

Mechanism Analysis of Pore Water Pressure Fluctuation During Clay Precompression Consolidation

Yueqin Wu, Dengheng Zheng*, Chenglong Jiao, Siying Xie, Qiaojing Li, Yingyi Tan, Yuling Tu

Guangzhou Railway Polytechnic, Guangzhou, China

Email: wuyueqin@gtxy.edu.cn

How to cite this paper: Wu, Y.Q., Zheng, D.H., Jiao, C.L., Xie, S.Y., Li, Q.J., Tan, Y.Y. and Tu, Y.L. (2024) Mechanism Analysis of Pore Water Pressure Fluctuation During Clay Precompression Consolidation. *World Journal of Engineering and Technology*, 12, 987-995.

<https://doi.org/10.4236/wjet.2024.124061>

Received: October 10, 2024

Accepted: November 9, 2024

Published: November 12, 2024

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Abstract

Pore water pressure fluctuations are an inherent phenomenon during the consolidation process of clayey foundations, and understanding its mechanism is crucial for comprehending the consolidation process and addressing issues such as drainage blockage during consolidation. This study investigates the consolidation behavior of clay, particularly focusing on pore water pressure fluctuations during the consolidation process of dredged marine sedimentary mud from Daya Bay, Guangdong Province. Given the prevalent use of clay in large-scale construction projects in southern China, understanding the factors influencing pore water pressure is crucial for optimizing consolidation times and improving construction efficacy. Using a custom vacuum preloading model, the research explores the impact of sodium hydroxide on the bound water content and its subsequent effects on pore water pressure dynamics. Experimental findings reveal a distinct inflection point in pore water pressure dissipation, suggesting that particle migration and bound water interactions contribute to the observed fluctuations. These results provide valuable insights for enhancing engineering applications in clay consolidation and mitigating drainage issues, ultimately informing construction practices and reducing project timelines.

Keywords

Clay Consolidation, Pore Water Pressure, Bound Water

1. Introduction

Clay is widely distributed in the southern, southwestern, and coastal areas of China, which necessitates constructing some large-scale projects on clay foundations [1].

*Corresponding author.

Due to its inherent engineering properties such as low permeability, low strength, high water content, and high liquid limit, pre-treatment of the foundation is required before clay construction, involving strengthening to improve its strength. The consolidation process of clay is often accompanied by the dissipation of pore water pressure. Observations have shown that pore water pressure does not always dissipate monotonically during clay consolidation; instead, there can be instances of rebounding water pressure during dissipation. The fluctuation of pore water pressure during dissipation prolongs the time of soil consolidation, affects the consolidation strength of the soil, and is closely related to drainage consolidation and clogging issues, directly impacting the construction period and cost. Therefore, understanding the mechanism of pore water pressure fluctuations is crucial for comprehending consolidation mechanisms and addressing problems like drainage clogging during clay consolidation.

Current research suggests that the clogging issue in clay consolidation may result from the combined action of water, particles, and pores [2]. The clogging issue in clay consolidation arises from the migration of solid particles with water flow. The migration distance of solid-phase substances in soil is short and does not move far from the drainage board, but rather migrates a short distance towards the drainage board from its original location. This step-by-step migration of soil particles leads to the accumulation of fine clay particles near the drainage board, causing clogging. Strongly bound water behaves similarly to a solid; when there is a high content of strongly bound water in the pores, it significantly reduces the volume of the pores, leading to poor drainage. Weakly bound water exhibits strong viscosity, which hinders the flow of free water, exerting a dragging effect. Combined water is believed to have a significant impact on the discharge of water and the migration of soil particles during the consolidation process [3].

Therefore, this study used marine sedimentary mud from Daya Bay, Huizhou City, Guangdong Province, as the research material. A custom vacuum preloading model was employed, incorporating different amounts of sodium hydroxide particles into the soil samples for the control group. Through basic physical property tests, indoor vacuum preloading model tests, and other experiments, the study investigated the factors on pore water pressure fluctuations to elucidate the dissipation mechanism of pore water pressure. This research aims to provide better guidance for engineering applications and shorten the consolidation time of clay.

2. Materials and Methods

2.1. Materials

The soil samples for this study were obtained from the reclamation mud at a construction site in Daya Bay, Huiyang District, Huizhou City, Guangdong Province, fully meeting the requirements for engineering applications and capable of addressing practical engineering issues. According to survey data and borehole information, the collected soil samples are identified as Quaternary marine sedimentary mud, classified as soft clay. The mud is deep gray, with fine particles,

soft and smooth texture, low sand content, occasional broken small shells, absence of large gravel particles, and a slight odor. To determine the organic matter content in the soil samples, the potassium dichromate method was employed, resulting in an organic matter content measurement of 1.69. X-ray diffraction (XRD) analysis revealed that the primary minerals in the sampled soft soil are quartz, mica, and feldspar, while the secondary minerals mainly consist of illite and kaolinite. Detailed physical parameters of the experimental soft soil are provided in **Table 1**.

