Vacuum preloading solution to shorten consolidation time of weak soil foundations under structures

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ABSTRACT

This paper presents the mechanism, technical development, and practical applications of the vacuum preloading method in treating weak soil foundations. This method allows accelerating the consolidation process, significantly shortening construction time compared to traditional preloading. Studies and applications in many countries, including Vietnam, demonstrate the superior effectiveness of this technology. The paper also introduces recent improvements, including membrane-less techniques, combination of vacuum preloading with static loads, and numerical analysis applications.

Keywords: *Vacuum preloading, weak soil consolidation, wick drains, ground improvement, foundation engineering.*

1. INTRODUCTION

Water-saturated weak soils pose many challenges in construction projects. Traditional preloading methods often require consolidation times spanning many years, affecting schedule and costs. The vacuum preloading method has been widely applied in China, South Korea, and many other countries. In Vietnam, the Ca Mau gas-power-fertilizer project is the first case using vacuum preloading technology, treating an area of about 90 ha. Results show a significant reduction in consolidation time, ensuring requirements for residual settlement and bearing capacity for important structural components.

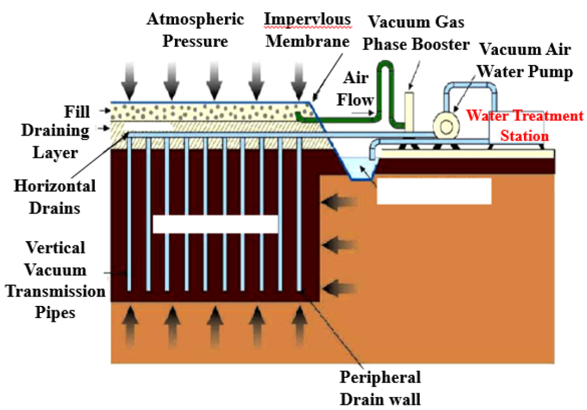
2. OVERVIEW OF THE VACUUM PRELOADING SOLUTION

Since 1952, Kjellman proposed the idea of using vacuum loading methods to treat weak soil foundations when constructing structures above. Several authors have published works on this method, such as [1-5]. By combining new equipment with new technology, this method has seen significant improvements. Generally, drainage in sand using wick drains distributes vacuum pressure and expels pore water. The nominal vacuum pressure is 80 kPa used in design, but in practice, this pressure sometimes reaches 90 kPa. When the load exceeds 80 kPa, a combination of vacuum suction and loading methods is often used.

When dealing with very weak soil, vacuum suction is more effective and faster than simple loading methods. For example, vacuum pressure at 80 kPa is usually maintained constant unless additional static loads are applied. The vacuum suction method to increase loading is also cheaper compared to loading alone with equivalent bearing capacity [4]. The vacuum loading method is part of the soil improvement process when clay sludge is dredged from the bottom and used as fill material to improve the soil. When clay sludge is used as fill material, the vacuum loading method is very effective in reinforcing the clay layer. Thousands of hectares of land in Tianjin, China, have been improved using this method [2, 6]. In recent years, similar vacuum technology has been used to improve construction sites [7]. Solutions based on vacuum technology have been applied to reinforce the stability of retaining wall structures [8]. The vacuum loading mechanism or traditional loading method, new inventions often relate to new equipment, machinery, and the digitized analog methods mentioned are introduced as follows.

An example in South Korea treated weak soil under a highway section, reducing the soil consolidation time by up to three years. Vacuum treatment was carried out by the company Vacuum Menard as illustrated in the area and diagram (Figure 1).

a) Implementation location



b) Implementation diagram

Figure 1. Vacuum treatment using the combined method of wick absorption and vacuum suction

The wastewater treatment plant area in South Korea (1995) was also carried out by Vacuum Menard Company, significantly shortening the consolidation time of the weak soil layer underneath.

