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Laboratory study for effects of vacuum preloading on physical and mechanical properties of soft clayey soils

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Abstract: A new triaxial apparatus was designed and manufactured. It is able to apply surcharge and combined vacuum-surcharge pressures on soil samples, and allows for monitoring of excess pore-water pressure, axial strain or settlement, and volumetric strain during the process of consolidation. Tests were performed using the apparatus on undisturbed soft clayey soil samples, which were collected from Wenzhou, Zhejiang Province, China, at average natural water content 72.5%. The consolidation behavior of the clay has no rigorous difference, whether it is consolidated under the vacuum, surcharge, or combined vacuum-surcharge preloading. The study shows that some physical properties of the soft clayey soils are changed and mechanical properties are improved to support excessive loads transferred to the soil foundation due to construction.

Key words: soft soil; vacuum preloading; consolidation; permeability; strength

Vacuum preloading is a technique used to improve the strength of soft clayey soils. The concept of using vacuum preloading to improve the strength of soils was first introduced in Ref. [1]. Vacuum preloading has been applied extensively in land reclamation projects with or without concurrent application of surcharge preloading[2]. The effectiveness of vacuum preloading consolidation in eliminating excessive settlement under static and dynamic loading on airport runways was demonstrated in Ref. [3]. A successful case study whereby vacuum preloading was used to improve the soil strength at an oil storage station was presented in Refs. [4 - 6]; Ref. [7] postulated the effectiveness of using vacuum preloading in soft soil improvement. In vacuum preloading applications, the surface of the ground is sealed with a membrane, and through a vacuum pump a negative pore-water pressure is generated in the sand cushion beneath the membrane and in the installed vertical drains in the soil. The change in the pore-water pressure produced from applied vacuum preloading induces discharge of the pore-water and consolidation thereby increasing the shear strength of the soil and improving the mechanical properties of soil foundation. Permeability of the soil governs such important mechanical properties as consolidation under loading[8]. Permeability k of intact soft clays at their in-situ void ratio is a function not only of void ratio and grain size but also of the plasticity and fabric of the clay[9]. A triaxial consolidation test has been conducted to describe the behavior of clay subjected to consolidation pressure. The deformation due to pulling of water from within the soil matrix occurs in both vertical and horizontal directions. In the case of a transient flow, water flow is caused by a gradual change in effective stresses that leads to a continuous rearrangement of solid particles, thus effecting a volume change.

If the soil under vacuum consolidation or combined vacuum-surcharge consolidation demonstrated the same behavior as that of a surcharge pressure of the same value, the design of vacuum consolidation systems can be based on the conventional test results. However, to do so, one must first examine the consolidation behavior of soil under both vacuum and vacuum-surcharge preloading.

1 Test Apparatus

The following aspects are considered for the design of triaxial test apparatus: ability to apply vacuum, surcharge, and combined vacuum-surcharge pressure on soil sample at desirable value. The apparatus should be able to measure the pore-water pressure, axial strain, and volume of expelled pore-water during the test; monitoring is very important to understand the mechanism of the vacuum preloading process. The ap-

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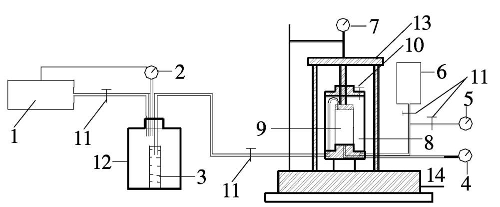
paratus is shown in Fig. 1. It is made of stainless steel. A confining pressure cell over the loading frame with a vertical surcharge load can be applied through a hanger on the soil sample. A vacuum pressure pipe, able to support the maximum vacuum pressure over 80 kPa, is used. A vacuum regulator is used to adjust the required vacuum pressure and kept stable during testing. A regulator is plugged into a rubber plug fixed on an airtight transparent glass bottle. A measured tube is fixed inside the bottle (accuracy of 0. 2 cm^3) to monitor the expelled water from the sample through a vacuum pipe controlled by a valve, and in turn is connected to the upper part of the soil sample. A second pressure transducer is connected to the base of the vacuum cell to measure the pore-water pressure at the bottom of the soil sample. A dial gauge (accuracy of 10 μm) is mounted on a loading piston of the vacuum cell to record the settlement. A thermometer is used to measure the room temperature during the test period. In the vacuum cell, there are two drainage pipes; one is used to apply the vacuum pressure and the other to measure the pore-water pressure. The cell can accommodate a soil sample 200 mm in height and 100 mm in diameter.



