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Combined prefabrication vertical drain (PVD) with variable preloading and vacuuming method to improve soft ground in the Mekong Delta

Thang Ngoc Nguyen[1], Tuan Anh Nguyen[*2], Nhan Tri Vo Tran[3]
[1]Faculty of Engineering Technology, Tien Giang University, Tien Giang Province, Vietnam
[*2]Institue of Civil Engineering, Ho Chi Minh City University of Transport, Ho Chi Minh City, Vietnam
[3]Long An University of Economics and Industry, Long An Province, Vietnam

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ABSTRACT

The treatment of the foundation of construction works on weak soil often raises issues that need to be resolved such as: the low load-bearing capacity of the ground, the large settlement, and stability of the large area. As a result, it is important to develop appropriate methods to treat the foundation of construction works on weak soil. Dealing with weak soil is a pressing issue in the construction industry. Currently, there are various measures that can be adopdetd to increase the soil durability and reduce settlement of construction works such as: reinforced concrete piles, sheet piles, bored piles, cushion of loose materials, soil mixing with cement or lime, and preloading with vertical drainage. The method, which uses a prefabrication vertical drain (PVD) combined variable preloading and vacuuming, has not been widely studied and implemented. This paper proposes a solution, which incorporates preloading and vacuuming in the PVD, to process weak soil in the residential areas of the Mekong Delta region. The results show that the settlement of weak soil at the core of the embankment is 2.36m after 135 days using the PVD with variable preloading and vacuuming. The safety factor is 1.295.

Keywords: PVDs, vacuum, consolidation, soft ground, Mekong Delta.

I. INTRODUCTION

Consolidation is the gradual process of settling and compacting of soil. The consolidation process is divided into two stages. Primary consolidation involves the drainage of water from the soil and the shrinkage of voids that causes the soil to compact. Secondary consolidation is the stage where water has been completely drained and the soil particles continue to slide over each other to achieve a more stable position. To evaluate the degree of soil consolidation, the over-consolidation ratio (OCR) is used, which is the ratio of the pre-consolidation stress to the current effective vertical compressive stress. Normally, consolidated soil has OCR = 1, over-consolidated soil has OCR > 1, and under-consolidated soil has OCR < 1.

Terzaghi made the following assumptions for the one-dimensional consolidation theory that was used to calculate the soil subsidence. The soil layer under compression is assumed to be homogeneous and saturated with water. The mineral particles in the soil and the water molecules in the voids are incompressible. Water escapes from the voids of the soil according to Darcy's Law, where the drainage and compression processes occur in a single direction. The compressed soil layer typically drains water at both the top and bottom layers, but we can simplify the assumption to have drainage occurring only at one layer. Both the coefficient of compressibility (a) and the permeability coefficient (k) remain constant throughout the consolidation process. The change in the volume of the voids is equal to the amount of water discharged.

Nguyen, A. T. (2020) and Nguyen, N. T (2022) conducted several studies on the deformation of weak soil when the cement soil column technology was appliedt to treat the weak soil beneath the road surface and stabilize the canal embankment slope in the Mekong Delta [1, 2]. These studies used the finite element method to simulate the process of constructing the upper soil layers in order to evaluate the stability and the deformation of the weak soil beneath.

Barron, R. A. (1948) presented several solutions to the problem of radial consolidation. These solutions involved water drainage wells [3]. The two distinct cases (the case with free deformation and the case with constant deformation), which considered both disturbed and undisturbed effects, were fully analyzed. Various solutions with different assumptions and boundary conditions were proposed by Yoshikuni, H. and Nakanodo, H. (1974), Hansbo, S. (1979), Onoue, A. (1988) and Holtz, F. And Johannes, W. (1991), to indicate that the average consolidation obtained in the two cases of "free deformation" and "constant deformation" were quite similar. Furthermore, the solution obtained from assumption of constant deformation is more straightforward than that obtained from the assumption of free deformation [4, 5, 6, 7]. It should be noted that a uniform settlement over the circular area of a vertical drainage object can be observed in reality, and therefore the assumption of constant deformation is commonly adopted in the analysis of drainage consolidation.

