of model test

In order to investigate the performance of vacuum preloading at bottom combined with surcharge loading on the treatment of slurry, a one-dimensional foundation treatment model test apparatus (Fig.2) independently developed by Zhejiang University was adopted. This apparatus includes model cylinder, vacuum pump, water-air separation tank, measurement system, and others. The model cylinder is composed of upper cylinder, main cylinder and lower cylinder. The cylinders are connected by bolts and O-ring. The height and diameter of cylinder are 2.2 m and 1.0 m, respectively. The inner wall of cylinder is coated with smooth coating to reduce the friction on the test. The upper cylinder is equipped with an air cylinder (JB 320×600-FA) to apply vertical pressure to simulate the surcharge loading. There are two horizontally arranged vacuum filter tubes with a diameter of 76 mm in a cross at the bottom of lower cylinder. A rotary vane vacuum pump is used to provide vacuum pressure. The water-air separation tank is used to stabilize the vacuum pressure and a glass tube is installed to monitor the volume of water discharged. The measurement system, as shown in Fig. 2, includes laser rangefinder, vacuum gauge, piezometer, etc.

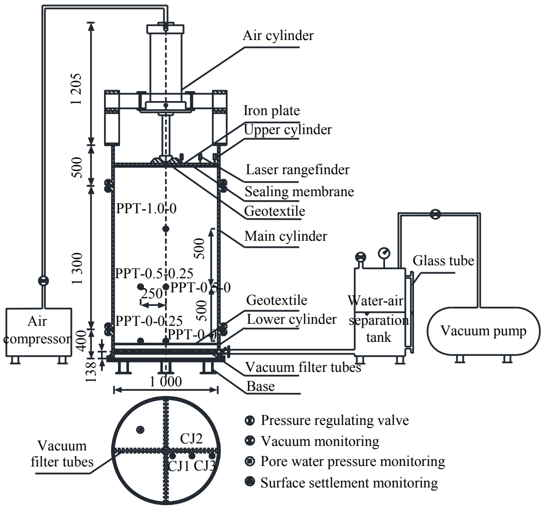


Fig. 2 Set up of model test apparatus (unit: mm)

2.3 Model test scheme

The model tests were divided into 3 stages, i.e., natural sedimentation stage (0−4 d), vacuum preloading (VP) stage (4−18 d), and vacuum combined surcharge preloading (VSP) stage (20−31 d). The whole model test lasted for 31 days. The test procedure is as follows:

(1) 10 cm thick gravel layer, 5 cm thick sand cushion layer and a layer of hot-rolled filament geotextile were laid at the bottom of lower cylinder, and the plastic sealing membrane was closely laid to the inner wall of the cylinder.

(2) Taking the top surface of the geotextile as the datum plane, five osmometers were set at the heights of 0.01, 0.5, 1.0 m, of which three were set on the central axis of cylinder and the other two were set at 0.25 from the central axis. All osmometers were set in the slurry.

(3) The slurry was poured into the model cylinder in 6 layers with each layer having a thickness of 0.3 m. Therefore, the initial total height of slurry is 1.8 m. Samples were taken from each layer for measurement of water content.

(4) The supernatant was drawn out after the end of natural sedimentation stage (i.e., the height of slurry became stable).

(5) Seal the model cylinder and install the laser rangefinder, connect the vacuum pump, water-air separation tank and model cylinder.

(6) Start vacuum preloading, hold the vacuum pressure at 60 kPa and apply the surcharge load as shown in Fig.3. Due to the limited strength of cylinder, the last two stages of surcharge load were not applied.

(7) After the vacuum preloading stage, the shear strength and water content at different layers were measured. After the vacuum combined surcharge preloading stage, the water content and shear strength at different layers were measured again, and samples at different heights were taken for particle size distribution test.

In order to investigate the consolidation characteristics of soil after treatment, samples were taken for consolidation and permeability tests. The consolidation test was carried out with standard odometer, and the load applied by stages was 50, 100, 200, 400 and 800 kPa; the permeability test was conducted with GDS flexible wall permeameter, and the effective stress applied was 25, 50, 100 and 200 kPa, and the corresponding osmotic pressure difference was 4, 6, 8, and 12 kPa, respectively.

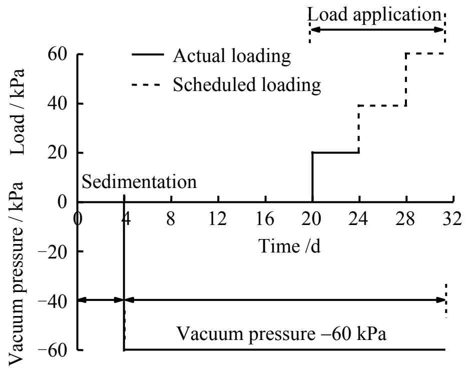


Fig. 3 Vacuum pressure and load application process in the model test

3 Results

3.1 Vacuum pressure

The variation of vacuum pressure in the water-air separation tank versus time is shown in Fig. 4. The results show that the vacuum pressure in the water-air separation tank increased rapidly with time, reaching 60 kPa after about 1 day of vacuum preloading. In the early stage of vacuum preloading (6−12 d), the vacuum pressure decreased obviously twice. The first time occurred at the 6th day which was caused by power outages and the second time appeared at the 8th day because of the leakage between sealing membrane and cylinder inner wall. After fixing the problem of leakage, the vacuum pressure was maintained at about 60 kPa. The reason for the decrease of vacuum pressure in 19−20th day was that the vacuum pump was turned off for measurement of water content and vane shear strength. After the test, the air cylinder was used to apply surcharge load and the vacuum pressure was reapplied.