Table 1. Physical and mechanical property index.

Moisture content	Density	Volumetric weight	Atterberg limits			Modulus of compression MPa
			Liquid limit	Plastic limit	Plasticity index	
$\omega/\%$	g/cm^3	Gs	%	%	%	
98	1.51	2.68	58.5	30.1	28.4	2.09

2.2. Vacuum Preloading Test Model

Through the preloading of soft soil in a vacuum, monitoring the values of pore water pressure at different times during the drainage process, plotting the curve of pore water pressure dissipation, observing the variations in each water pressure fluctuation, identifying the peak value of each fluctuation, this peak value point represents a moment when water, free water, and soil particles interact. To obtain the fluctuation curve of pore water dissipation during the consolidation process of clay preloading, the reasons for the fluctuation of pore water pressure are further analyzed through the curve. A self-made vacuum preloading test model (**Figure 1**) was used in this study. The temperature was set at 25°C at the beginning of the experiment, and the air conditioning was turned on to maintain the room temperature at 25°C. The specific experimental procedures were as follows:

(1) Lay plastic film at the bottom of the model box, and fill the retrieved clay into three model boxes numbered 1, 2, and 3, with dimensions of 50 cm × 50 cm × 50 cm.

(2) After filling the soil, use a pH tester to test the acidity and alkalinity of the test soil. Once the pH values of the undisturbed soil are obtained, designate Box 1 as the original box without adding any chemicals. Add NaOH solid particles to Boxes 2 and 3 and stir until the pH of Box 2 is adjusted to 9 and Box 3 to 10.

(3) Insert a drainage pipe in the middle of Boxes 1, 2, and 3, and wrap the outer surface of the drainage pipe with geotextile to ensure that soil particles do not flow out with water. Connect the drainage pipe to the vacuum pump with a soft plastic tube and also connect it to a filter flask to observe the drainage volume. On the first day of the experiment, which is the self-weight settlement stage, the following pH values were observed: Box 1 - 7.8, Box 2 - 9.2, Box 3 - 10.3.

(4) Place a pore pressure gauge 10 cm away from the drainage pipe on the same side in each of the three model boxes and 15cm above the bottom of the box. Connect the pore water pressure gauge to a data analyzer via wiring, allowing for real-time readings of water pressure at any given moment.

(5) After assembling the devices, seal the plastic film tightly to prevent air leakage. Cover the top of the model box with a 5 cm-thick layer of sand. Record the initial readings of the pore pressure gauge and place a ruler on the side of the model box to record the initial readings at the start of the experiment. Turn on the vacuum pump to begin draining.

(6) Record the water pressure values while simultaneously checking for air leaks by monitoring the vacuum level. Record the daily water output and settlement volume in the filter flask. This experiment was designed to run for 25 days.

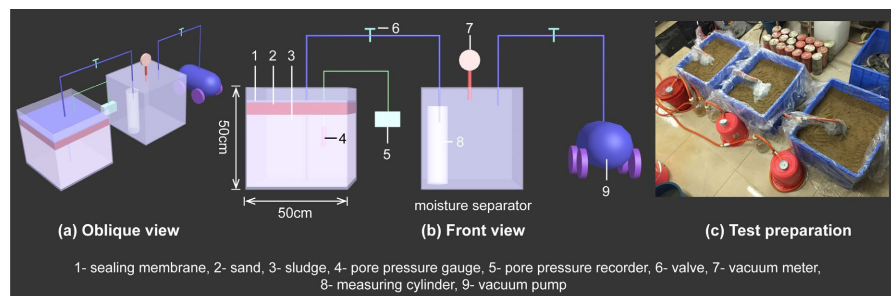


Figure 1. Vacuum preloading test diagram.

3. Results and Analysis

On the first day of consolidation is the self-weight settlement stage, where the soil mass is only subjected to self-weight stress. On the second day, the vacuum pump starts operating, causing the soil mass to experience not only self-weight stress and pressure from the sand cushion but also suction due to the vacuum. The dissipation fluctuation curve of pore water under the influence of these three forces during preloading consolidation processes is shown in **Figure 2**. It can be observed from the graph that at the beginning of the consolidation process under the influence of these three forces, the dissipation rate of pore water pressure is rapid. After approximately five days, the dissipation of pore water pressure slows down for all three sets of tests, showing a clear inflection point, and indicating a significant change in drainage difficulty at this stage. **Figure 3** illustrates the relationship between settlement and time. As time progresses, the consolidation rate curve becomes noticeably flatter. In terms of timing, the slowdown in pore water pressure dissipation aligns well with the reduction in settlement rate. The slowing down of drainage initially suggests that particle migration causes pore blockage, which is a gradual process; hence, the slowdown in pore water pressure dissipation should be monotonic. However, our experimental results show a distinct inflection point occurring between 20-15 kPa in the dissipation of pore water pressure, indicating that the dissipation of pore water pressure is not solely caused by particle migration.