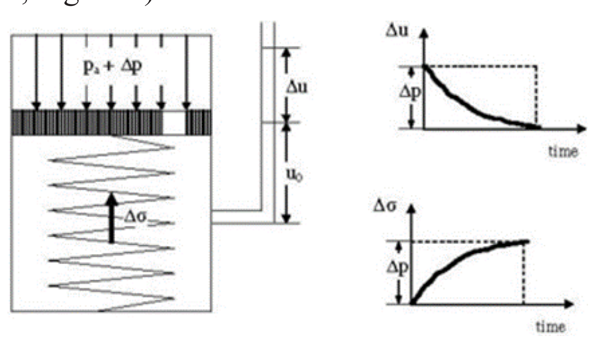
In Vietnam, at the Ca Mau gas-power plants, the vacuum loading method is also used. The results show that the consolidation time of the weak water-saturated clay layer under the structure can be shortened. One of the concerns is whether the pore pressure allows water to escape to make room for clay particles to fill in, thereby increasing consolidation. Through many experiments, combining the vacuum suction method with static loading and the use of wick drains (vertical drainage), the effects caused by vacuum suction are minimized.

For the first time in Vietnam, the vacuum consolidation method is used in the Ca Mau gas-electric-fertilizer complex area. The vacuum consolidation method has been successfully applied in some countries, in areas that were formerly fields. In our country, an area of 90 hectares is allocated for the combined gas, electricity, and fertilizer plant. Phase I involves constructing a 720MW power plant. Phase II is the construction of a second power plant with the same capacity, and Phase III is the construction of a plant with a capacity of 800,000 tons per year. The most important part of the plant is the water distribution section, which must be completed within 8 months from the start of installing the vertical drainage equipment (wick drains). This is a time challenge, so the vacuum surcharge method has been applied. Below, we introduce the principle of the vacuum surcharge method, which shortens the consolidation time of weak soil under the foundation layer of the construction.

3. RESEARCH METHODS

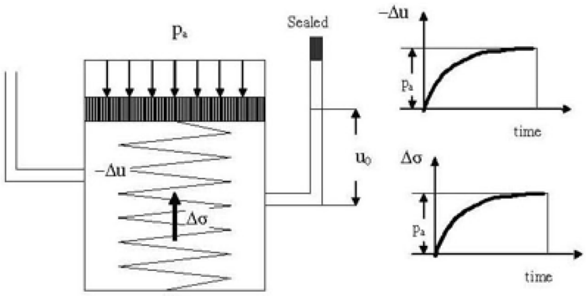
3.1. Principles and Mechanisms

The principle and mechanism of vacuum loading have been analyzed in the literature [4-5, 9-10]. Compared with the loading method by simple loading, the pore pressure of water and stress during the vacuum creation process have changed and analyzed as (Figure 2, Figure 3).



$$u_o = P_a;\ \Delta\sigma = P_a + \Delta p - (u_o + \Delta u) = \Delta p - \Delta u \quad (0)$$

Figure 2. Spring-type analog model for the consolidation process under the impact of the simple surcharge method [11]



$$u_o = P_a \; ; \; \Delta\sigma = P_a - (u_o - \Delta u) = \Delta u \qquad (1)$$

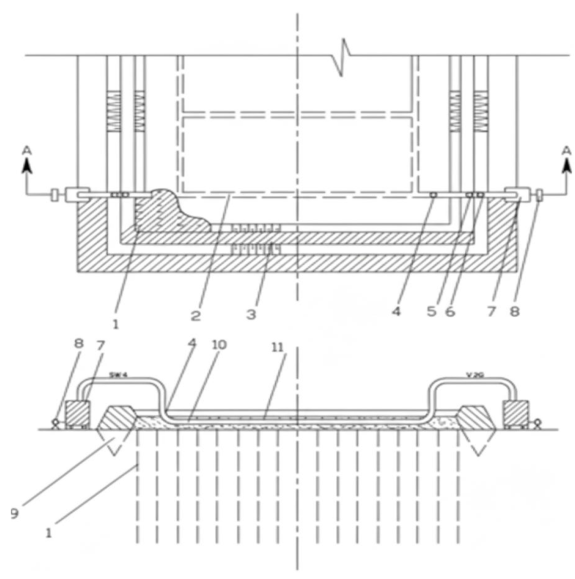
Figure 3. Spring-type analog model for the consolidation process under vacuum loading [12]