Nguyen, T. N. et al (2021) proposed a simple method which employed a preloading stage and a vacuum pump to consolidate weak soil for prefabrication vertical drains (PVDs) [8]. This method could be easily integrated into a conventional calculation method for PVDs with vacuum preloading as it involved the Laplace transformation technique. The proposed method considered realistic construction conditions, such as the initial surcharge, the vacuum pumping test duration, the variations of radial permeability, and the time-dependent loading. The results were validated by finite element results and experimental results obtained from a case study of the Cai Mep International Terminal project in Southern Vietnam.

The study on the influence of vacuum pressure removal on the consolidation settlement was conducted by Pengpeng, N. (2019) under the condition which involved preloading and vacuuming [9]. In this study, the stress state of the soil layer was divided into two components: (a) static consolidation at different depths and (b) loading/unloading in the direction of minor principal stress. A series of consolidated drained triaxial tests were conducted to simulate the behavior of the soil after vacuum removal. The results showed that the unloading in the direction of the minor principal stress determined the level of elastic recovery after vacuum removal, and therefore allowed settlement to predominate.

Bergado, D. T. (2022) attempted to reinforce weak clay soil in Bangkok by employing a numerical simulation and a PVD method that incorporated preloading and vacuuming through a gas–water separation system [10]. The 17m long PVDs were installed from the top of the embankment in a triangular pattern. The PVDs were positioned 0.9m apart from each other. Monitoring devices were installed to measure surface settlement, lateral movement, and pore-water pressure within the soft clay layer. The analyses included settlement calculations, settlement predictions using observational methods, back-calculation of parameters, comparison of soil properties before and after the improvement, and finite element simulations. Experimental results showed that soft clay was converted to medium hard clay. The shear strength in the absence of water drainage and the maximum pressure were increased while the water content, void ratio, and compression index were decreased. The evaluation of the consolidation degree using one-dimensional methods, real observations, and numerical simulations, was conducted to predict consolidation settlement points. Predicted results were then compared to field observations.

Wu, J. et al. (2021) conducted a study on the treatment of weak soil underneath an elevated embankment using the method with preloading an vacuuming [11]. In this study, the soil treatment involved an initial pressure of 85 kPa (before vacuum application) and an auxiliary load with a height of 4.8m. Measurement devices were installed to record results at the site along with visual observations. The soil foundation was found to have a settlement of 1.4m and an average consolidation degree of 90%. The water content, void ratio, and compression coefficient significantly decreased, while the density, compression modulus, and adhesion force greatly increased.

The clogging of the PVD system during the consolidation process caused by vacuum preloading was studied by Wang, P. et al (2020). Three models were tested in the laboratory with different soil types to investigate the clogging effects. First, the effect of filter clogging was examined using scanning electron microscopy and plane permeability test. Second, the change in particle size distribution due to particle movement were analyzed at micro and macro levels. The blinding effect caused by particle movement was assessed through the results of compression and permeability tests. The test results showed that the particle movement in pure clay soil was not significant, and the blinding effect was relatively high in mixed soil. It was found that the clogging effect was mainly due to the uneven consolidation rather than the blinding effect caused by particle movement, especially for sticky clay soil [12].

Wang, J. et al. (2019) studied the effect of surcharge ratio on vacuum preloading with PVDs [13]. Feng, S. et al. (2021) analyzed the reinforcement of weak soil treated by vacuum loading thermal consolidation [14]. This paper employs a finite element method, called Plaxis, to simulate the process of treating weak soil for residential construction in the Mekong Delta. The proposed method applies vacuuming and variable preloading to the PVD system to improve the weak soil. This study will examine the relationship between vacuum suction pressure, preloading level, and preloading time in each stage. In addition, the relationship between the load-bearing capacity and the deformation of the foundation will be analyzed.