3.2 Pore water pressure

The variation of pore water pressure measured by the osmometer at different heights with time is shown in Fig.5, and the pore water pressure distribution profile along the height is shown in Fig. 6. The initial pore water pressure in the sedimentation stage is slightly higher than the hydrostatic pressure (Fig. 6(c)), because the slurry is in the unconsolidated state, which is similar to the results of municipal sludge model test conducted by Zhan et al.[15]. The initial water content of slurry used in this model test was 450%, sedimentation and self-weight consolidation occurred during the natural sedimentation stage. Therefore, the excess pore water pressure at different depths gradually dissipated with the progress of sedimentation and self-weight consolidation. After 4 days of natural sedimentation, the settlement of mud was stable, and the pore water pressure was basically equal to the hydrostatic pressure.

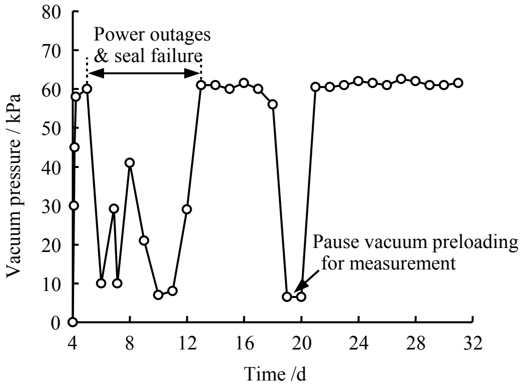
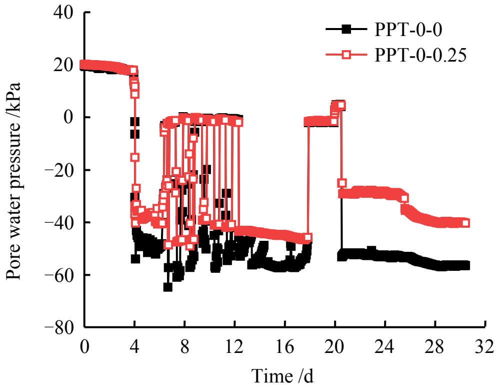
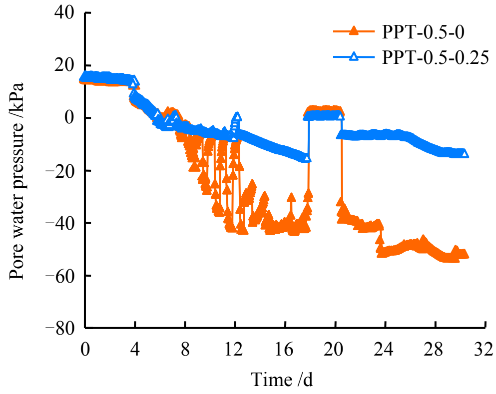


Fig. 4 Variation of vacuum with time in the water-air separation tank

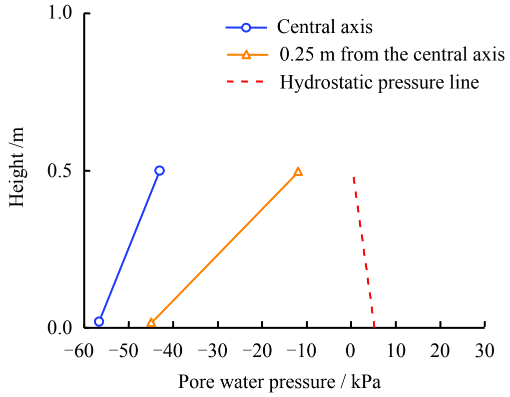


(a) 0 m

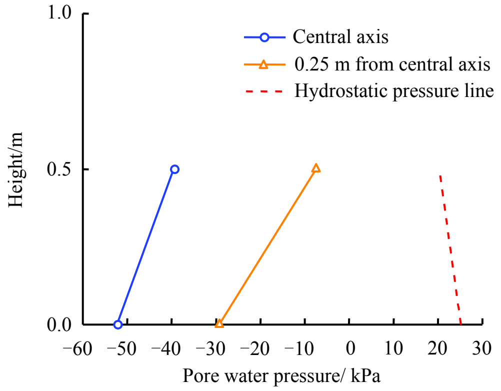


(b) 0.5 m

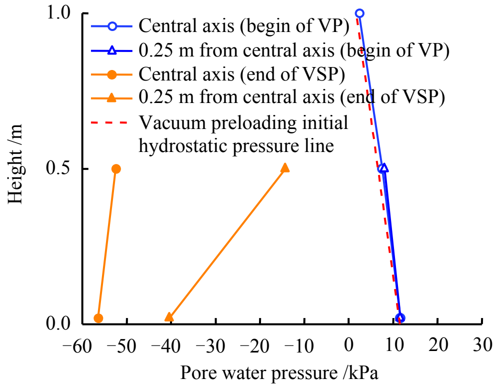
Fig. 5 Variation of pore pressure with time at different heights



