

An evaluation of vacuum pressure effects in ground improvement using prefabricated vertical drain (PVD)

Đánh giá vai trò của áp lực chân không trong gia cố nền đất bằng bấc thấm

> PHAN MINH SANG¹, TRAN DUC KHANH²,
LE NGOC TAN³, PHAM MINH TRIET⁴, PHAM HUU HA GIANG^{4*}

¹Master student, Faculty of Engineering and Technology - Tra Vinh University

²Undergraduate student, College of Engineering - Can Tho University, Campus II

³Research Assistance, College of Engineering - Can Tho University, Campus II

⁴Lecturer, College of Engineering - Can Tho University, Campus II

*Email: phhgiang@ctu.edu.vn

ABSTRACT

The role of vacuum pressure in enhancing the consolidation of soft soils treated with prefabricated vertical drains (PVD) and surcharge loading is critically assessed in this study. Three approaches were employed: analytical modeling, finite element analysis using PLAXIS 2D, and validation against field monitoring data. The results show that increasing vacuum pressure from 70 kPa to 90 kPa leads to a settlement increase of up to 10.5%, with the most significant acceleration occurring within the first 90 days. The relationship between vacuum intensity and settlement is nonlinear yet stable. During the early phase (0–30 days), the FEM model overestimated settlement by approximately 47%, primarily due to idealized assumptions of uniform vacuum distribution, which diverge from in-situ vacuum pressure losses along depth. Over time, this deviation decreased significantly, and by day 180, the discrepancy between FEM and field measurements was reduced to 5.6%, within an acceptable engineering margin. Although the field improvement achieved a high degree of consolidation (>90%), the process was not fully optimized, particularly in the early stage of vacuum application. Moreover, the model did not account for staged embankment construction or variable vacuum schedules, which can strongly influence consolidation behavior. These findings underscore the need for more refined modeling approaches and control strategies to maximize the performance of vacuum-assisted ground improvement systems.

Keywords: Vacuum pressure, PVD, soft soil.

TÓM TẮT

Nghiên cứu này đánh giá vai trò của áp lực hút chân không trong việc tăng cường quá trình cố kết của nền đất yếu được gia cố bằng bấc thấm đứng (PVD) kết hợp với gia tải. Ba phương pháp được sử dụng: mô hình giải tích, phân tích phần tử hữu hạn bằng phần mềm PLAXIS 2D và so sánh với dữ liệu quan trắc hiện trường. Kết quả cho thấy khi áp lực hút tăng từ 70 kPa lên 90 kPa, độ lún cuối cùng tăng đến 10,5%, với tốc độ cố kết cao nhất trong 90 ngày đầu. Mối quan hệ giữa áp lực hút và độ lún thể hiện tính phi tuyến nhưng ổn định. Trong giai đoạn đầu (0-30 ngày), mô hình FEM dự báo độ lún lớn hơn thực tế khoảng 47%, chủ yếu do giả định phân bố áp lực hút đều theo chiều sâu, không phản ánh tổn thất áp lực thường xảy ra trong điều kiện hiện trường. Sai lệch này giảm dần theo thời gian và đến ngày 180, sai số giữa kết quả mô phỏng và quan trắc thực tế còn 5,6%, nằm trong giới hạn chấp nhận kỹ thuật. Dù nền đất tại hiện trường đạt độ cố kết cao (>90%), quá trình xử lý vẫn chưa được tối ưu, đặc biệt trong giai đoạn đầu áp dụng áp lực hút. Ngoài ra, mô hình chưa xét đến tải trọng đắp theo giai đoạn và biến thiên áp lực hút, những yếu tố ảnh hưởng đáng kể đến tiến trình cố kết. Kết quả cho thấy cần hoàn thiện hơn nữa mô hình và chiến lược thi công để nâng cao hiệu quả xử lý nền bằng phương pháp hút chân không.

Từ khóa: Áp lực bơm hút chân không, bấc thấm, đất yếu.