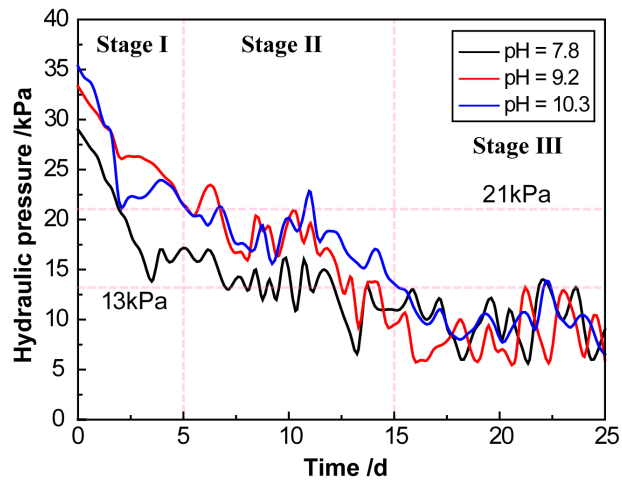


Figure 2. Comparative analysis of pore water pressure dissipation curves of three soil samples.

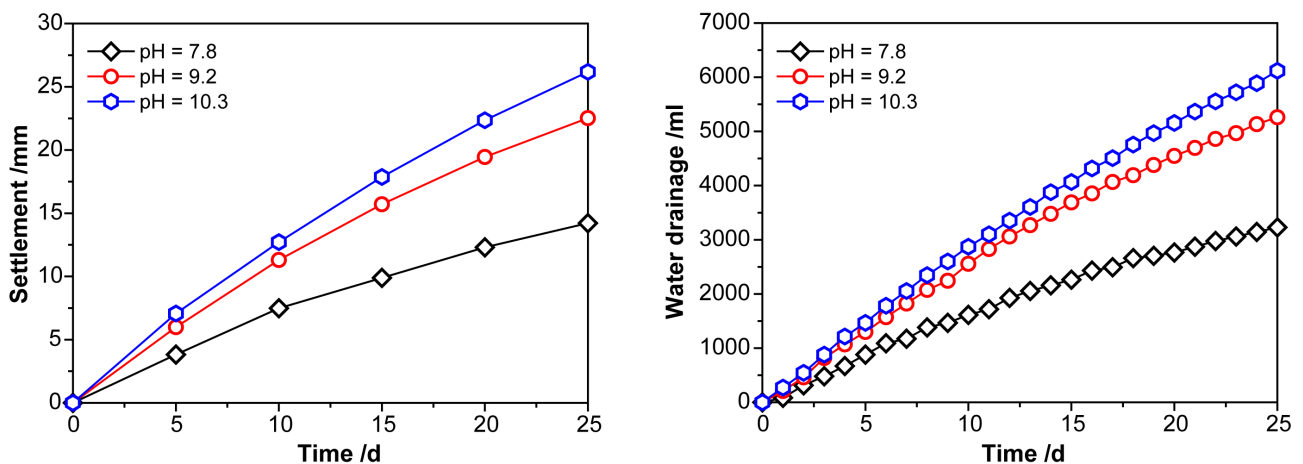


Figure 3. The change of settling amount and displacement in the vacuum preloading test.

As an inherent phenomenon of clay, there are mainly two explanations for the fluctuation of pore water pressure during the consolidation process: one is that changes in temperature and atmospheric pressure alter the magnitude of pore water pressure [4] [5]; The other attributes it to the Mandel-Cryer Effect, which suggests that water pressure gradually increases in the initial stages of consolidation until a certain moment when it starts to decrease [6]-[7]. The establishment of four widely accepted combined water models (Helmholtz model, Quincke model, Gouy-Chapman model, and Stern double-layer model) has laid the foundation for in-depth research on combined water [8]. Low *et al.* first found a relationship between the expansive properties of clay and the structure and properties of combined water [9], but due to the limitations of experimental equipment and conditions at the time, they did not draw many conclusions. Scholars, including Tone [10], observed the structure of combined water and found that various factors, such as temperature, adsorbed cations, and surface charge, influence the thickness of the combined water film [11]-[13]. Numerical simulation results in a clay

thermal environment have also demonstrated that the thickness of combined water is temperature-dependent, decreasing as the temperature rises [14]. Therefore, combined water, which is also temperature-related, may play a role in the fluctuation of pore water pressure during clay consolidation.