(a) Vacuum preloading（15 d）



(b) Combined vacuum and surcharge preloading（22 d）



(c) Begin of the vacuum preloading (VP) (4 d) and end of combined vacuum and surcharge preloading (VSP) (31 d)

Fig. 6 Pore pressure profiles at different locations and times

In the early stage of vacuum preloading stage (4−18 d), the pore water pressure fluctuated at heights 0 and 0.5 from the bottom (Fig. 5). The reason is the power outages and sealing failure described in section 3.1, which leads to the vacuum pressure decrease. In the vacuum preloading stage, the vacuum pressure was transferred from the bottom to sand cushion and then to the slurry layer. Under the effect of pressure difference, the pore water in the mud layer is gradually discharged, and the vacuum pressure was gradually transferred upwards, and finally reached the sealing membrane. During the drainage consolidation process, the pore water pressure u in the mud gradually decreased. Figure 6 shows the change of pore water pressure along the height at different times of vacuum preloading stage. It can be seen that the pore water pressure at 0.01 m from the bottom is close to the magnitude of vacuum pressure applied (i.e., −60 kPa), and it is about −40 kPa at 0.5 m from the bottom, indicating a significant loss of vacuum pressure along the height. The pore water pressure at 0.25 from the central axis was significantly higher that that on the central axis. For example, the pore water pressure at 0.01 m from the bottom is −45 kPa and it is about −10 kPa at 0.5 m from the bottom. It indicates that there is a hydraulic gradient along the radial direction. The pore water in the mud seeps downward and toward to the center, not completely one-dimensional downward seepage. According to Terzaghi's effective stress principle, when the total stress remains constant, the decrease of pore water pressure u leads to the increase of effective stress, which causes consolidation and settlement of soil.

In the vacuum combined surcharge preloading stage (20−31 d), the application of load causes the increase of total stress, thus the effective stress σ' and settlement further increase along with the progress of consolidation. When the first stage load was applied at 20th day, the pore pressure at the bottom dissipated quickly, but the subsequent load was not applied due to insufficient strength of cylinder. Thus, the pore water pressure did not change significantly. Figure 6(b) shows the change of the pore pressure along the height at 22nd day. It can be seen that the pore pressure at a height of 0.5 m from the central axis is significantly lower than before, which is closer to that at the bottom. The pore water pressure at 0.25 m from the central axis increases and is still significantly higher than that on the central axis, indicating that the hydraulic gradient along the radial direction still exists.

3.3 Water discharged amount and settlement

The variation of settlement and volume of water discharged with time is shown in Fig. 7. The total volume of water discharged during the model test is 955 L, of which the supernatant drained out during the natural sedimentation stage is about 440 L, and its solid content is 0.3%. The volume of water discharged in vacuum preloading stage and vacuum combined surcharge preloading stage is 515 L with a solid content of 0.07%.

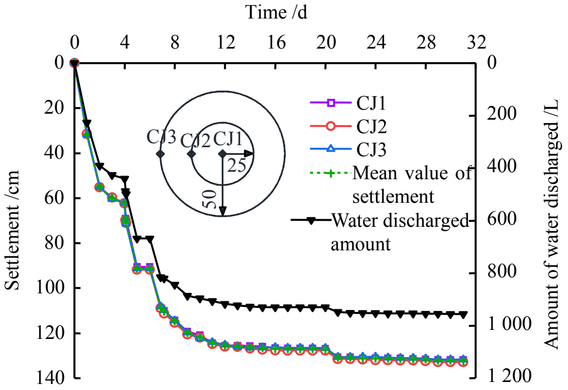


Fig. 7 Variations of amount of discharged water and settlement with time

It can be seen from Fig.7 that the settlements measured by settlement plate at three different positions are very close. After 31 days of model test, the total settlement is 132.1 cm and the final height of mud is 47.9 cm, and the corresponding volume reduction ratio (the ratio of settlement to initial height) is 73.4%. The settlement in the natural sedimentation stage is about 62.2 cm. In the early stage of natural sedimentation, the settlement value of slurry basically increases linearly, with a settlement rate of 22.9 mm/h. With the progress of self-weight consolidation, the settlement rate is reduced. In the early stage of vacuum preloading, the settlement rate can reach 7 mm/h, and the 5th−6th day settlement curve has a plateau period because of the power outage. The settlement rate gradually slows down in the later stage of vacuum preloading, and finally tends to be stable (about 2−3 mm/d), and the settlement in the vacuum preloading stage is 65.0 cm. After the first level of load is applied, the settlement increases by 5 cm. It can be found that the settlement on the surface is relatively uniform, with a maximum settlement difference of 1.9 cm appears in the early stage of vacuum preloading.