Where: P_a is the atmospheric pressure; Δp is the pore water pressure under load. When the soil is saturated with water, Δu is the initial excess pore water pressure.

3.2. New solutions in vacuum loading

3.2.1 Operation technique

The typical vacuum loading system is introduced in Figure 4 [13]. The wick tubes and horizontal tubes are used to distribute vacuum pressure and remove pore water. The horizontal tubes and the top end of the wick tubes are located in the loading sand layer, transmitting vacuum into the wick tubes. The tubes containing wick tubes with diameters ranging from 50 to 100 mm with ribs are used as horizontal tubes.



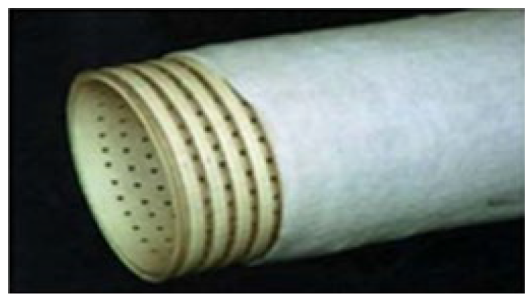
1. Wick pipe; 2. Horizontal pipe; 3. Coating; 4. Drainage; 5. Check valve; 6. Vacuum valve; 7. Jet pump; 8. Centrifugal pump; 9. Groove; 10. Main vacuum suction pipe; 11. Protective membrane

Figure 4. Illustration of the vacuum suction system

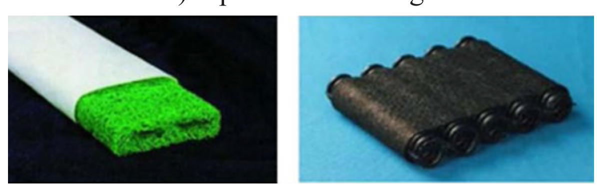
These tubes have perforations along their bodies and are wrapped with water-absorbent fabric used as a filter layer (Figure 5a). The transverse tube connects to the main tube to distribute the vacuum force. Three thin nylon layers cover the surface of the vacuum suction area. These nylon layers have outer edges placed in grooves along the four sides surrounding the vacuum suction area. Therefore, the land area requiring vacuum suction is divided into smaller sections to facilitate the placement of the nylon layers.

3.2.2 New vacuum reinforcement method

a) Using drainage plates



a) Pipe with soft flange



b) Other pipes

Figure 5. Horizontal pipe used for vacuum loading

b) Free membrane technique

When the land has been divided into small areas convenient for placing membrane sheets and vacuum loading equipment sequentially in the small land areas. (Figure 6).

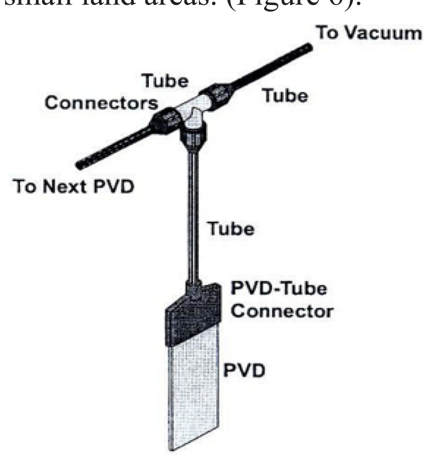


Figure 6. Wick container tube and pipe installation for vacuum loading

This pipe placement method was used in the construction of Bangkok International Airport. Unfortunately, this method was not used for the entire construction site, so the effectiveness was not high. The vacuum pressure was only applied at 50 kPa or lower. This method is usually used when there are soil layers of clay with very low permeability. Later, another method called the weak vacuum loading method was used. This method is introduced in (Figure 7).