1. INTRODUCTION

Soft soils in Vietnam's Mekong Delta and HCM City exhibit high water content, low shear strength, and low permeability, leading to significant settlement and delayed consolidation under loading [1], [2]. To address these challenges, the method of vacuum preloading combined with prefabricated vertical drains (VCM-PVD) has been widely applied across Asia over the past two decades for the improvement of soft soil. The key principle of this method is to accelerate radial drainage through vertical drains while applying vacuum pressure to increase the hydraulic gradient, thereby expediting the dissipation of excess pore water pressure, increasing effective stress, and shortening the overall consolidation time.

Field studies in China [3], [4], Japan [5], and Thailand [6] have demonstrated that the VCM-PVD method can achieve degrees of consolidation exceeding 90% and accelerate settlement rates by 1.5 to 2 times compared to conventional preload methods. Maintaining vacuum pressures in the range of 70-90 kPa plays a vital role in ensuring pressure transmission to deeper soil layers and enhancing uniformity in settlement and consolidation. Theoretical frameworks developed [6]-[8] have provided practical tools for simulating vacuum pressure distribution and for transforming axisymmetric conditions into equivalent plane strain models, facilitating numerical analysis using software such as Plaxis and ABAQUS. In addition, finite element method (FEM) simulations conducted by [9], [10] and [11] have shown the capacity of FEM to quantitatively assess the vacuum consolidation process, including vertical settlement, lateral displacement, and pore pressure dissipation. Notably, advanced 2D-3D FEM models that consider soil stratification and anisotropic permeability have revealed that the vertical distribution of vacuum pressure significantly influences settlement and consolidation time [6], [9]. These results challenge the common assumption of uniform vacuum pressure in many previous models, which may lead to substantial errors in settlement prediction and design control.

In Vietnam, key projects such as the Long Phu Thermal Power Plant (Soc Trang) [12], Thu Thiem Urban Area (Ho Chi Minh City) [13], and Nhon Trach Industrial Zone [14] have successfully applied the VCM-PVD method using vacuum pressures of 70-80 kPa. These case studies show good agreement between FEM simulations and field measurements. However, most studies still focus on the overall efficiency of the method, without specifically analyzing the role of vacuum pressure magnitude on consolidation and settlement behavior. Moreover, the use of idealized or non-ideal vacuum drain models remains ambiguous, even though pressure transmission in practice often varies with depth and construction conditions. [13]

There remains a research gap in accurately quantifying the relationship between vacuum pressure and consolidation efficiency in space and time, especially considering influencing factors such as smear zones, soil depth, loading patterns, and membrane effectiveness [10], [11], [15], [16]. This underscores the need for modeling multiple vacuum scenarios and validating against field data to propose an optimal vacuum design strategy.

Accordingly, this study aims to clarify the influence of vacuum pressure magnitude on the consolidation performance of soft ground treated with VCM-PVD and preloading. This is achieved through numerical modeling using the finite element method and comparison with field data from Vietnamese case study.

2. METHODOLOGY

The research methodology was structured around three types of data to ensure a comprehensive evaluation and allow cross-

verification among different approaches: analytical calculations, numerical modeling, and field monitoring data. This multi-source approach aims to assess the effect of vacuum pressure on the consolidation behavior of soft ground treated with prefabricated vertical drains (PVD) combined with vacuum preloading and surcharge loading.

2.1. Analytical method

The analytical dataset was developed based on the consolidation calculation formulas presented in TCCS 41:2022 [17] and supported by theoretical models referenced in [6]. The soil is assumed to be homogeneous and fully saturated, with vertical drainage under one-dimensional consolidation conditions. This method provides preliminary estimations of settlement magnitude, consolidation time, and excess pore pressure dissipation for comparison with numerical simulations and field observations.

2.2. Finite element method

Finite element method (FEM) was carried out using Plaxis 2D to model the consolidation process of soft ground treated with PVDs in combination with vacuum pressure and a surcharge embankment. A series of simulation scenarios were designed with varying vacuum pressure levels (0 to 90 kPa) to quantitatively analyze their effects on settlement. The constitutive model was applied to replicate the nonlinear behavior of saturated soft clay, using geotechnical parameters derived from field data.