Ignoring the influence of evaporation, the average void ratio is calculated according to the average settlement and volume of water discharged. The variation of average void ratio with time is shown in Fig. 8. In the early stage of natural sedimentation stage and the early of vacuum preloading stage, the average void ratio decreases rapidly. As the progress of consolidation, the effective stress increases, the permeability and compressibility of mud decrease, and the average void ratio decreases slowly at the end of the test. After 31 days treatment, the average void ratio of slurry decreases from 12.24 to 2.52.

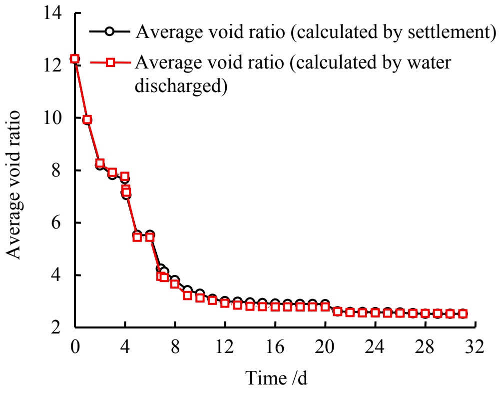


Fig. 8 Variation of average void ratio with time

3.4 Water content and undrained strength

After vacuum preloading, samples were taken every 5 cm along the height of mud to measure the water content, as shown in Fig.9. The water content decreased from 450% (i.e., the initial water content) to 282% (calculated based on the volume of the supernatant) after the natural sedimentation stage. After vacuum preloading, the water content was reduced to 100%−116% with water content at upper part slightly higher than that at lower part. That is because the lower part is closer to the drainage surface, the drainage path is relatively shorter and the water is more easily discharged than that at upper part. Moreover, there was losses of vacuum pressure during the upward transfer. The water content at the bottom of model cylinder was 85.8% because this position was close to the drainage boundary, where the hydraulic gradient was the largest and the effect of vacuum preloading was the best. In the stage of vacuum combined surcharge preloading, the water content of mud was further reduced to about 95%−105%. Similarly, the water content of the mud at the bottom of model cylinder (84.9%) was lower than other positions.

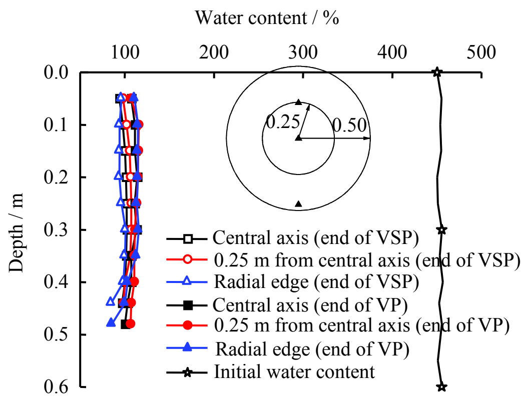


Fig. 9 Variation of water content with depth at different locations

At the end of vacuum preloading stage and vacuum combined surcharge preloading stage, three areas of the cylinder center, 0.25 m from the central axis and close to the cylinder wall were selected for the measurement of vane shear strength. Three mud samples were taken from each area for vane shear strength test, as shown in Fig.10, and the average value of these three tests was used as the vane shear strength of the corresponding area. The results show that the vane shear strength on the central axis is the largest and that close to cylinder wall is the smallest. After the vacuum preloading stage, the vane shear strength of mud is about 6.0−8.9 kPa. The shear strength of the bottom of mud is larger than that of the middle and surface, and the variation of mud strength at different positions corresponds to the test results of water content. After the vacuum combined surcharge preloading stage, the strength of mud further increased to 9.8−13.4 kPa. The strength increase at the mud surface is the most obvious because of the evaporation before the application of load (19th−20th day). The evaporation can cause water content of the surface to decrease.

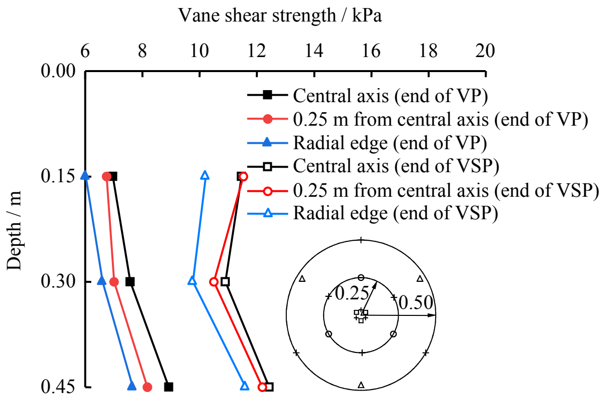


Fig. 10 Shear strength distribution at different depths after vacuum preloading and upper surcharge loading

