Introducing the method of improving soft soil by combining prefabricated vertical drains with the vacuum preloading method

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ABSTRACT

In the context of modern infrastructure development, addressing soft soil to ensure the durability and stability of construction projects has become critically important. In Vietnam, particularly in the Mekong Delta, soft soil with unstable geotechnical properties is widespread. An advanced and effective method for improving soft soil is the use of prefabricated vertical drains (PVD) combined with vacuum preloading. This paper provides a detailed overview of the method of treating soft soil using PVD in conjunction with vacuum pumping, covering theoretical foundations, construction procedures, and practical applications. Experimental results demonstrate that this method achieves over 90% consolidation, reduces settlement to below 20cm, and ensures the safety of structures in compliance with Vietnamese standards. Simulation models and field experiments also confirm that combining PVD with preloading and vacuum pumping not only enhances stability but also minimizes deformation and potential failures. This method is particularly suitable for projects in areas with extensive soft soil and high urban development demands, such as the Mekong Delta.

Keywords: *Cohesive Soil, Atterberg Limits, Standard proctor, Unconfined Compressive Strength.*

1. INTRODUCTION

In modern infrastructure development, improving soft soil is an important and urgent task to ensure the strength and stability of construction works. In Vietnam, soft soil is widely distributed in the Mekong Delta region [1]. Soft soil has unstable mechanical properties, low bearing capacity, low strength, and large deformation. Because of these characteristics, it cannot be used as a natural foundation for construction [2]. In the Mekong Delta, soft soil is often very weak clay with high organic content (Table 1). To ensure safety and reduce construction problems or failures, engineers must choose a suitable ground improvement method that matches the geological conditions and the project requirements. Combining prefabricated vertical drains (PVD) with vacuum preloading is one of the effective solutions for this type of soil.

Table 1: Geotechnical characteristics of soft soil in the Mekong Delta [3]

Characteristic	Value
Bearing capacity	0,5-1 kg/cm²
Compressibility	a > 0,1 cm²/kg
Void ratio	e > 1,0
Clay content	B > 1
Deformation modulus	E < 50 kg/cm²
Shear resistance	Low C
Permeability	Low
Water content	High
Degree of saturation	G > 0,8
Unit weight	Low

The selection of a ground improvement method must be based on the soil properties and the structural requirements to ensure safety and long-term stability. One advanced and effective technique for soft soil improvement is the use of PVD combined with vacuum preloading.

Prefabricated vertical drains, also known as vertical drains (PVD), are widely applied in soft soil treatment [1-5]. In 1960, Hansbo [9] from the Swedish Geotechnical Institute introduced the use of PVD with preloading to accelerate consolidation in clay. The main function of PVD is to shorten the drainage path, from the full soil layer thickness to the radial drainage zone, thereby increasing the rate of consolidation. With faster consolidation, the shear strength of the soil can also improve during the process [10]. Recently, many studies in Vietnam and other countries have combined vacuum pressure with PVD to further accelerate consolidation in soft soil [8, 11-17]. By reducing the pore-water pressure while keeping the total stress nearly constant during vacuum loading, the effective stress in the soil increases [18, 19]. This method was first tested by Choa's research group in China in 1989, achieving a consolidation effectiveness of about 70–80% [16]. In 2019, Cao and his team studied the influence of PVD clogging on consolidation under vacuum preloading. Their results showed that higher clogging levels lead to lower consolidation at the same time point. They also reported that the effect on Up (stress-based consolidation degree) is greater than on Us (strain-based degree), and external clogging has a stronger impact than internal clogging at the same clogging ratio [13].