1—Vacuum pump (p_{max} = 100 kPa); 2—Dial gauge and regulator of the vacuum (p_{max} = 100 kPa); 3—Measured tube to collect the pore-water of soil sample; 4—Transducer to measure the pore-water pressure of soil sample; 5—Dial gauge to measure the surrounding pressure; 6—Gas cylinder; 7—Dial gauge to measure settlement; 8—Vacuum cell; 9—Soil sample; 10—In/outlet of water for generating surrounding pressure; 11—Valves; 12—Airtight vacuum bottle; 13—Stainless steel frame; 14—Stainless steel base

Fig. 1 Description of the apparatus

2 Experiment

Three series of tests are conducted to examine and evaluate the soil behavior during consolidation. Undisturbed soil samples are used in tests after saturation. Physical and mechanical properties of the soft soil of Wenzhou, Zhejiang Province, China appear very soft, with high water content (72. 5%), liquid limit (67%), plastic limit (28%), plasticity index (39%), specific gravity (2. 72), and void ratio (2. 06). The soil can be classified as clay with high plasticity and other properties as shown in Fig. 2. From hydrometer test, it can be found that the soil sample used in this study mainly consists of clay (67. 5%), silt (29%), and sand (4%). The grain size distribution is shown in Fig. 3.

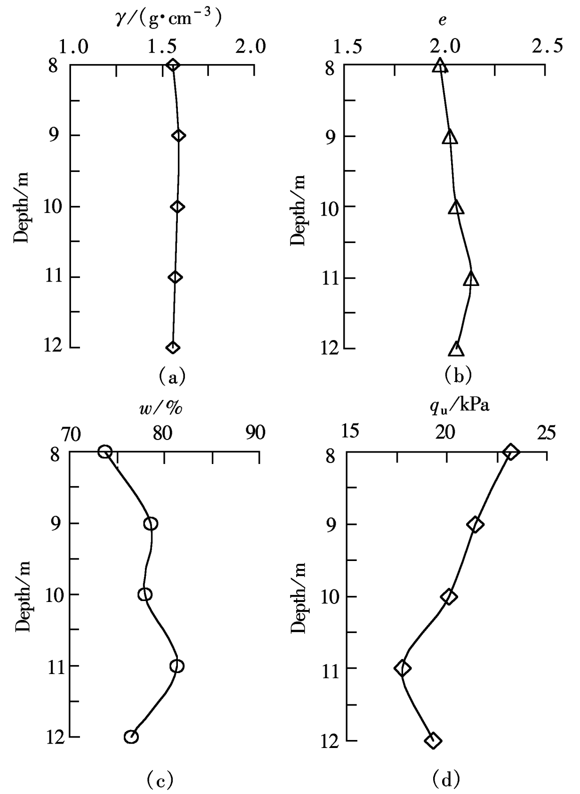


Fig. 2 Physical and mechanical properties of the soft soil. (a) Density; (b) Void ratio; (c) Water content; (d) Unconfined compressive strength

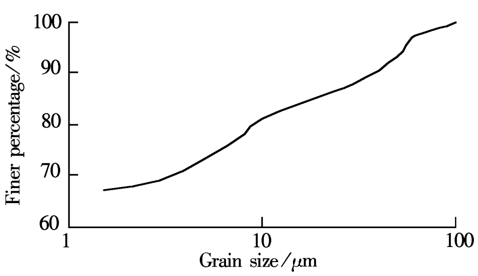


Fig. 3 Grain size distribution of the soft soil

2. 1 Sampling

The quality of sampling is a key element in any investigation of the behavior of natural clays. It has been recognized in the past that common, small diameter piston sampling techniques often adversely affect the structure and the behavior of soft clay specimens. New sampling methods have been developed to avoid this problem, and are used in the present research. The clays were sampled by means of a 100 mm diameter thin tube sampler with overcoring device developed for the specific purpose of undisturbed sampling of soft sensitive clays.