3.5 Influence of sedimentation on particle size distribution

After the model test, soil samples at different depths at the center of the model cylinder were taken to measure the particle size distribution. A laser particle size analyzer was use to analyze the variation of particle size distribution with depth. Figure 11 shows that the particle distribution curve moves to the right as the depth increases, and the d_{90} gradually increases, indicating that the proportion of large particles in the mud at the bottom is larger than that at the top. The Stokes sedimentation velocity formula shows that the particle sedimentation velocity is proportional to the square of the particle diameter. In the natural sedimentation stage, particles with large diameters settle first, and particles with small diameters settle subsequently. However, the sedimentation velocity of particles does not completely conform to the Stokes sedimentation velocity formula considering the influence of additives. Therefore, there will be particles with large diameters on the upper part. There was no obvious clogging phenomenon in this test[16]. The reason is that the particles with large dimeter form a structure on the surface of the geotextile, which constitutes a drainage channel during the natural

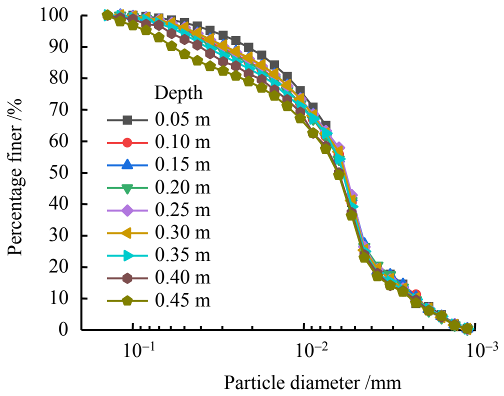


Fig. 11 Particle size distribution at different depths along the central axis

sedimentation stage. Therefore, the pore water in the mud can be smoothly discharged in the subsequent vacuum preloading stage. It is evident that the gravity differentiation of natural sedimentation is beneficial to alleviate the clogging problem of vacuum preloading.

3.6 Consolidation characteristics

The basic parameters and compressive properties of specimen in the consolidation tests are provided in Table 2. The compression index of the mud after vacuum preloading is 1.04–1.54. The difference in the compression index may be caused by the difference in water content and particle size distribution at different depths. Figure 12 presents the relationship between void ratio and effective stress obtained from consolidation tests of soil samples at different depths. Figure 13 shows the nonlinear relationship between permeability coefficient and effective stress of soil sample. Compared with the test data of Xiaoshan soft soil[17], the compressibility of mud after vacuum preloading is similar and it has the characteristics of high compressibility. When the effective consolidation stress is 100 kPa, the mud permeability coefficient is 1.48×10^{-8}–1.80×10^{-8} m/s, which is larger than that of Xiaoshan soft soil. It should be noted that the constitutive relationship (i.e., compressibility and hydraulic conductivity) of mud treated is highly nonlinear and this should be considered in the analysis of foundation consolidation.

Table 2 Basic parameters and compressibility indexes of the specimens in the consolidation tests

No.	Depth /cm	Water content /%	Void ratio	Density /(g • cm^{-3})	Compression coefficient $a_{1\text{-}2}$ /MPa^{-1}	Compre -ssion index
CS-1	0–5	90.82	2.47	1.458	1.20	1.04
CS-2	5–10	99.52	2.71	1.418	1.42	1.54
CS-3	10–15	100.52	2.73	1.429	1.89	1.28
CS-4	15–20	97.50	2.65	1.455	1.65	1.16
CS-5	20–25	99.52	2.71	1.409	1.26	1.27
CS-6	25–30	98.80	2.69	1.435	1.11	1.48
CS-7	30–35	95.80	2.61	1.474	0.91	1.38
CS-8	35–40	88.47	2.41	1.462	0.90	1.13