López-Acosta (2023) [17] studied the effectiveness of vacuum consolidation on the mechanical properties of very soft clay at the former Lake Texcoco area. This area in Mexico contains very soft clay with high water content and high compressibility, where a new airport was planned to be built. To stabilize the soft ground, a vacuum preloading system with prefabricated vertical drains was used. Two test embankments were constructed using the "drain-to-drain" vacuum technique (drains connected to each other) and an airtight membrane system. During six months, the average vacuum pressures were −58 kPa and −63 kPa, respectively. The airtight membrane technique reduced water content and void ratio by up to 50% and 46%, while the drain-to-drain technique reduced them by 15% and 13%. The degree of consolidation reached about 86% to 88% for both embankments.

In Vietnam, Vinh et al. (2015) analyzed different simulation methods for vacuum preloading combined with PVD to improve soft soil. They compared the simulation results with field monitoring data on settlement, horizontal displacement, and excess pore-water pressure, and emphasized the importance of selecting ideal and non-ideal PVD types in numerical modelling [18].

Thang et al. (2023) used prefabricated vertical drains combined with vacuum pressure and surcharge loading to improve soft soil in the Mekong Delta. After 135 days of treatment, the soft soil showed a settlement of 2.36 m and a stability factor of 1.295, which satisfies the safety requirement of Vietnamese standards. The combined method of PVD, surcharge, and vacuum pressure is suitable for residential construction projects in the Mekong Delta, where large areas of soft soil and high urban development demands are common [19].

This paper presents a detailed overview of the soft ground improvement method using PVD with vacuum pumping. The content includes an introduction to the method, theoretical background, construction steps, and practical applications in real projects. By summarizing, analyzing, and evaluating previous studies and completed projects, the authors aim to provide useful information and an overall perspective on this technique, contributing to better performance and quality in construction and geotechnical engineering.

2. OVERVIEW OF THE PVD–VACUUM PRELOADING TECHNIQUE

2.1. Introduction to the method of PVD with surcharge preloading and vacuum pumping

2.1.1. Conventional surcharge preloading

Conventional surcharge preloading uses the weight of fill layers to apply load on soft ground. In this method, the excess pore-water pressure in the soft soil is designed to dissipate through a horizontal drainage system placed above the PVD, which can be a sand layer or prefabricated drains. The sand layer method has been successfully applied with a minimum sand thickness of 0.5 m [20], and the PVD embedded at least 0.3 m into the sand layer.

To increase the efficiency of surcharge loading, an additional drainage system is needed inside the sand layer. This system includes horizontal drainage pipes and a main collector pipe connected to a sump and pump. It helps control the groundwater level inside the embankment fill, as assumed in design calculations [11].

This method has several advantages: it only requires common equipment for transporting, spreading, and compacting soil; it can be carried out by most contractors; and the quality control process is simple.

2.1.2. PVD combined with vacuum pumping (vacuum preloading)

In very soft ground, placing fill may cause instability even when the embankment height is only about 1.5 m. Therefore, the vacuum preloading method was developed to solve this problem [21].

Kjellman (1952) was the first to introduce the vacuum consolidation method, in which atmospheric pressure is used as a substitute for surcharge loading [22]. To create vacuum pressure, a suitable engineering system is required. There are two main techniques: using an airtight membrane that covers the whole treatment area, and applying vacuum drainage directly to each individual PVD.

The main advantages of vacuum preloading are lower applied stress, smaller horizontal displacement, no need—or only a small need—for counterweight fill, and a shorter construction period [21].

2.2. Theoretical background

2.2.1. Primary consolidation settlement according to TCVN 9355:2013 [20]

$$S_c = \sum_{i=1}^{n} \frac{H_i}{1+e_o^i}\left[C_r \log\frac{\sigma_{pz}^i}{\sigma_{vz}^i} + C_c \log\frac{\sigma_z^i + \sigma_{vz}^i}{\sigma_{pz}^i}\right] \quad (1)$$

Where: H_i – thickness of soil layer i;

e_o^i - initial void ratio of soil layer *i* in the natural state;

σ_{vz}^i - effective vertical stress caused by the self-weight of natural soil layers above layer *i*, corresponding to depth *z* at the middle of the soft soil layer;

σ_{pz}^i - preconsolidation pressure of soil layer i;

σ_z^i - vertical stress at layer *i* induced by embankment loading, corresponding to depth *z* at the middle of the soft soil layer;

C_c - compression index of soil layer *i*.