2.2 Sample preparation

The sample is carefully trimmed to 200 mm height and placed in a vacuum-air chamber system to make it saturated before test[10]. Then the soil sample is filled inside an airtight membrane between two water-saturated porous discs, a filter paper is placed between the soil sample and the porous disc to prevent clogging of the porous disc with fine materials during testing. A brush is used to remove the bubbles or any noticeable air voids, that form between the membrane and the wall of the sample. However, it is quite possible that soil samples prepared by this method may not be fully saturated at the beginning of testing.

2.3 Testing methods

The pipes at the base of the cell are examined and filled with water, and the pressure transducers are calibrated following the standard triaxial test. The cell is filled with water, and tied very well. Then anisotropic consolidation is applied, effective vertical stress is $\sigma_3' = \gamma' h$ and $k_o = \dfrac{\sigma_3'}{\sigma_1'}$, where k_o is the coefficient of earth pressure at rest for normally consolidated soil ($k_o \approx 1 - \sin\phi$[11]), σ_3' is the effective surrounding stress, γ' is the submerged unit weight of the soil sample, h is the depth of the soil sample (9 to 11 m), and ϕ is the angle of shear resistance. The piston is lubricated and pushed carefully into the upper part of the cell. After adjusting the vacuum pressure to the desired value, the valve of vacuum pipe is opened. The test is continued until the primary consolidation is completed. This is normally determined through the plots of excess pore-water pressure and axial strain versus elapsed time where the end of primary consolidation (EOP) is at the lowest value of excess pore-water pressure. During all of the tests discussed in this paper, the room temperature is monitored and fluctuations of less than 1 ℃ are recorded.

3 Results and Discussions

With vacuum and surcharge combined, a three-dimensional consolidation is modeled laboratorially to study the vacuum preloading effects on soft clayey soils in terms of the excess pore-water pressure, axial strain and volumetric strain. The soil samples are subjected to vacuum (80 kPa), surcharge (80 kPa), and combined vacuum-surcharge pressures (40 kPa + 40 kPa). Pore-water pressure, settlement (axial strain), and volumetric strain have been monitored. The results of the three series of tests are presented and discussed in the following sections.

3.1 Excess pore-water pressure and effective stress

Excess pore-water pressures generated due to applied pressures that have been monitored. Fig. 4 presents the relationship between the excess pore-water pressure and elapsed time. It is shown that surcharge preloading generates a positive pore-water pressure, which falls down to zero with time, and that vacuum preloading generates negative pore-water pressure that approaches the applied pressure with time. In case of combined vacuum-surcharge preloading, the consolidation starts with an excess pore-water pressure equal to the surcharge pressure and ends with a negative pore-water pressure equal to the applied vacuum pressure. As shown in Fig. 4, the excess pore-water pressures in the three cases of loading converge to the applied vacuum pressure with the end of test, indicating that vacuum preloading is equally effective under various surcharge pressures.