The most prominent property of bound water is its viscosity. Weakly bound water still exhibits liquid properties, but its fluidity decreases, resulting in a slower flow rate. Taking an average pore water pressure of 17 kPa between 15 - 20 kPa as a threshold, this value is used as the turning point for the deceleration of dissipation and consolidation rates. It can be interpreted that when pore water pressure is above 17 kPa, the area within a certain distance from the drainage plate is dominated by free water, meaning that free water occupies a large proportion of the soil pores near the drainage pipe. Below this threshold, the area within a certain distance around the drainage plate is dominated by bound water, indicating that bound water constitutes a larger proportion of the pores near the drainage pipe. This phenomenon suggests that the slowing of pore water pressure dissipation is not solely caused by particle migration but is also influenced by the interaction between bound water and soil particles, as confirmed by time-based evidence.

After the pore water pressure curve passes 17 kPa, it gradually flattens. However, from this point onward, the pore water pressure fluctuates periodically. As previously discussed, at this stage, bound water dominates in the soil within a certain distance from the drainage plate, causing the soil particles to become enveloped by the bound water and “float” within it, without direct contact with each other. Due to the attraction of Coulomb forces, water molecules are arranged directionally. When two soil particles come into contact, the water film between them can be equalized, but it becomes difficult to expel the bound water, requiring a significant load to do so. Furthermore, not only is bound water difficult to discharge, but when the water content is low, it also obstructs the expulsion of free water, which can only exist in the space between the bound water regions in the pores.

After eight days of consolidation, the fluctuation amplitude of pore water pressure in the soil sample with a pH value of 7.8 began to increase. As shown in **Figure 3**, by the eighth day, the drainage volume reached approximately 2000 ml. At this point, a significant amount of water had been expelled from the soil near the drainage plate, causing the soil pores to shrink and the drainage channels to become noticeably blocked, increasing the difficulty of drainage.

The fluctuation of pore water pressure indirectly reflects changes in the soil skeleton. According to the principle of effective stress, when vacuum pressure and top loading are applied to the soil, the free water (specifically, the water pressure generated by free water) bears the initial load. Due to self-weight stress, the vertical pores gradually decrease, and due to vacuum suction, the horizontal pores also gradually decrease, causing the pore water pressure to increase. As soil particles move closer together, bound water also begins to deform. When the pore water pressure gradient reaches a certain value, free water flows through the pores. If

the bound water completely encloses the free water, as pressure increases, at a certain point, the water pressure will exceed the viscosity of the bound water, causing the free water to break through the bound water film and discharge from the soil. During this discharge, free water carries fine clay particles with it. The migration and accumulation of these clay particles cause clogging in the drainage channels, resulting in the rebound and fluctuation of pore water pressure. Under the action of vacuum suction, distant free water continues to migrate toward the drainage pipe. Combined with pore compression and the migration of fine soil particles, pore water pressure increases again. When the pressure again breaks through the bound water layer or particle blockage, water is expelled from the soil, completing the second drainage cycle, and this process repeats cyclically.

In comparing soil samples with and without the addition of NaOH, it is evident that the peak fluctuations of pore water pressure are significantly reduced when NaOH is added. This indicates that the introduction of NaOH causes certain structural changes within the soil, making it less prone to clogging. However, the duration of each fluctuation remains largely unchanged, suggesting that external conditions can only alter the magnitude of pore water pressure dissipation, rather than fundamentally changing this characteristic. Further analysis of soil samples treated with varying concentrations of NaOH solution reveals that higher concentrations lead to smaller peak fluctuations, indicating that different concentrations have varying effects on the soil, potentially by reducing the bound water content.

When comparing the two soil samples with pH values of 7.8 and 9.2, it is observed that during the early drainage phase, the fluctuations of the pH 9.2 sample are noticeably smaller than those of the pH 7.8 sample. In the later stages, however, both samples show an increasing amplitude of fluctuations, with the pH 9.2 curve exhibiting a greater increase. It is anticipated that as consolidation progresses, the amplitudes of the two soil samples will converge, suggesting that the addition of NaOH contributes to alleviating clogging.

4. Conclusion

This study selected dredged sludge from a construction site in Daya Bay, Huizhou City, Guangdong Province, as the material. By adding varying amounts of sodium hydroxide to the soil samples to alter the bound water content, establishing a control group, and constructing a homemade vacuum preloading model, a series of experiments, including basic physical property tests, and indoor vacuum preloading model tests were conducted. The research focused on the role of bound water during the fluctuation of pore water pressure, yielding the following conclusions: In the experimental results, a distinct inflection point in pore water pressure dissipation was observed between 20 - 15 kPa, indicating that the dissipation of pore water pressure is not solely caused by particle migration but also by other factors. The fluctuation of pore water pressure may be related to the content of bound water.

Acknowledgements

This work was financially supported by the Foundation for Young Talents in Higher Education of Guangdong, China (NO. 2023KQNCX218).

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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