2.2.2. Time-dependent consolidation settlement according to Hansbo *(1979)*

The consolidation settlement at time *t*, St, based on Hansbo's theory (1979), is given by Equation (2):

$$S_t = S_c \cdot U_t \quad (2)$$

Where: U_t - degree of consolidation at time *t*. By assuming ideal drain conditions, Ut can be calculated using Equation (3) (Hansbo 1979):

$$U_h = 1 - \exp\left(\frac{-8T_h}{F(n)}\right) \quad (3)$$

Where: $T_h = \frac{C_h t}{D_e^2}$ – time factor for radial consolidation;

D_e - equivalent diameter of the influence zone around one drain, $D_e = 1.13S$ for a square pattern or $D_e = 1.05S$ for a triangular pattern (Figure 1);

S - spacing between vertical drains;

C_h - coefficient of consolidation for radial drainage;

$F(n) = \ln(n) - \frac{3}{4}$ (Hansbo 1979) - drain spacing factor;

$n = \frac{D_e}{d_w}$; $d_w = \frac{2(a+b)}{\pi}$ (Hansbo 1979) - equivalent diameter of a PVD, where a and b are the thickness and width of the drain.

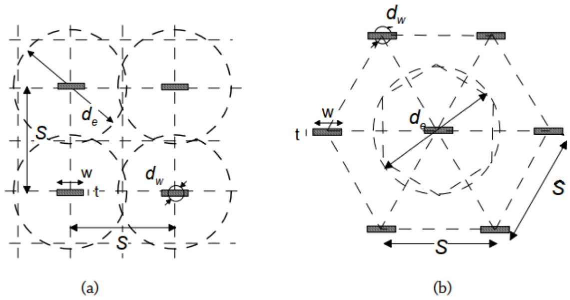

Figure 1. Relationship between spacing (S) and equivalent diameter D_e [23]. (a) Square pattern; (b) Triangular pattern.

2.3. Construction steps for PVD installation combined with vacuum pumping

The construction procedure for vacuum consolidation is carried out through the following steps:

1. Site preparation;

Clear the site and remove all obstacles.

Check and adjust construction equipment, and prepare all required materials.

Ensure that all preparation work is completed so that construction can proceed safely and smoothly.

2. Installation of the separation geotextile layer;

Place a geotextile layer on the ground surface to separate and protect the underlying soft soil.

Make sure the geotextile is laid flat, without wrinkles or damage.

3. Construction of the sand drainage layer and surface drainage system;

Spread a uniform sand layer on top of the geotextile to create a horizontal drainage blanket.

Install the surface drainage system to prevent water accumulation on the ground.

4. Installation of PVD and construction of airtight trenches or airtight walls (according to design);

Install the prefabricated PVD into the ground following the designed layout.

Construct airtight trenches or airtight walls to ensure the vacuum system operates effectively.

5. Installation of the horizontal drainage system and vacuum pressure gauges;

Install the horizontal drainage system to collect and discharge water from the treated area.

Install vacuum pressure gauges to monitor and control vacuum pressure during construction.

6. Installation of the monitoring system;

Install monitoring instruments to observe the consolidation process of the soft ground.

Ensure that the monitoring system works continuously and provides accurate data.

7. Installation of the airtight membrane;

Place the airtight membrane over the ground surface and over the PVD heads to create a sealed environment for the vacuum system.

Ensure that the membrane is fixed securely and has no leakage.

8. Installation of the vacuum loading system;

Install the vacuum pump and connect it to the PVD system.

Start the vacuum loading process to create suction pressure and accelerate soil consolidation.