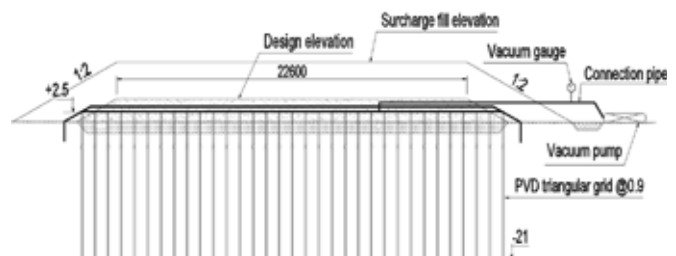
2.3. Field data

Field measurements were obtained from Road N5 in the Thu Thiem New Urban Area, An Khanh Ward, Thu Duc City, Ho Chi Minh City an area undergoing large-scale urban infrastructure development on soft soil Figure 1.



Figure 1. Study Area

The treated section spans 23.6 m in width, slightly exceeding the design road width of 22.6 m to improve lateral drainage efficiency. PVDs were installed at 0.9 m spacing in an equilateral triangular grid, with each drain penetrating to a depth of 23.5 m (elevation -21.0 m). A vacuum pressure of no less than 60 kPa was maintained continuously for 180 days, in combination with a uniform 4.5 m-high surcharge embankment. Settlement monitoring data from this project were used to validate and calibrate the analytical and numerical models.



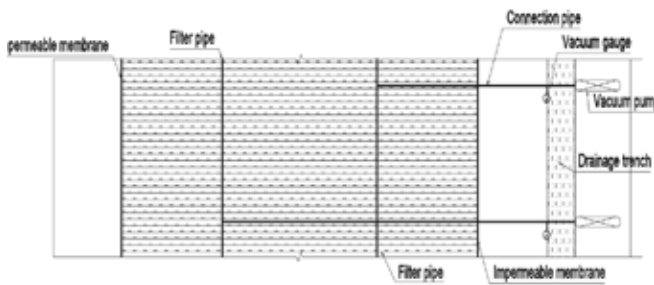


Figure 2. Cross-sectional view and plan layout of PVD arrangement

2.4. Geological conditions and input parameters

The subsoil consists predominantly of a thick soft clayey silt layer extending to 22.5 m depth, characterized by low unit weight, high void ratio, low cohesion, and a small internal friction angle indicating poor load-bearing capacity. Beneath this layer lies a stronger soil stratum with significantly improved mechanical properties, capable of acting as a natural bearing layer. The geotechnical parameters used in this study are summarized in Table 1.

Table 1. Geological data

Soil layer	Depth (m)	γ_w (g/cm ³)	C (kG/cm ²)	ϕ (°)	e_0
1	0-22,5	1,64	0,06	4	2,1
2	22,5 – 24,45	2,3	15	28	0,4

By integrating these three data sources, the study evaluates the accuracy, applicability, and limitations of each approach. The findings aim to support the development of an optimized simulation model for the design and performance prediction of ground improvement works in soft soil conditions commonly found in southern Vietnam.

2.5. Fundamental Principles of Analysis

2.5.1. Estimation of consolidation settlement

The consolidation settlement S_c is estimated as follows:

$$S_c = \sum_{i=1}^n \frac{H_i}{1 + e_0^i} \left[C_c^i \log \left(\frac{\sigma_z^i + \sigma_{vz}^i}{\sigma_{pz}^i} \right) \right]$$

Where

- H_i Thickness of the i^{th} soil sublayer
 - e_0^i Initial void ratio of the i^{th} soil sublayer
 - C_c^i Compression index or the slope of the void ratio–log pressure curve ($e \sim \log \sigma$)
 - σ_{vz}^i Vertical effective stress due to the self-weight of overlying natural soil layers above layer i
 - σ_{pz}^i Preconsolidation pressure of the i^{th} soil sublayer.
 - σ_z^i Stress increment due to embankment loading at the midpoint of the i^{th} soil sublayer.
- C_c^i và σ_{pz}^i are determined in accordance with TCVN 4200:2012 [17].
 σ_z^i is calculated using Osterberg’s stress distribution chart