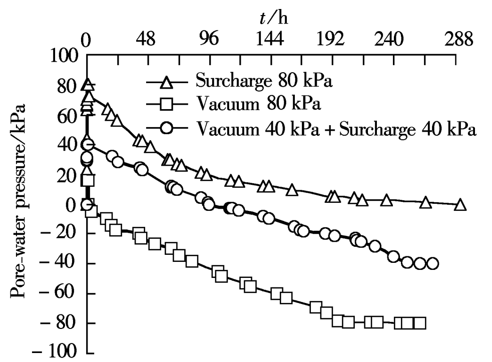


Fig. 4 Excess pore-water pressure vs. time

3.2 Settlement and volumetric strain

Soil settlement (axial strain) and volumetric strain with elapsed time are shown in Fig. 5 and Fig. 6, respectively. The combination of vacuum and surcharge preloading is more advantageous than surcharge or vacuum individually. The settlement induced by the surcharge is more than that induced by the vacuum case (see Fig. 5), but the volumetric strain induced by surcharge loading is less than that induced

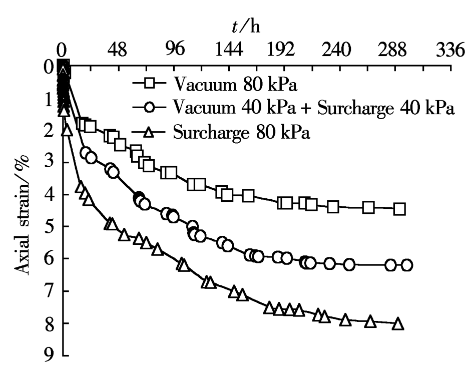


Fig. 5 Axial strain vs. time

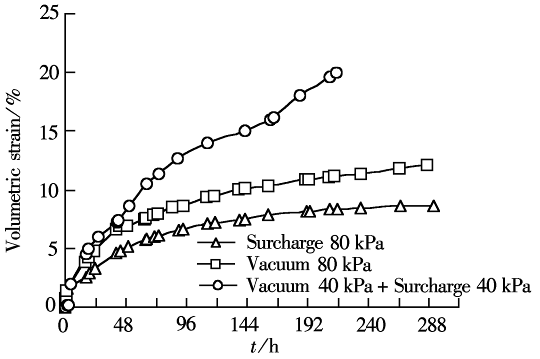


Fig. 6 Volumetric strain vs. time

by vacuum preloading (see Fig. 6). This discrepancy may be due to the fact that the vacuum preloading is able to generate negative pore-water pressure and gently accelerate the soil sample consolidation by vertical and radial flow of the pore-water, but the surcharge in the point of the microstructure of the soil may cause deformation faster than draining the pore-water out to the drainage paths; consequently, the drainage paths of the soils in vertical and radial directions may be destroyed or coagulated. This also means that under combination, expelling the pore-water will be more than each one individually. Because in the case of combined vacuum-surcharge preloading, the surcharge can assist the consolidation with draining the pore-water to the drainage paths and the vacuum can assist consolidation by pulling the pore-water through the same drainage paths. Thus the drai-nage paths may not destroy or coagulate during consolidation.

The results of tests indicate that a vacuum can be effectively used in combination with a surcharge load to consolidate normally consolidated soils. A vacuum is recommended when the soil is very soft to improve it without shear failure.

The effects of the vacuum, surcharge, and combined vacuum-surcharge preloading on the physical and mechanical properties of soft clayey soils are presented in Tab. 1 and Tab. 2. The results of the tests show that the changes of the physical properties and improvements of the mechanical properties due to using vacuum preloading method in which the soft clayey soils became stiff and compacted. The reductions in void ratio, hydraulic conductivity K, and increase in dry density γ, shear strength of the soils C, and unconfined compressive strength q_u in case of combined vacuum-surcharge are more than those in the vacuum, which are more than those in the case of surcharge.

Tab. 1 Test results showing the effects of using the vacuum preloading method on the physical properties of the soil

Applied pressure	Water content/%		Void ratio		Dry density/($g\cdot cm^{-3}$)		Permeability/($nm\cdot s^{-1}$)			
							BT		AT	
	BT	AT	BT	AT	BT	AT	K_h	K_v	K_h	K_v
Vacuum 80 kPa	72.72	54.32	2.06	1.54	0.911	1.466	11.62	5.66	3.9	3.56
Surcharge 80 kPa	72.17	58.21	1.98	1.52	0.930	1.410	8.85	5.34	3.3	4.30
Vacuum 40 kPa + Surcharge 40 kPa	72.63	51.92	2.06	1.48	0.900	1.580	11.00	3.31	1.5	0.67

Note: BT—before tests; AT—after test.