II. MATERIALS AND METHOD

A. Geotechnical Conditions

The geotechnical condition is preliminary evaluated as follows. Layer 1 has an average thickness of 11m. The main components of Layer 1 are most organic with clay, silty clay, and muddy clay. The soft and weak sedimentary layer has a low load-bearing capacity and a low durability. Layer 2 is located under the bottom of Layer 1 with an average thickness of 6 m. The main components of Layer 2 are clay, brown-yellow clay, and green clay with semi-hard state. The soil condition improves at greater depths underneath the ground. From laboratory test and field survey results, the geological structure at the most dangerous drilling position (borehole number 1) can be divided into the following layers [15]:

Layer 1: Composed of muddy clay and blue-gray sandy layers with a thickness of 11.50m.

Layer 2: Contains yellow-brown, blue-gray, and brown-gray clay with a semi-hard state; the layer thickness is 5.70 m.

Layer 3: Made up of silty clay in yellow-brown, red-brown, and blue-gray colours; the layer has a semi-hard state and a thickness of 3.30 m.

Layer 4: Consisted of sandy clay in yellow-gray, blue-gray, and white-gray colours; the layer has a plastic state.

TABLE 1. PROPERTIES OF SOIL LAYERS

ID	Properties	Symbol	Layer 1	Layer 2	Layer 3	Layer 4
1	Grain size distribution: - *Clay* - *Silt* - *Sand*	P (%)	 48.5 48.6 2.9	 33.8 54.7 11.5	 24.5 66.7 8.8	 7.8 67.6 24.6
2	Water content	W(%)	127.0	23.5	23.4	21.6
3	Wet unit weight	γ_w(g/cm^3)	1.345	1.968	1.986	1.904
4	Density	γ_s(g/cm^3)	2.693	2.700	2.687	2.621
5	Liquid limit	LL(%)	87.1	41.0	37.0	
6	Plastic limit	PL(%)	40.2	21.8	20.9	
7	Plasticity index	PI	46.9	19.2	16.1	
8	Liquidity index	LI (%)	1.85	0.09	0.16	
9	Friction angle	$\varphi(^0)$	$5^0$23'	$16^0$45'	$20^0$40'	$22^0$20'
10	Cohesion	c (kG/cm^2)	0.032	0.429	0.461	0.177

B. Calculation model

In solving pile foundation problems, there are two basic types: settlement compression and vertical drainage consolidation. Both problem types can be modifed to be suitable to the solving of vacuum consolidation problems. Today, there are numerous advanced geotechnical software that can be used to solve these consolidation problems. There is, however, no software that specializes on solving problems that involve PVDs with preloading and vacuuming. Most of the software available needs to use equivalent transformation problems for modeling. In the Plaxis software, although the PVDs can be simulated using drainage elements, the vacuum pressure cannot be simulated and therefore it has to be converted into an equivalent preloading force.

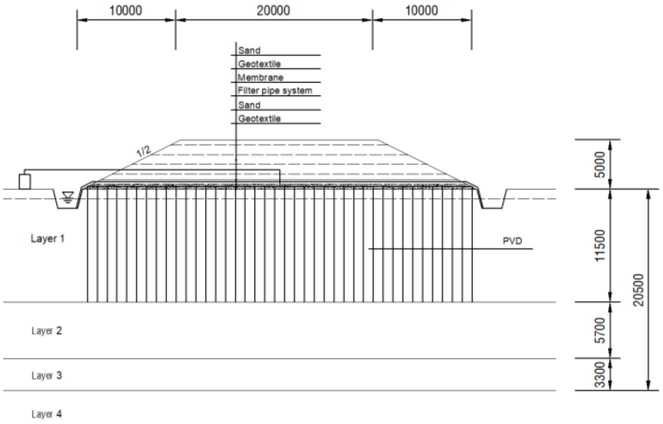

Fig. 1. A conventional cross section

The arrangement of the PVDs is as follows: square layout diagram, depth of PVD is 11.5 m, Spacing of PVDs is 1.0 m, diameter of PVD is determined by Eq.(1).

$$d = \frac{a.b}{\pi} = \frac{20x1}{\pi} = 6.4cm \tag{1}$$

where a and b are the dimensions of the PVDs (a=20cm, b=1cm).