2.5.2. Estimation of settlement over time for soil treated with PVD and preloading

The consolidation settlement of an embankment on soft ground improved with vertical drains at time t is determined as follows:

$$S_t = S_c U$$

Where

- S_c the settlement of soft soil without PVD
- U the degree of consolidation of soft soil with PVD

The degree of consolidation U achieved at time t after the completion of embankment filling is determined by the following equation:

$$U = 1 - (1 - U_v)(1 - U_h)$$

Where

- U_v vertical degree of consolidation
- U_h horizontal degree of consolidation

2.5.3. Estimation of consolidation settlement over time for soil treated with PVD, preloading, and vacuum pressure

In the case of vacuum consolidation, determine the vacuum pressure (p_0), the total design stress ($\Delta\sigma$), the surcharge pressure (Δp), and evaluate the degree of consolidation achieved ($U_{t,vac}$) under the condition of equal settlement:

$$U_{t,vac} = \left(\frac{\Delta\sigma}{p_0 + \Delta p} \right) U_t$$

2.6. Finite element method (FEM)

The finite element method (FEM) using Plaxis 2D was employed to analyze the effects of vacuum pressure on the consolidation behavior of soft soil treated with prefabricated vertical drains (PVD), vacuum preloading, and embankment loading. The Mohr-Coulomb material model was selected to simulate the mechanical behavior of the soil throughout the consolidation process. The simulation scenarios are summarized in Table 2.

Table 2. Simulation cases

No.	Elapsed time (day)	Vacuum process					
		VP (atm)	Time (day)	VP (atm)	Time (day)	VP (atm)	Time (day)
1	180	90	60	90	60	90	60
2	180	80	60	80	60	80	60
3	180	70	60	70	60	70 <td 60	
4	180	80	30	70	60	60	90

A total of 4 simulation scenarios were developed to investigate the influence of vacuum pressure magnitude and its application duration on the consolidation behavior of soft ground treated with prefabricated vertical drains (PVD), vacuum preloading, and surcharge loading, as summarized in Table 2. Cases 1 to 3, designed to validate the numerical model against analytical predictions by varying vacuum pressures from 70 to 90 kPa under a constant embankment load. Case 4 representing field data obtained from settlement monitoring, with staged vacuum pressures applied at 80 kPa (30 days), 70 kPa (60 days), and 60 kPa (90 days). Figure 3 illustrates the finite element model developed in Plaxis 2D to simulate the vacuum consolidation process using prefabricated vertical drains under various vacuum pressure conditions.

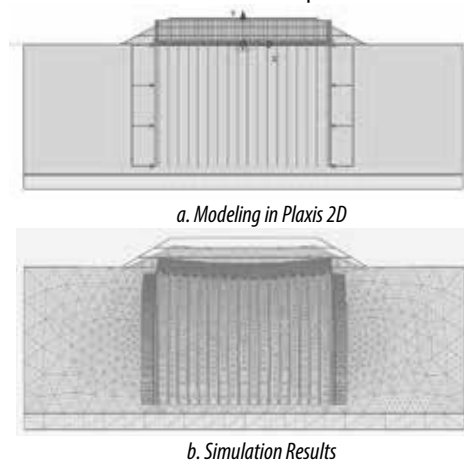


Figure 3. Illustration of the Plaxis 2D model

3. RESULTS & DISCUSSION

3.1. Comparison results between the analytical method (AM) and Finite element method (FEM)

The settlement results calculated from the analytical method under different vacuum pressures are summarized in Table 3.