9. Construction of the surcharge fill and settlement compensation layer;

After a period of vacuum loading, measure the settlement and add a compensation layer if needed.

Continue adding surcharge fill to achieve the required settlement and consolidation level.

10. Termination of vacuum pumping and unloading

When the required degree of consolidation is achieved, stop the vacuum pumping process.

Remove the construction equipment and vacuum pumping system.

Clean and prepare the ground surface for the next construction stages or for project handover.

The method of using PVD combined with vacuum pumping has been widely applied in many geotechnical projects. It has shown high effectiveness in improving soft ground, while saving time and cost compared with traditional methods..

3. FIELD PROJECT

3.1. Long Phu Thermal Power Plant – Soc Trang

In 2016, Nguyen Thi Nu [14] applied the ground improvement technique using prefabricated vertical drains combined with vacuum preloading and surcharge loading at the Long Phu Thermal Power Plant in Soc Trang. The subsurface profile at the site consists of three distinct soil layers. Undisturbed samples from Layer 2 were obtained using a Piston sampler, and laboratory testing was conducted at LAS–XD 442 and LAS–XD 928 to determine the key geotechnical parameters required for consolidation analysis.

The evaluated parameters include bulk unit weight, void ratio, preconsolidation pressure, compression index, swelling index, and the vertical and horizontal coefficients of consolidation. A summary of the predicted settlement parameters is presented in Table 2.

Table 2: Predicted consolidation parameters [14]

Layer	Description	Thickness, m	γ, T/m3	e_0	s_c, T/m2	Cc	C_r	Cv, m^2/year	C_h, m^2/year
1	Fill soil	2,5	1,70						
2	Soft clay	8,0	1,54	2,003	4,1	0,660	0,140	1,58	5,88
		5,0	1,55	1,897	4,1	0,670	0,140	1,58	5,88
		1,9	1,56	1,959	4,5	0,630	0,110	1,58	5,88
3	Stiff clay	30,0	1,80	1,035	9,0	0,220	0,060		

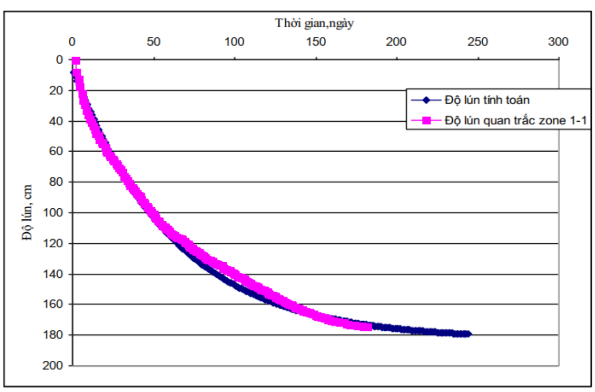

Figure 2. Theoretical and field-monitored settlement for Zone 1–1 (Long Phu Thermal Power Plant)

During the ground improvement work at the Long Phu Thermal Power Plant in Soc Trang, the settlement of the soft ground was monitored and predicted using the Asaoka method (1978). A comparison between the predicted settlement and the field-measured settlement is presented in Figure 2. The results show that the degree of consolidation exceeded 90%, and the residual settlement was less than 20 cm, meeting the requirements for soft ground treatment.

The ground improvement method using PVD combined with vacuum preloading and surcharge loading proved to be effective. It reduced the total settlement from 1.3–1.8 m to less than 20 cm within 150–170 days, which is consistent with the theoretical findings of Rujikiatkamjorn and Indraratna.

3.2. SITV Port, Ba Ria - Vung Tau Province

In 2022, the research team of Vo Nguyen Phu Huan [24] evaluated the effectiveness of surcharge preloading combined with vacuum pumping for soft ground improvement at the SITV Port, located along the Thi Vai River in Ba Ria – Vung Tau Province. The study area covers 33.7 ha, mainly used for container handling and general cargo operations. The ground improvement zone includes the entire storage yard, with two design operating loads of 4 T/m² and 2 T/m².