When conducting a finite element analysis in two directions, it is possible to combine the plane strain model and the axisymmetric model. In the case of embankment on weak soil, the embankment can be considered as a raft foundation. Thus, the embankment will be modeled as a plane strain model in Plaxis.

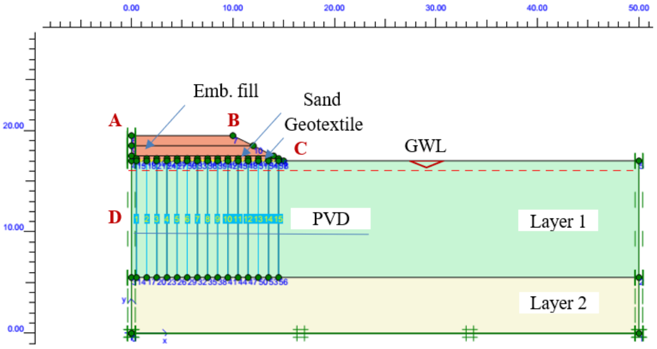

Fig. 2. Soft ground treatment model

To model the soil layers, 6-node or 15-node triangular elements can be used to simplify the problem to a planar problem. The 6-node triangular element is the default element for a two-dimensional analysis. It provides a two-node interpolation for the displacements. The element stiffness matrix of the 6-node triangular elements can be estimated using the integral rule with the sum of three Gauss stress points while the computation of the element stifness matrix of the 15-node triangular elements requires twelve Gauss stress points.

In Plaxis, the acceptable soil models are the Linear Elastic model (LE), the Mohr-Coulomb model (MC), the Hardening Soil model (HS), the Soft Soil model (SS), the Soft Soil Creep model (SSC), and the User-Defined model (UD).

Among all the models above, the Mohr-Coulomb model is chosen to describe soil properties. It is an ideal elastic model consisting of five basic soil parameters: the modulus of elasticity (E), the Poisson's ratio (ν), the unit cohesion (c), the internal friction angle (φ), and the dilation angle (ψ). All model parameters are used to describe the effective stress state of the soil. An important property of the soil is the existence of pore water pressure. The influence of pore water pressure is classified in the software as: drained behavior, undrained behavior, and non-porous behavior.

The properties of the soil layers and the embankment sand are shown in Table 2. Geotextile is simulated by a Geogrid element with EA=2500 kN/m.

In practice, to reduce the computational cost, the problem of soil consolidation treated with PVDs is considered as a planar problem. To achieve the equivalence of the average consolidation of the soil for a planar problem, it is necessary to change the geometric conditions, for example, changing the distance of the PVDs but keeping the permeability coefficient the same; or changing the permeability coefficient but keeping the distance between the PVDs the same; or changing both. Hird et al., 1992; Indraratna and Redana, 1997).

Another simple method to simulate the operation of the PVDs was proposed by Chai et al. (2001). As the PVD could increasee the permeability of the soil in the vertical direction, it would be reasonable to propose a vertical permeability coefficient value that could approximate the effects of both vertical and horizontal water drainage on the soil.

The equivalent vertical permeability coefficient (kve) can be calculated using the equivalent average consolidation value under one-dimensional consolidation conditions in Eq. (2):

$$k_{ve} = \left(1+\frac{2,5l^2}{\mu D_e^2}\frac{k_h}{k_v}\right)k_v \qquad (2)$$

where kv is th permeability coefficient of the soil in the vertical direction, kh is the permeability coefficient of the soil in the horizontal direction, and l is the length of the drainage strip.