Including: To Vacuum: leads to the vacuum device; Tube: pipe; Connector: joint; To next PVD: leads to the wick tube; PVD: wick tube container.

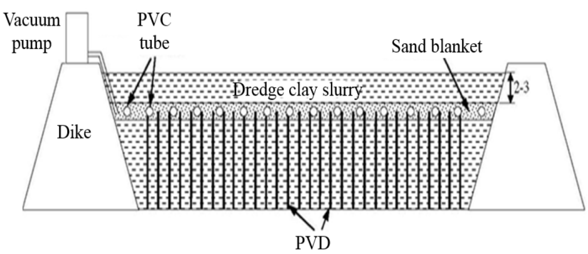


Figure 7. Vacuum loading method without using a diaphragm [14]

When the clay layer is used to cover the reclaimed land, vacuum pipes and wick drains are placed in the surcharge layer or at a few meters below ground level. According to this method, the clay layer lies above the vacuum suction pipes. Clay is very slow to absorb water, and the filling material forms a good water barrier, so no membrane layer is needed. Thus, some issues arise here. Tensile cracks will develop in the lower surface layer under the influence of sunlight. Vacuum pressure appears where the wick drains are placed within the wick drain arrangement area or at the seepage lines connected to the vacuum pipes. This causes difficulties in arranging the wick drains or seepage devices underwater. However, this method does not require building external dikes around the water suction area, thereby reducing costs.

3.2.3 Solution using a permeable layer inside the thickness of the surcharge soil layer

The vacuum surcharge method will not work well if the surcharge soil layer consists of sand lenses or permeable layers because these layers cause diffusion to the boundary of the land area, pushing the weak clay layer beneath the sand out of the area that needs improvement. In this case, it is necessary to build a retaining wall around the boundary of the land area. An example [15] handled this by constructing a 120 cm thick retaining wall, 4.5 meters deep, made of clay slurry used as a retaining wall layer for the clay layer beneath the fine sand layer. Building this type of retaining wall increases costs when the area to be treated is large.

Another method is to use wick drains with a waterproof plastic casing that penetrates through the permeable layer. This requires a very clear understanding of the thickness of the permeable layer of the land area to be improved.

3.2.4 Enhanced Dynamic Consolidation Method

The vacuum preloading method or preloading method shortens the consolidation time of the weak soil layer beneath the structure. One of the methods used is the combination of vacuum preloading and dynamic compaction. The basic idea of the dynamic compaction method with low impact energy is that the excess pore water pressure generated is dissipated during the vacuum creation process [16-17]. The dissipation of pore water pressure is caused by dynamic compaction.

4. EXAMPLE

4.1 Establishing the Digital Model

In the case of combined loading from vacuum and surcharge through wick drain columns (PVD) at the storage yard in Tianjin Port, China, the finite element analysis method was used [18]. In this area, a vacuum pressure of 80 kPa and a surcharge of 40 kPa were applied on weak and unstable soil. The data on soil properties measured over time are illustrated (Figure 8)

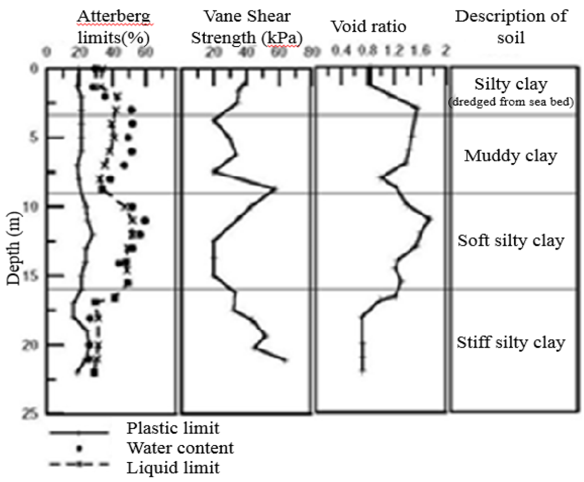


Figure 8. Overall cross-section of soil layers and soil properties at Tianjin port