Based on the site investigation and laboratory testing results, the soil profile at the project area is divided into four main layers from top to bottom as follows:

1. Layer 1 – Soft soil:

○ Layer 1a: Very soft clay containing organic matter and shell fragments, greyish green to dark grey.

○ Layer 1b: Soft clay, greyish green to dark grey.

○ Layer 1c: Clay with sand (thin layer), greyish green; for design purposes, this layer is grouped with Layer 1b.

2. Layer 2 – Sand layer:

○ Layer 2a: Fine to medium sand with silt, light grey to greyish green, loose. Layer 2b: Fine to medium sand containing silt and some gravel, yellowish, light grey to greyish green, medium dense.

3. Layer 3 – Stiff clay: Greyish green, yellow-green, and reddish brown.

4. Layer 4 – Granite bedrock: Highly weathered granite, hard condition.

The authors developed a numerical model to predict settlement rate and pore-water pressure dissipation during unloading. The model combined the Modified Cam-Clay model for soft clay and a linear elastic model for the sand layer. The surcharge fill loading was simulated by placing layer-by-layer elements over time. Negative excess pore-water pressure generated by the vacuum system was gradually applied with a pumping pressure of 70 kPa in the soft soil layer. The PVD system was incorporated into the soil model, with corresponding drain properties and permeability adjusted using the Miura and Chai method.

The ground improvement results show that horizontal displacement occurred outward, as commonly observed in surcharge loading, but the magnitude was much smaller due to the use of vacuum consolidation. The excess pore-water pressure decreased continuously during vacuum pumping, with the influence depth reaching elevation −17.4 m. When additional surcharge was applied, pore pressure increased but dissipated quickly under the vacuum effect.

The monitored primary consolidation settlement ranged from 1.623 m to 2.260 m, with an average of 1.9 m, and the rebound (heave) after releasing vacuum pressure was 1.8 cm. The settlement curves from field measurements and from finite element modelling are presented in Figure 3.

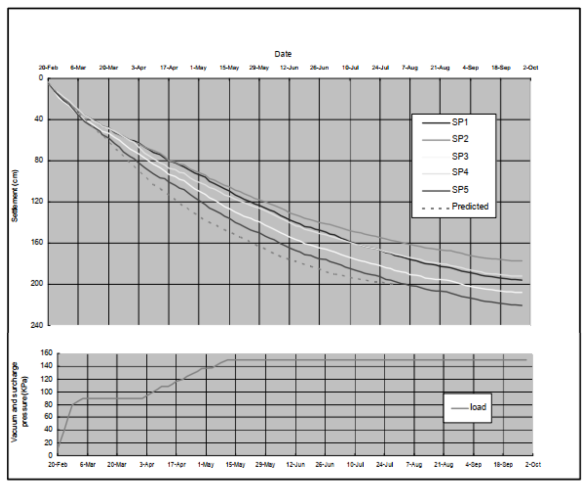

Figure 3. Comparison of settlement results from PLAXIS and field monitoring [24]

4. CONCLUSION

The ground improvement method using prefabricated vertical drains combined with vacuum pumping has shown high effectiveness in improving the mechanical properties of soft soil in the Mekong Delta region. Field results from the Long Phu Thermal Power Plant and the SITV Port demonstrate that this method can achieve a degree of consolidation greater than 90%, reduce residual settlement to less than 20 cm, and ensure construction safety in accordance with Vietnamese standards.

In addition, numerical modelling and field measurements confirm that the combination of PVD, surcharge loading, and vacuum pressure not only increases ground stability but also reduces deformation and potential failure risks. This method is particularly suitable for construction projects located in large soft-soil areas with high urban development demands, such as the Mekong Delta.

The author hopes that this paper provides useful information and an overall perspective on the method, contributing to improved efficiency and quality in construction and geotechnical engineering.

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