Tab. 2 Test results showing the effects of using the vacuum preloading method on the mechanical properties of the soil

Applied pressure	c_v/($m^2\cdot y^{-1}$)	q_u/kPa		C/kPa		ϕ	
		BT	AT	BT	AT	BT	AT
Vacuum 80 kPa	2.21	20.10	39.2	11.7	26.5	20.3	24.1
Surcharge 80 kPa	2.23	23.23	47.2	10.5	26.6	19.5	21.8
Vacuum 40 kPa + Surcharge 40 kPa	2.44	19.30	49.1	11.8	30.5	20.5	27.5

Effective stress is the main stress which affects the consolidation process, where it can be generated directly by adding a surcharge load or indirectly by generating a negative pore-water pressure within soil by using vacuum pressure, while keeping the total stress constant[12]. Fig. 7 depicts the relationship between void ratio e and vertical effective stress σ'_v. It can conclude that, vacuum has the capability to consolidate the soft soil especially with combination of surcharge, and the behaviors of e-σ'_v curves are quite similar for all applied pressures, but vacuum can provide an alternative in reducing the length of the preloading period for soft soil consolidation.

3.3 Permeability anisotropy

Clays are anisotropic materials. Ref. [13] showed the permeability anisotropy ratio; $r_k = k_h/k_v$ indicates its typical values which are in the range of 1.0 to 1.5 for marine clays, and of 1.5 to 40 for varve clays. Tab. 3 shows the effects of using vacuum preloading and its combination with surcharge on r_k of the soft clayey soils, where the reduction of r_k in case of surcharge preloading is relatively more than that in vacuum preloading, which is also relatively more than that in combined vacuum - surcharge preloading . It is be

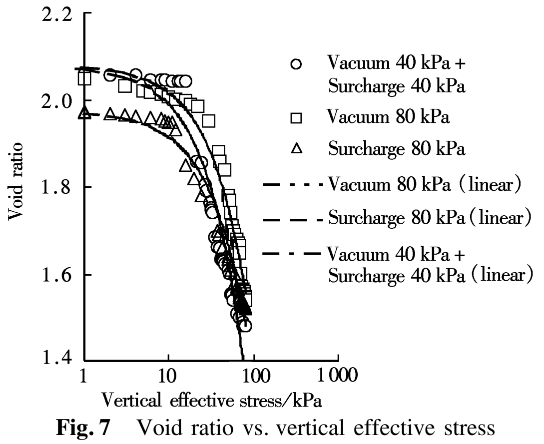


Fig. 7 Void ratio vs. vertical effective stress

Tab. 3 Test results showing the effects of using the vacuum preloading method on the permeability anisotropy ratio of the soil

Applied pressure	Anisotropy ratio r_k	
	BT	AT
Vacuum 80 kPa	2.05	1.10
Surcharge 80 kPa	1.66	0.77
Vacuum 40 kPa + Surcharge 40 kPa	3.32	2.24

cause the vertical strain in the surcharge case is more than that in the vacuum preloading case. The variation of k with the void ratio during the compression of the soft natural clays has been investigated by Ref. [9] and described as

$$\log(k) = \log(k_o) - \frac{e_o - e}{C_k} \quad (1)$$

where k is the hydraulic conductivity; k_o and e_o are in-situ permeability and void ratio, respectively; C_k is the permeability change index for volumetric strain less than 20% and C_k has a direct relation with e_o as in Eq. (2) within a simple linear relation.

$$C_k = 0.5 e_o \quad (2)$$

In this study, the application of the above two equations may be valid and can be used to predict the permeability and permeability change index in our case of study confirming the design of the apparatus, and its validity to design vacuum preloading projects under the same prevailing conditions (see Fig. 8).