TABLE II. PARAMETERS OF SOIL LAYERS AND EMBANKMENT FILL IN PLAXIS MODEL

ID	**Parameters**	**Symbol**	**Layer 1**	**Layer 2**	**Emb. fill**
1	Material model	Model	Mohr - Coulomb	Mohr - Coulomb	Mohr – Coulomb
2	*Type of behavior*	*Type*	*Undrained*	*Undrained*	*Drained*
3	Unsaturated unit weight (kN/m³)	γ_{unsat}	13.45	19.68	18.00
4	Saturated unit weight (kN/m³)	γ_{sat}	13.72	20.12	20.50
5	Horizontal permeability (m/day)	k_x	10^{-5}	10^{-6}	1
6	Vertical permeability (m/day)	k_y	10^{-5}	10^{-6}	1
7	Young's modules (kN/m²)	E_{oed}	628.4	23074.4	20000.0
8	Poisson's ratio	ν	0.35	0.35	0.3
9	Cohesion (kN/m²)	c_{ref}	3.20	4.29	1.00
10	Friction angle (degree)	φ	$5^0 23'$	$16^0 45'$	30^0
11	Dilatancy angle (degree)	ψ	0^0	0^0	0^0

In the calculation of the settlement and stability of the embankment on weak soil as mentioned above, it is recommended to use 15-node triangular elements to model the soil to increase solution accuracy (please see Fig. 3).

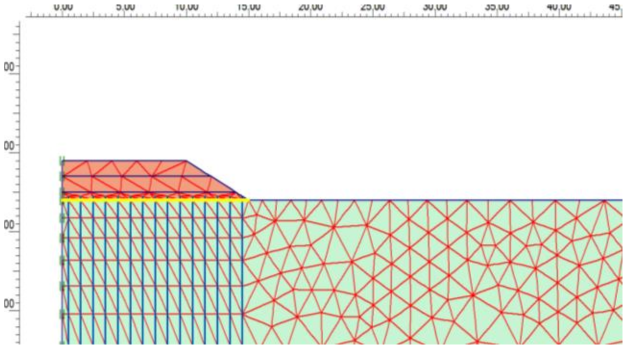

Fig. 3. Finite element mesh

The groundwater level (phreatic level) is predicted to be at a depth of -1.0m as shown in Fig. 4. The closed consolidation boundaries (which are found at the two vertical boundaries on the left and the right of the problem) are defined. The water pressure is selected based on the generation of pressure on the horizontal water level (Phreatic level) and the initial effective stress of the soil (please see Fig. 5).

The calculation of vacuum consolidation under the effect of vacuum loading is modeled by the process of reducing the groundwater level from the original level to a specific level that stays within the range of the PVDs. After defining the input parameters and the initial conditions, the calculation procedure is performed. To determine the stability of the embankment, the stability of the construction work should not only be evaluated in the long term (e.g., after the project is completed), but also should be evaluated in the construction steps as shown in Table 3.