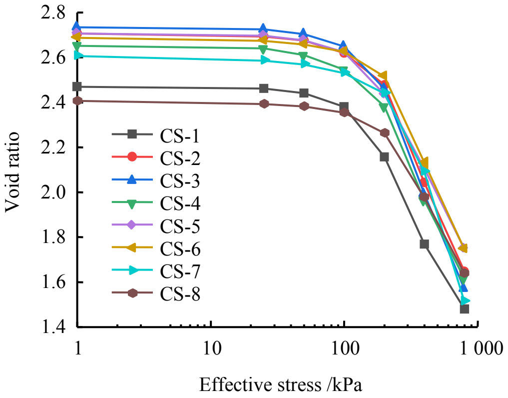


Fig. 12 Relationship between void ratio and effective stress

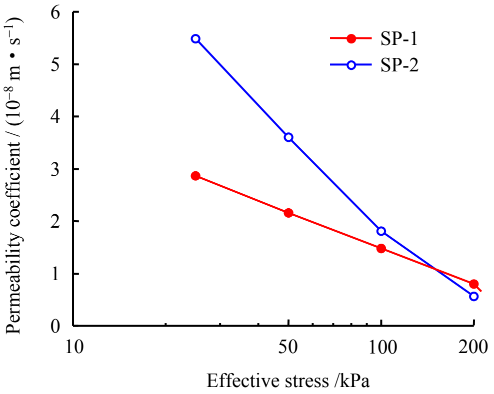


Fig. 13 Relationship between coefficient of permeability and effective stress

4 Discussion and analysis

There are a large number of abandoned open pit in China, and the safety risks of these mines cannot be ignored, and they need to be backfilled and repaired. For the mine pits with large depth, it is difficult to ensure good improvement effect if the pits are fully backfilled with slurry at one time. It is necessary to backfill in layers and the mud needs to be treated to make sure it has enough bearing capacity to bear the upper load. According to the results of model test, the bottom vacuum combined surcharge preloading method can reduce the volume of slurry and increase the mud strength. The following procedures can be referred to in the field backfill construction: 1) leveling the bottom of mine pit; 2) installing vacuum filter pipes; 3) placing sand cushion to cover the vacuum filter pipe; 4) connecting the vacuum filter pipe with the drainage pipe, and connecting the water collector and vacuum pump; 5) laying a layer of geotextile (the effective aperture of the geotextile is determined according to the particle size distribution of slurry); 6) pouring a certain height of slurry into the mine pit; 7) sealing the site with geomembrane; 8) starting the vacuum preloading after the natural sedimentation; 9) measuring the undrained strength of mud to determine the time of next layer of backfill and the bearing capacity of foundation can be calculated using the undrained strength. The process parameters are very important for this technology. Among them, the initial height of slurry layer and the treatment time are of great significance to the performance of this method.

According to the results of model test and based on Gibson's large strain consolidation theory[18], the method proposed by Gong et al. [19] was used to analyze the process of self-weight and vacuum preloading consolidation of backfill slurry with considering the effect of self-weight, nonlinear constitutive relationships (i.e., compressibility and hydraulic conductivity). It is assumed that the self-weight consolidation has single drainage, and the vacuum preloading consolidation has double drainage. The constitutive relationships are as follows:

$$e = e_0 - C_c \lg\left(\frac{\sigma'}{\sigma'_0}\right) \tag{1}$$

$$k = k_0 (10)^{(e-e_0)/C_k} \tag{2}$$

where σ'_0 and k_0 are the initial effective stress and initial permeability coefficient of slurry at the top boundary, and are related to the initial void ratio e_0. The general range of σ'_0 is 0−1.0 kPa; C_c and C_k are compression index and permeability index, respectively, and the general range of C_c/C_k is 0.5−2.0 [20].

In the back analysis, e_0 of self-weight consolidation stage was taken from the measured results, and k_0 was taken according to the range reported in the literature [21]. C_c/C_k was assumed 1.0. The parameters obtained from back analysis of self-weight consolidation are shown in Table 3. Substituting the void ratio at the end of self-weight consolidation into Eqs. (1) and (2), the σ'_0 and k_0 for the vacuum preloading stage can be obtained. The permeability coefficient of the top boundary at the end of vacuum preloading can be obtained from the fitting relationship between permeability coefficient and effective stress (Fig. 13), and substituting it into Eq. (2) to obtain the C_k, and the parameters obtained from the back analysis of settlement data for vacuum preloading stage are shown Table 3. Figure 14 shows the comparison between the back analysis and the measured data. It can be seen that in the stage of self-weight consolidation and later stage of vacuum preloading, the finite difference solution is in good agreement with the measured data. In the early stage of vacuum preloading, the difference between the simulation and test data is relatively large and the maximum error is 15%, because the change of vacuum pressure applied in the model test is not considered in the simulation. The results show that the accuracy of finite difference method can meet the requirements of practical engineering.

Using the abovementioned finite difference method, the self-weight and vacuum preloading consolidation processes of slurry with different initial heights were analyzed. In the simulation, the consolidation times for self-weight and vacuum preloading are 4 days and 50 days, respectively. The predicted settlement curve is shown in Fig. 15. It can be seen that, for the cases of initial height larger than 1.8 m, self-weight consolidation has not been completed after 4 days. With the increase of initial height, the sedimentation rate and final settlement increase, but the time required for consolidation increases significantly. Figure 16 shows the influence of initial height on the volume reduction ratio and treatment time. It can be seen from the figure that as the initial height of slurry increases, the times required to reach 90% and 95% average consolidation degree increase significantly. When the initial height is larger than 3.6 m, the slope of treatment time increases obviously. When the initial height of slurry is 7.2 m, it takes 47.4 days to reach 95% average consolidation degree. As the initial height of slurry increases, the volume reduction ratio decreases under the same treatment time. It should be noted that the parameters used in the analysis are taken from the back analysis. For the case of initial height over 1.8 m, the settlement obtained from the finite difference analysis is larger than that of measured, because the consolidation parameters are related to the stress state of mud. According to the analysis results, when the slurry is treated with bottom vacuum preloading method, the initial slurry layer should not be too large with consideration of the treatment efficiency. The recommended initial slurry thickness is about 3.6−5.4 m, and the time required to reach 90% average consolidation degree is 10−20 days. The initial height of slurry can also be adjusted appropriately according to the practical engineering.