Table 3. Analytical method results (AM)

Elapsed time (day)	Analysis method		
	90kPa S (m)	80kPa S (m)	70kPa S (m)
0	0	0	0
30	-1.32	-1.27	-1.23
60	-2.05	-1.98	-1.90
90	-2.63	-2.54	-2.44
120	-3.11	-3.01	-2.90
150	-3.53	-3.41	-3.28
180	-3.89	-3.75	-3.61

A clear trend of increasing settlement over time is observed across all three vacuum pressure scenarios (70, 80, and 90kPa) in the analytical method. At 30 days, the settlement reached -1.32 m under 90kPa of vacuum pressure, which is 3.8% higher than the -1.27 m recorded at 80kPa and 6.8% higher than the -1.23 m at 7 kPa. This difference becomes more pronounced as time progresses. By day 180, the settlement under 9 kPa reached -3.89 m, exceeding that of the 80kPa and 70kPa cases by 3.6% and 7.5%, respectively.

These results highlight the critical role of vacuum pressure in accelerating the consolidation process. Higher vacuum levels not only enhance the hydraulic gradient but also increase the rate of excess pore water pressure dissipation, which translates into faster settlement and a greater degree of consolidation within the same treatment period. The steady growth in the settlement gap over time further indicates that the benefit of higher vacuum pressure becomes increasingly significant as the consolidation process progresses. This reinforces the importance of maintaining strong and stable vacuum conditions to optimize the efficiency of ground improvement using vertical drains combined with vacuum preloading.

3.2. Vacuum pressure effects and FEM-based evaluation against field data

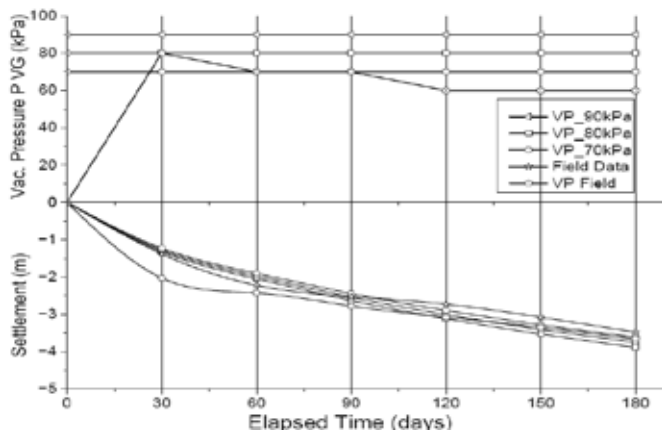


Figure 4. Comparison of settlement between FEM simulation and field data under staged vacuum pressure conditions.

The influence of vacuum pressure on the consolidation behavior of soft soils was investigated through a series of finite element method (FEM) simulations, corresponding to three representative vacuum levels: 70 kPa, 80 kPa, and 90 kPa. The settlement-time responses obtained from the simulations are presented in Table 4 and illustrated graphically in Figure 4, which together provide a comprehensive view of consolidation progression over a 180-day treatment period. A separate FEM scenario simulating staged vacuum application was also implemented to match actual field procedures, enabling a direct comparison between numerical predictions and monitored data.

Table 4. Simulation Results

Elapsed time (day)	90kPa	80kPa	70kPa	VP based on Field		Field data	
	S (m)	S (m)	S (m)	VP (kPa)	S (m)	VP (kPa)	S (m)
0	0	0	0	0	0	0	0
30	-1.02	-0.61	-0.82	80	-2.03	80	-1.38
60	-2.26	-2.06	-1.87	70	-2.43	70	-2.22
90	-2.74	-2.54	-2.34	70	-2.78	70	-2.53
120	-3.18	-2.98	-2.78	60	-3.08	60	-2.73
150	-3.69	-3.69	-3.49	60	-3.35	60	-3.08
180	-4.28	-4.07	-3.87	60	-3.67	60	-3.48

The FEM results clearly indicate that higher vacuum pressures lead to greater settlement. After 180 days, the final settlements for the 70 kPa, 80 kPa, and 90 kPa cases were -3.87 m, -4.07 m, and -4.28 m, respectively. The increase in settlement from 70 kPa to 80 kPa was 5.2%, and from 70 kPa to 90 kPa was 10.5%, with a similar 5.2% increase observed between 80 and 90 kPa. These results indicate a nonlinear but stable relationship between vacuum pressure and consolidation, especially prominent during the early stages of treatment (0-90 days), when pore pressure dissipation is most rapid due to higher effective stress gradients.

