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Comparative Study of PVD Preload and Vacuum Consolidation on Road Stability

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Abstract The construction of highways on soft soils presents significant challenges due to the inherent characteristics of high compressibility and low permeability, which often lead to excessive settlement and stability problems. To address these issues, soil improvement techniques are required to accelerate consolidation and ensure long-term performance of embankments. This study compares two widely applied methods Prefabricated Vertical Drains (PVD) with preload and vacuum consolidation using numerical modeling through the finite element method. The analysis employed both the Soft Soil and Mohr–Coulomb models to capture soil behavior under staged loading conditions. The results indicate that both methods fulfill technical requirements related to stability and allowable settlement. However, vacuum consolidation demonstrates superior performance by achieving a higher safety factor throughout construction and operational stages, while also reducing the implementation time. In contrast, the PVD with preload method generates larger settlements and requires a higher surcharge load, which not only increases material demand but also introduces potential risks of instability during construction. These findings highlight the effectiveness of vacuum consolidation as a more efficient and reliable technique for soft soil improvement, particularly in large-scale highway infrastructure projects.

Keywords Soft soil · PVD preload · Vacuum consolidation · Slope stability · Embankment settlement

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1 Introduction

Road construction on soft ground, such as in Pekanbaru, encounters major difficulties due to its low bearing strength and large settlements resulting from slow consolidation [1]. To address this, ground improvement techniques like PVD with preloading and vacuum consolidation are often applied. Although PVD is easier and commonly used, vacuum consolidation provides better time efficiency and is well-suited for areas with limited land [2]. This research specifically compares the performance of both methodssettlement, stability, and construction time efficiency in the context of a toll road project in Pekanbaru.

2 Literature Review

2.1 *Soft Soil*

Soil is a natural material consisting of minerals, organic matter, and pore spaces that may be filled with either water or air, which strongly influences its behavior, particularly in soft soils [3]. Soft soils are typically cohesive types, such as clay and silt, commonly found in low-lying regions like swamps or coastal zones. These soils are defined by their low shear strength, high compressibility, and poor permeability, making them highly susceptible to settlement and instability unless proper reinforcement is applied beforehand [4].

2.2 *Consolidation*

Consolidation refers to the reduction in the volume of saturated soil caused by the expulsion of pore water when subjected to an external load [5]. This process occurs gradually until the soil skeleton bears the entire load. In highway construction, accelerating consolidation is essential to achieve immediate soil stabilization [6]. The characteristics of the soil strongly influence both the rate and extent of settlement; coarse-grained soils consolidate more quickly, whereas clay soils take longer due to their low permeability [7].

2.3 *Cone Penetration Test with Pore Pressure (CPTu)*

The Cone Penetration Test with pore pressure measurement (CPTu) is a static penetration method that employs instrumented cones to record tip resistance (qc), sleeve friction (fs), and pore pressure (U) continuously during soil penetration. In contrast to the conventional CPT, the CPTu incorporates a piezometer, enabling the evaluation of hydrogeological conditions and soil consolidation behavior. The results provide a vertical soil profile with essential parameters including qc, fs, the friction ratio Rf (fs/qc), pore pressure U, as well as Bq and IC, which are used for soil classification [8].

2.4 Preloading

Preloading is a ground improvement technique for soft soils that involves placing a temporary surcharge, commonly using fill material, prior to the start of main construction. Its purpose is to speed up primary consolidation, enhance the soil's bearing capacity, and minimize long-term settlement. This approach is frequently combined with vertical drains, such as PVD or vacuum methods, to facilitate faster pore water dissipation and achieve the required stability [9].

2.5 Prefabricated Vertical Drain (PVD)

Prefabricated Vertical Drains (PVD) are band-shaped drainage elements inserted vertically into soft soils to reduce the travel distance of pore water toward the surface. By expediting the consolidation process particularly in soils with low permeability such as clay PVD effectively enhance soil densification. This technique is commonly applied together with preloading to achieve quicker and more uniform ground improvement outcomes [10].

2.6 Vacuum Consolidation

Vacuum consolidation is a soft soil improvement technique that does not require the placement of heavy embankment loads. The process involves applying negative pressure via a sealed membrane connected to a vacuum pump, which decreases pore water pressure and accelerates consolidation. This method is especially effective for very soft soils or locations with limited availability of fill material [11].