Table 3 Parameters from back analysis

Parameters	Compression index C_c	Permeability index C_k	Initial effective stress σ_0/kPa	Initial permeability coefficient k_0/(m • s^{-1})
Self-weight consolidation	5.450	5.450	0.132	3.2×10−5
Vacuum preloading	2.854	2.178	0.910	4.5×10−6

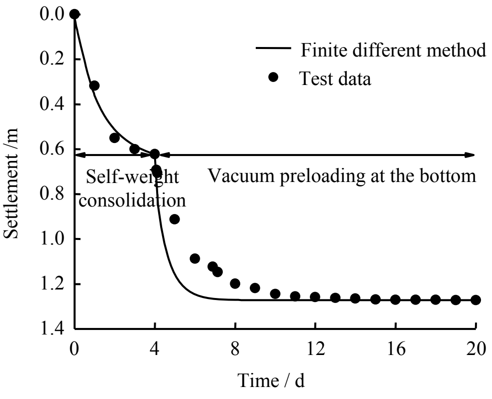


Fig. 14 Settlement curve of self-weight consolidation and vacuum preloading stages

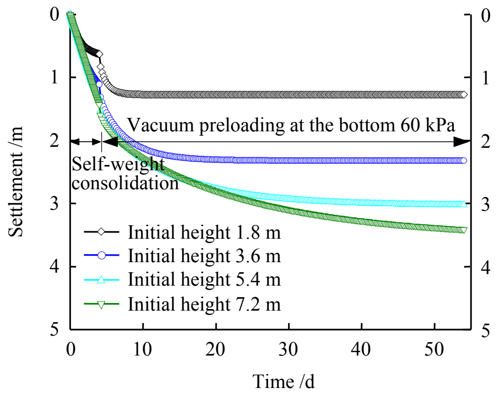


Fig. 15 Settlement curves of self-weight consolidation and vacuum preloading for slurry with different initial thicknesses

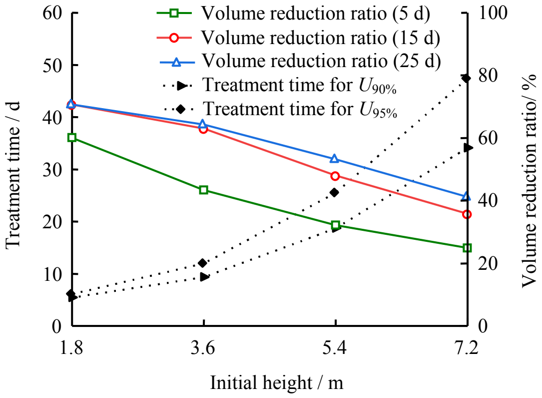


Fig. 16 Effect of initial height on volume reduction ratio and treatment time

5 Conclusions

(1) In the natural sedimentation stage, the slurry changes from sedimentation to self-weight consolidation under gravity. With the development of self-weight consolidation, the pore water pressure gradually decreases from a high value (larger than the hydrostatic pressure) to the hydrostatic pressure. Under the effect of gravity differentiation, coarser particles are deposited at the bottom, which can help alleviate the clogging problem of vacuum preloading.

(2) In the vacuum preloading stage, the pore pressure at the bottom of slurry decreases rapidly to negative. With the vacuum pressure transferring upward, the pore water in the slurry seeps downward and toward the central axis, not completely one-dimensional downward seepage. After the vacuum preloading stage, the settlement of slurry reaches 36.1% of the initial height, and the undrained strength increases from 0 to 6.0−8.9 kPa.

(3) In the stage of vacuum combined surcharge preloading, the vacuum pressure in the slurry is almost constant. Under the surcharge loading, the settlement is small, but the shear strength increases by 3.2−4.8 kPa.

(4) The installation of drainage board on the slurry surface is not required in the proposed method, which is suitable for the treatment of slurry with low strength. This method can significantly reduce the water content and improve the strength of slurry. After treatment by this method, water content can be reduced from 450 % (i.e., initial water content) to 95%−105%, the volume can be reduced by 73.4% and the undrained strength can be increased from zero to 9.8−13.4 kPa. The compressibility of treated mud is similar to that of Xiaoshan soft soil, but its permeability is better than that of Xiaoshan soft soil.

(5) The results of numerical simulation show that the time required for slurry to reach 90 % average consolidation degree increases gradually with the increase of the initial height. When the initial height of slurry is larger than 5 m, the treatment time increases significantly and the volume reduction ratio under the same consolidation time decreases significantly. When the vacuum preloading at the bottom is carried out in the field, the recommended single layer height of slurry for treatment is about 3.6−5.4 m.

Bottom vacuum preloading method is a simple and efficient method for slurry treatment, which can meet the requirements of volume reduction and strength increase, and provides suitable conditions for subsequent construction. In order to meet the requirements of subsequent foundation construction, the mud strength can be further improved by other methods. In this paper, only one group of model test is carried out, but different muds have an influence on the performance of this method. Therefore, it is suggested that more groups of model test should be carried out in the future, and field test should be conducted to further optimize this method.