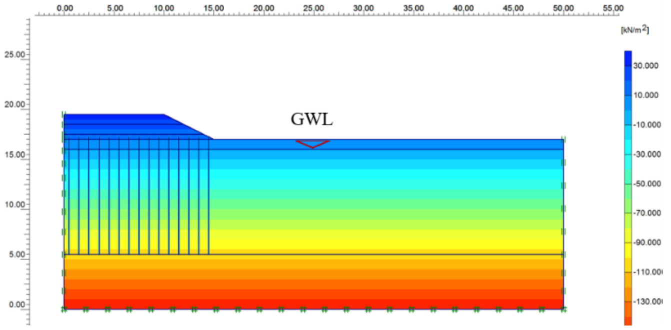

Fig. 4. Active pore pressures

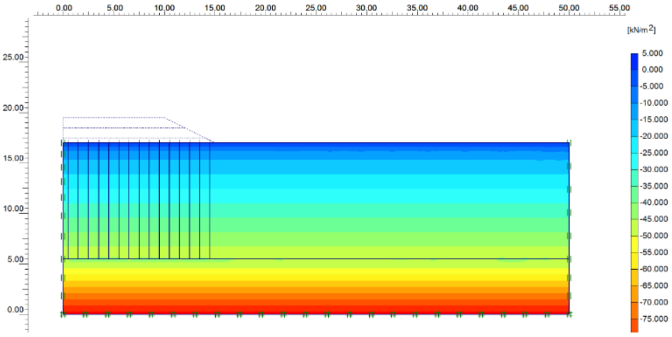

Fig. 5. Effective mean stresses

TABLE III. CALCULATION PHASES

Phase	Construction Steps	Cal. type	Loading input	Time
Initial	N/A	N/A	N/A	0 day
Phase 1	Construction of PVDs	Plastic	Staged construction	5 days
Phase 2	Construction of geotextile	Plastic	Staged constructio	5 days
Phase 3	Construction of emb. fill layer, 0.5m thick	Conso	Staged construction	5 days
Phase 4	Vacuuming, p_0= 20 kPa	Conso	Staged construction	15 days
Phase 5	Stability, FS_7	Phi/c reduction	Incremental multipliers	0 day
Phase 6	Construction of Layer 1, 1m thick	Conso	Staged construction	10 days
Phase 7	Vacuuming, p_0= 40 kPa	Conso	Staged construction	15 days
Phase 8	Stability, FS_7	Phi/c reduction	Incremental multipliers	0 day
Phase 9	Construction of Layer 2, 1m thick	Conso	Staged construction	10 days
Phase 10	Vacuuming, p_0= 60 kPa	Conso	Staged construction	15 days
Phase 11	Stability, FS_{10}	Phi/c reduction	Incremental multipliers	0 day
Phase 12	Vacuuming, p_0= 80 kPa	Conso	Staged construction	15 days
Phase 13	Stability level, FS_{12}	Phi/c reduction	Incremental multipliers	0 day
Phase 14	Vacuuming, p_0= 100 kPa	Conso	Staged construction	15 days
Phase 15	Stability, FS_{14}	Phi/c reduction	Incremental multipliers	0 day

III. RESULTS AND DISCUSSION

The simulation results of are illustrated in Figs. 7-10.