Cross-sectional area of the vertical section and the installation position of the measuring devices (Figure 9a). The devices installed include settlement measuring instruments, pore pressure transfer devices, instruments for changing the measurement depth, inclination measuring instruments, and pore water pressure measuring devices in the soil. The 20-meter-long wick drains (cross-section 100mm x 3mm) are installed in a square pattern with one pipe every 1 meter. The finite element group of wick drain piles has 8 nodes, including 2 squares measuring displacement and 2 lines representing the variation function of pore pressure (Figure 9b).

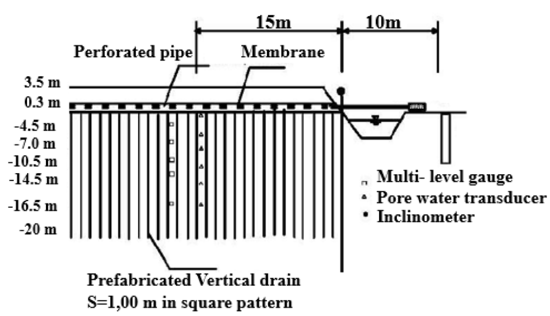


Figure 9. a) The position of the monitoring device

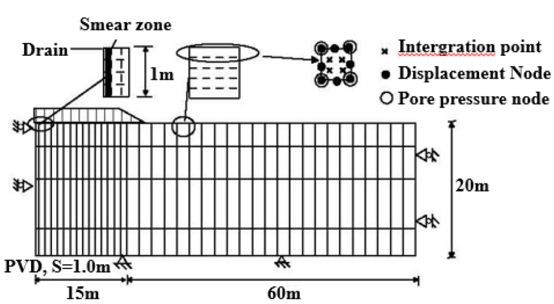


Figure 9. b) Finite element mesh for plane stress analysis [19]

4.2 Results of Vacuum Preloading in the Field

Field inspection is conducted to monitor the project when using vacuum preloading, in order to determine the results of vacuum preloading. Typically, data on the settlement of each soil layer, pore water pressure, and horizontal displacement at different depths need to be collected. The degree of consolidation is calculated based on settlement or pore water pressure data. The degree of consolidation (DOC) is predicted by the settlement using the maximum settlement method. Using observed pore water pressure data, the distribution of pore water pressure with depth can be graphed from the initial appearance, the final stage, and at specific moments. The degree of consolidation based on the pore water pressure dissipation curve method, according to the study in [20], is supported by settlement data as shown in (Figure 10). Using this method achieves a higher degree of consolidation compared to using pore water pressure data.