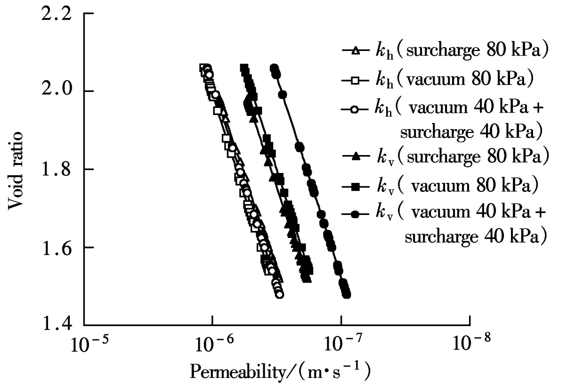


Fig. 8 Variation of horizontal and vertical permeability (k_h and k_v) with void ratio

4 Conclusions

Vacuum pressure generates the same effect as that of surcharge pressure under one-dimensional consolidation conditions[14]. However, the lateral displacement of soil is quite different between vacuum preloading and surcharge preloading as reported in Refs. [2, 15].

This research studies three-dimensional consolidation behavior of soft clayey soil subjected to vacuum, surcharge, and combined vacuum-surcharge preloading. A new triaxial apparatus is introduced to accommodate designated consolidation pressure. The results indicate that vacuum pressure generates different effects from those of surcharge pressure under three-dimensional consolidation, where the lateral displacement in the case of vacuum pressure induces inward displacement (shrinkage) but in the case of surcharge induces outward displacement (bulging). Vacuum preloading can be effectively used in combination with surcharge loading to consolidate the normally consolidated soils as indicated by this study. The conclusions of this study are as follows.

1) The new triaxial apparatus can simulate the consolidation behavior of the soils well. Therefore, the apparatus can be used in the design of soil improvement projects that use vacuum preloading when three-dimensional consolidation prevails.

2) The application of Eqs. (1) and (2) may be valid and can be used with confidence to predict the permeability property in our case of study confirming the design of the apparatus, and its validity to design vacuum preloading projects under the same prevailing conditions.

3) Vacuum preloading has the ability to change the physical and mechanical properties of soft soils under consolidation, see Tabs. 1, 2, and 3.

4) The discrepancy between vacuum and surcharge in terms of volumetric and axial strain may be due to the fact that the vacuum is gently accelerated during the consolidation by vertical and radial flow of pore-water but the surcharge may cause deformation faster than draining the pore-water out to the drainage paths; consequently, the drainage paths of the soils in the vertical and radial directions may be destroyed or coagulated. Hence, under combination, water drainage will be more than under each one individually, because the vacuum may assist and accelerate the surcharge consolidation by pulling the water out without destroying or coagulation of the drainage paths.

5) Vacuum pressure generates identical effects compared to surcharge pressure of the same value un-

der three-dimensional consolidation as evidenced by pore-water pressure, axial strain, volumetric strain, coefficient of vertical and horizontal consolidation due to vertical and radial flow respectively, and hydraulic conductivity. Consequently, the soil characteristics obtained in accordance with the consolidation tests can be used for design of soft clayey soil improvement by vacuum preloading.

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真空预压技术对软粘土物理与力学属性影响的试验研究

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摘要: 研制了一套新三轴试验仪, 该仪器能将堆载和真空加载在土样上, 在固结进行中能同时监控超孔隙水压力、轴向应变(沉降)与体积应变. 并根据浙江省温州市原状软粘土进行了固结试验, 软粘土的天然含水率是 72.5%. 试验结果发现, 真空预压、堆载预压或真空-堆载联合预压 3 类加固方式中, 粘土的固结特性没有明显差异. 研究表明 3 种加固方法改变了软土的一些物理属性并改善了它的力学属性.

关键词: 软土; 真空预压; 固结; 渗透性; 强度

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