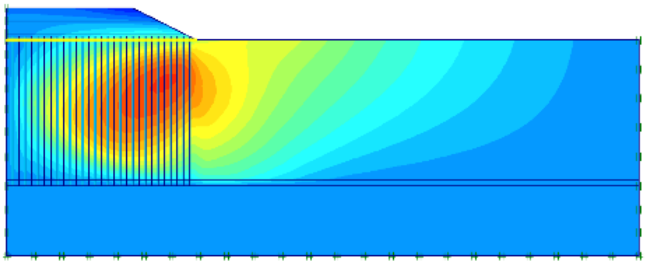

Fig. 6. Horizontal displacement, Ux= 0.76m

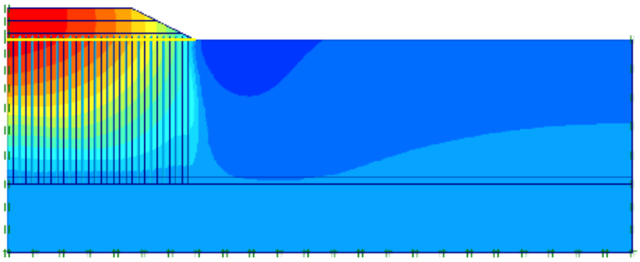

Fig. 7. Vertical displacement, Uy= -2.36m

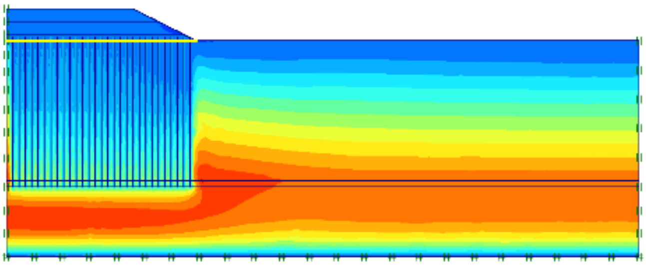

Fig. 8. Excess pore water pressure, u= -11.68kN/m2

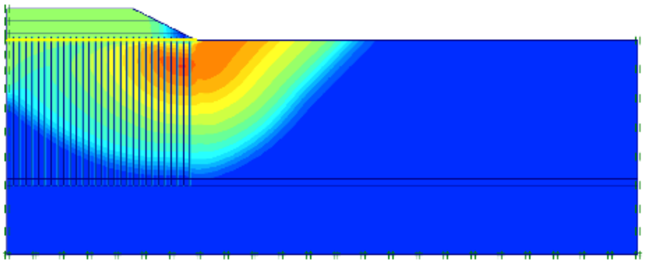

Fig. 9. Safety factor, FS= 1.295

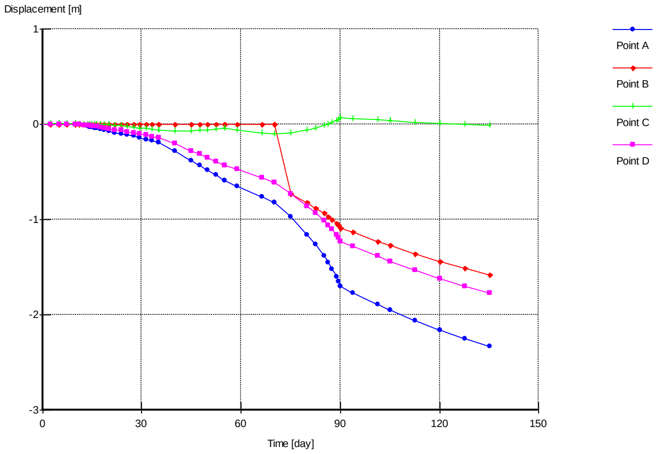

Fig. 10. Settlement vs. time graph at points A, B, C, D

Fig. 10 shows how settlement varies with time based on the finite element method. The vertical displacement at the heart of the embankment (Point A) is 2.36 m after 135 days (Fig. 7). The safety factor is: 1.295 (Fig. 9).

The method of improving soil that involves PVD with preloading and vacuuming is often applied to the embankment on weak ground. To reduce the length of the PVD path, the treatment of weak soil creates artificial drainage boundaries to allow water to escape in both directions through a vertical drain and a sand cushion on the soil surface.

The PVD has a much larger permeability coefficient than the permeability coefficient of the clay ground. When placing the PVD in the soil and applying preloading, thanks to the external load, the excess pore water in the soil flows towards the PVD and then quickly drains out of the soil in the vertical direction.

IV. CONCLUSIONS

After 135 days of treating weak soil in the Mekong Delta using the PVD combined with variable preloading and vacuuming, the soil achieved a settlement of 2.36 m and a stability factor of 1.295. This factor was considered to be safe for construction according to the Vietnamese standards.

The finite element method can be used to effectively simulate the vacuum consolidation problem. This method can determine stress and excess pore pressure at any point in the soil. The degree of consolidation in the case of vertical drainage is quite small, and therefore the sole application of preloading will not be effective. The preloading combined with the PVD is an ideal solution that can replace the.... All three components of settlement, including immediate settlement, primary consolidation, and secondary consolidation, decrease significantly under the impact of preloading. With a large area of weak soil along with the need for urban space development and the increasingly exploitation of material resources, the method that combines PVD with preloading and vacuuming combined with preloading and vacuum is suitable for residential projects in the Mekong Delta region.

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