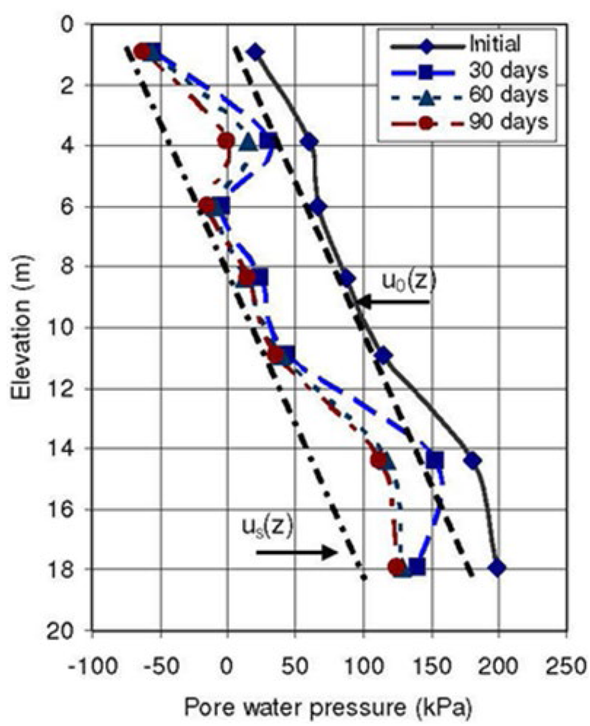


Figure 10. Pore water pressure chart used in consolidation level calculation

Consolidation settlement forecast and excess pore pressure are consistent with the recorded results. The actual excess pore pressure is negative (suction), avoiding damage caused by undrained pressure [21]. (Figures 11a, 11b).

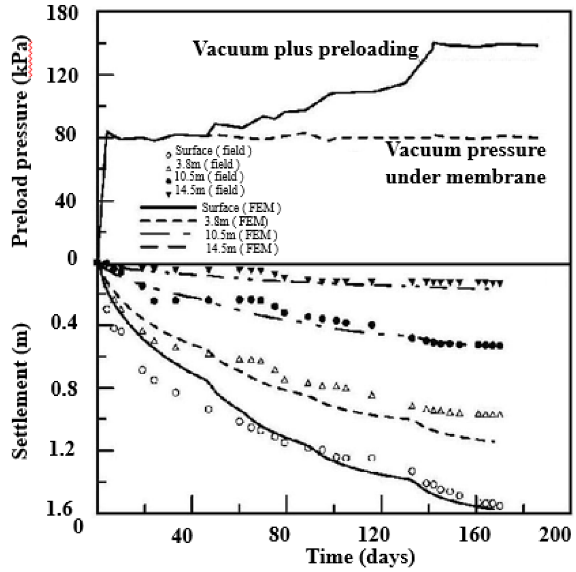


Figure 11. Cross-section II: (a) Traditional carrier and (b) Consolidation settlement

(Figure 12) illustrates a comparison between the predicted and measured horizontal displacement at the base layer after 180 days. Negative horizontal displacement indicates the soil moving inward toward the centerline of the base layer. Predictions at shallow depths (such as 0.5 meters) are made through the observation well excavation method, but it is difficult to obtain measurement results at depths from 5 to 10 meters (within the weak clay layer). The vacuum consolidation method can be considered to reduce the outward horizontal displacement of the clay layer and increase the stability of the clay layer at the base.

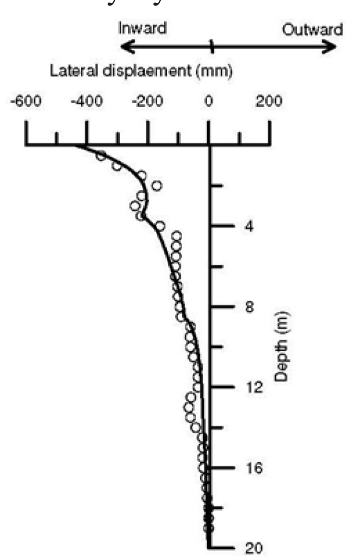


Figure 12. Horizontal displacement after 180 days at the bottom layer

5. CONCLUSION

Vacuum loading demonstrates the ability to shorten construction time from several years to a few months to one year, while also limiting lateral displacement compared to traditional loading methods. However, there are still issues that require further research, such as the effectiveness of the non-membrane method, equipment investment costs, and reliability when applied to complex geological conditions.

The vacuum loading method is an advanced, effective, and economical solution for treating weak soil foundations. Combining it with other techniques (dynamic compaction, numerical analysis) further enhances application efficiency. With initial results in Vietnam, this technology promises the potential for expansion in large infrastructure projects, contributing to shortened schedules and ensuring construction safety.

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