References

[1] WU Ya-jun, LU Yi-tian, NIU Kun, et al. Experimental study on solid-liquid separation of construction waste slurry by additive agent-combined vacuum preloading[J]. Chinese Journal of Geotechnical Engineering, 2016, 38(8): 1365−1373.

[2] ZHU H, SUN H, WANG F, et al. Preparation of chitosan-based flocculant for high density waste drilling mud solid-liquid separation[J]. Journal of Applied Polymer Science, 2012, 125(4): 2646−2651.

[3] FANG Kai, ZHANG Zhong-miao, LIU Xing-wang, et al. Pollution of construction waste slurry and prevention measures[J]. Chinese Journal of Geotechnical Engineering, 2011, 33(Suppl.2): 238−241.

[4] Shanghai Institute for Design & Research on Environmental Engineering Co., Ltd. CJJ/T134－2019 Technical standard for construction and demolition waste treatment[S]. Beijing: China Architecture & Building

Press, 2019.

[5] WAN Yu-gang, YU Xue-hai. Treating technology of waste slurry from pile foundation engineering[J]. Environmental Engineering, 1999, 17(1): 14−15.

[6] ZHANG Zhong-miao, FANG Kai, WANG Zhi-jie, et al. Zero discharge treatment technology for slurry and engineering properties of separated soil[J]. Chinese Journal of Geotechnical Engineering, 2011, 33(9): 1456−1461.

[7] ZHANG Qin-xi, TAO Tao, WANG Xiao-jie, et al. Experimental study on treatment of waste slurry in cast-in-situ bored pile[J]. Journal of Hydraulic Engineering, 2015, 46(Suppl. 1): 40−45.

[8] LIANG Zhi-shui, YANG Cai-qian, GAO Hai-ying, et al. Experimental study on rapid separation between water and slurry from construction engineering[J]. Journal of Southeast University (Natural Science Edition), 2016, 46(2): 427−433.

[9] GENG Peng-fei, SUN Lin-zhu. Experimental study on construction waste slurry dehydration composite flocculants[J]. Journal of Wuhan University of Technology, 2014, 36(5): 118−122.

[10] LOU Chun-hui, ZHANG Zhong-miao, FANG Kai. Theoretical and experimental analysis on the pressure filtration technology in slurries treatment[J]. Journal of Civil, Architectural & Environmental Engineering, 2012, 34(6): 57−61.

[11] QIN Yu-sheng LI Zhi-yi, CAO Da-zheng, et al. Consolidation of soft soil foundation by vacuum-pumping in low level position[J]. Geoscience, 1999, 13(4): 471−476.

[12] YANG Ai-wu, PAN Ya-xuan, CAO Yu, et al. Laboratory experiment and numerical simulation of soft dredger fill with low vacuum pre-compression[J]. Rock and Soil Mechanics, 2019, 40(2): 539−548.

[13] WEI Yan-bing, FAN Ming-qiao, LIN Sheng-fa, et al. Experimental study on construction waste slurry treatment by vacuum preloading[J]. Journal of Zhengzhou University (Engineering Science), 2016, 37(1): 65−69.

[14] The State Bureau of Quality and Technical Supervision. GB8978－1996 Integrated wastewater discharge standard[S]. Beijing: Standards Press of China, 1996.

[15] ZHAN Xin-jie, LIN Wei-an, ZHAN Liang-tong, et al. Model test study of vacuum preloading on municipal sludge[J]. Rock and Soil Mechanics, 2013, 34(Suppl. 1): 88−96.

[16] WU Si-lin, ZHU Wei, MIN Fan-lu, et al. Clogging mechanism and effect of cake permeability in soil-water separation using vacuum filtration[J]. Chinese Journal of Geotechnical Engineering, 2017, 39(8): 1530−1537.

[17] QI Tian. Theoretical and experimental studies on one-dimensional nonlinear consolidation of soil[D]. Hangzhou: Zhejiang University, 2008.

[18] GIBSON R E, ENGLAND G L, HUSSEY M J L. The theory of one-dimensional soil consolidation of saturated clays[J]. Geotechnique, 1967, 17(3): 261−273.

[19] GONG Wen-hui, ZHAO Xu-dong, QIU Jin-wei, et al. Nonlinear analysis of one-dimensional consolidation of saturated cohesive soil including self-weight effects and large strain[J]. Rock and Soil Mechanics, 2019, 40(6): 2099−2107, 2118.

[20] BERRY P L, WILKINSON W B. The radial consolidation of clay soils[J]. Geotechnique, 1969, 19(2): 253−284.

[21] PU He-fu, SONG Ding-bao, ZHENG Jun-jie, et al. Model for large-strain nonlinear self-weight consolidation of saturated soft soil[J]. Rock and Soil Mechanics, 2019, 40(5): 1683−1692, 1703.