This behavior is consistent with the theoretical mechanism of vacuum preloading, where increased vacuum pressure enhances the hydraulic gradient and accelerates the discharge of pore water, leading to faster settlement. The FEM simulations captured this mechanism effectively, particularly at 80 kPa and 90 kPa, where settlement rates were noticeably higher during the initial 90 days. Such early-stage acceleration is of practical importance when time constraints in construction require expedited consolidation.

However, during the initial phase of treatment-particularly within the first 30 days the FEM model was found to overestimate settlement compared to field measurements. The deviation reached approximately 47% during this period. This discrepancy is likely due to idealized modeling assumptions in FEM, where vacuum pressure is applied uniformly along the entire depth of the vertical drains. In reality, vacuum pressure often decreases with depth due to system losses and air leakage, resulting in reduced effectiveness in deeper layers. The inability of the model to reflect this vertical pressure decay leads to an overestimation of settlement, particularly at the beginning of the treatment process. Additional sources of error may include imperfect field installation conditions such as lack of airtight sealing and potential inaccuracies in field instrumentation or measurement protocols.

Later in the consolidation process, the differences between numerical results and field data diminish significantly. In the field, vacuum pressure was applied in stages: 80 kPa for the first 30 days,

followed by 70 kPa for 60 days, and then 60 kPa for the remaining 90 days. The total observed settlement after 180 days was -3.48 m, while the corresponding FEM simulation under the same staged pressure regime produced a settlement of -3.67 m, with a deviation of 0.19 m, or approximately 5.6%. This small difference confirms that the FEM model can reasonably approximate real-world behavior when input conditions are properly calibrated to reflect actual site procedures.

Furthermore, comparisons between constant and staged vacuum pressure scenarios underscore the importance of maintaining a high and consistent vacuum level throughout the treatment period. When vacuum pressure was held constant at 90 kPa in the simulation, the resulting settlement exceeded that of the staged-pressure case by more than 10%, indicating the potential efficiency gains from avoiding pressure losses. Nonetheless, in practice, staged vacuum reduction is often necessary to ensure overall ground stability and limit excessive displacement or differential settlement.

The FEM-based evaluation against field data accurately captures the consolidation behavior of soft soil and provides a robust basis for assessing ground improvement performance. Nevertheless, the comparison suggests that although the field treatment achieved a high degree of consolidation (>90%), further refinement is possible to enhance overall optimization.

4. CONCLUSION

By integrating analytical method (AM), FEM, and field data, the impact of vacuum pressure on the consolidation behavior of soft soils was comprehensively assessed in this study. The findings lead to the following conclusions:

(i) Higher vacuum pressures significantly enhance vacuum consolidation, with settlement increasing by up to 10.6% when vacuum pressure rises from 70 to 90 kPa, particularly during the early stages of soil improvement.

(ii) FEM simulations effectively capture the nonlinear and time-dependent behavior of vacuum-assisted consolidation and show good agreement with field data when calibrated, with deviations remaining within acceptable engineering limits (<6%).

(iii) Although high consolidation efficiency was achieved in the field, the vacuum application regime was not fully optimized. Future design strategies should incorporate staged loading and adaptive vacuum pressure

5. ACKNOWLEDGMENT

The research group would like to express sincere thanks to REDSTAR Construction Joint Stock Company (REDSTAR CONS JSC) for their support in conducting the field data for this study.

REFERENCES

[1]. C. M. Tran, Y. W. Hung, F. Sitepu, G. H. H. Pham, and E. L. Huynh, "Assessing Influence of Waves on Riverbank Stability: A Centrifuge Modeling Approach," *Geomech. Eng.*, vol. 40, no. 1, pp. 1-11, 2025.

[2]. P. H. H. Giang, L. H. Tri, and N. T. Phat, "Enhancing riverbank stability A case study on soil improvement through Jet grouting along Can Tho riverbank." p. CTU Journal of Innovation and Sustainable Developm, 2024.

[3]. J. C. Chai, J. P. Carter, and S. Hayashi, "Ground deformation induced by vacuum Consolidation," *J. Geotech. geoenvironmental Eng.*, vol. 131, no. 12, pp. 1552-1561, 2005.

[4]. J. Chu, S. W. Yan, and H. Yang, "Soil improvement by the vacuum preloading method for an oil storage station," *Geotechnique*, vol. 50, no. 6, pp. 625-632, 2000.

[5]. T. A. Tran and T. Mitachi, "Discussion of 'Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading,'" *Can. Geotech. J.*, vol. 43,

no. 12, pp. 1395-1403, 2006.

[6]. Buddhima Indraratna, C. Rujikiatkamjorn, A. S. (Bala) Balasubramaniam, and G. McIntosh, "Soft ground improvement via vertical drains and vacuum assisted preloading," *Geotext. Geomembranes*, vol. 30, pp. 16-23, 2012.

[7]. B. Indraratna, I. Sathanathan, C. Rujikiatkamjorn, and A. S. Balasubramaniam, "Analytical and numerical modeling of soft soil stabilized by prefabricated vertical drains incorporating vacuum preloading," *Int. J. Geomech.*, vol. 5, no. 2, pp. 114-124, 2005.

[8]. B. Indraratna, C. Rujikiatkamjorn, and I. Sathanathan, "Analytical and numerical solutions for a single vertical drain including the effects of vacuum preloading," *Can. Geotech. J.*, vol. 42, no. 4, pp. 994-1014, 2005.

[9]. D. Apriadi, R. A. Barnessa, and N. A. I. Marsa, "Finite Element Study of Vacuum Preloading and Prefabricated Vertical Drains Behavior for Soft Soil Improvement," *J. Tek. Sipil*, vol. 26, no. 3, pp. 189-194, 2019.

[10]. A. M. Kaisarta and T. Ilyas, "Finite Element Modeling of Soil Improvement Using Vacuum Consolidation with Vertical Drain Method (Case Study: Apartment Project, Tangerang)," *SSRN Electron. J.*, 2021.

[11]. N. Q. Tới and N. T. Chinh, "Nghiên cứu hiệu quả của bắc thấm dọc chế tạo sẵn sử dụng gia tải trước chân không và gia tải trước phụ tải," vol. 14, no. 4, pp. 31-37, 2024.

[12]. N. T. Nụ, "Ứng dụng phương pháp xử lý nền đất yếu bằng bắc thấm kết hợp hút chân không và gia tải trước tại nhà máy nhiệt điện Long Phú - Sóc Trăng," *Tạp chí Khoa học Kỹ thuật Mỏ - Địa chất*, vol. 55, pp. 46-54, 2016.

[13]. Lê Bá Vinh, "Phân tích ảnh hưởng của bắc thấm lý tưởng và bắc thấm không lý tưởng trong mô phỏng xử lý nền bằng phương pháp hút chân không kết hợp với bắc thấm," *Tạp chí Khoa học và Công nghệ Thủy lợi*, vol. 4, 2015.

[14]. P.V.Long, "2015_Performance of PVD improved soft ground using vacuum consolidation methods with and without airtight membrane.pdf."

[15]. Thang Ngoc Nguyen, Tuan Anh Nguyen, and Nhan Tri Vo Tran, "Combined prefabrication vertical drain (PVD) with variable preloading and vacuuming method to improve soft ground in the Mekong Delta," *Int. J. Sci. Res. Sci. Eng. Technol.*, vol. 4099, pp. 455-463, 2023.

[16]. N. Puspita and A. Capri, "The effectiveness of vacuum consolidation to soft soil settlement," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 10, no. 4, pp. 1610-1616, 2020.

[17]. "TCCS 41:2022. Tiêu chuẩn khảo sát, thiết kế nền đường ô tô trên nền đất yếu," *Tiêu chuẩn Quốc gia Việt Nam*.