2.7 Geotextiles

Geotextile is a permeable, sheet like geosynthetic material produced from synthetic polymers such as polypropylene or polyester. It is widely applied in soft soil reinforcement, slope stabilization, and drainage purposes. According to its manufacturing method, geotextiles are classified into two types: woven, which provides high tensile strength for reinforcement, and non-woven, which is more suitable for filtration and protection. In this research, a woven geotextile with a tensile strength of 60 kN/m was utilized to enhance embankment stability on soft soils [12].

2.8 Load Criteria

In this study, the traffic load is determined based on SNI 8460:2017, Article 7.5.1.2 concerning Traffic Load. A design load of 15 kPa was applied as a uniform load to represent the effect of vehicles on the road embankment. This value was selected as the minimum reference in accordance with national standards for operational road conditions [13].

2.9 Finite Element Method

The Finite Element Method (FEM) is a numerical technique employed to analyze the interaction between soil and structures [14]. In this research, FEM was utilized to assess the performance of soil improvement techniques, namely PVD with preloading and vacuum consolidation. The analysis focused on soil response to loading, distribution of effective stress, deformation, and pore water movement.

3 Research Methodology

See Fig. 1.

3.1 Project General Description

The toll road project under study is situated in the Rimbo Panjang area, Pekanbaru, with a total length of approximately 2.4 km. This research specifically focuses on the section between STA 1 + 900 and STA 2 + 200. Soil investigations were carried out through two boreholes near STA 1 + 900 and one CPTu test at STA 2 + 175. Figure 2 presents the top view of the studied toll road alignment.

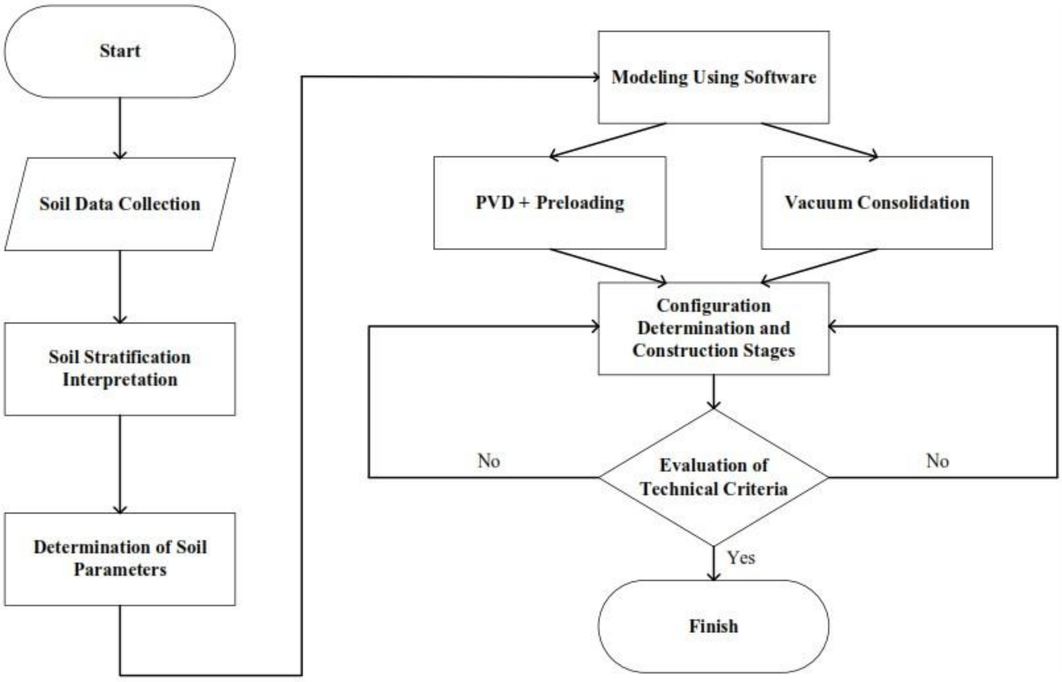

Fig. 1 Flowchart of the research process

Fig. 2 Top view of the toll road trajectory

3.2 Soil Investigation Results

The soil investigation revealed a very soft clay layer extending to a depth of approximately 4 m, underlain by a sand layer with conditions ranging from loose to dense. Figure 3 illustrates the results of the soil investigation.

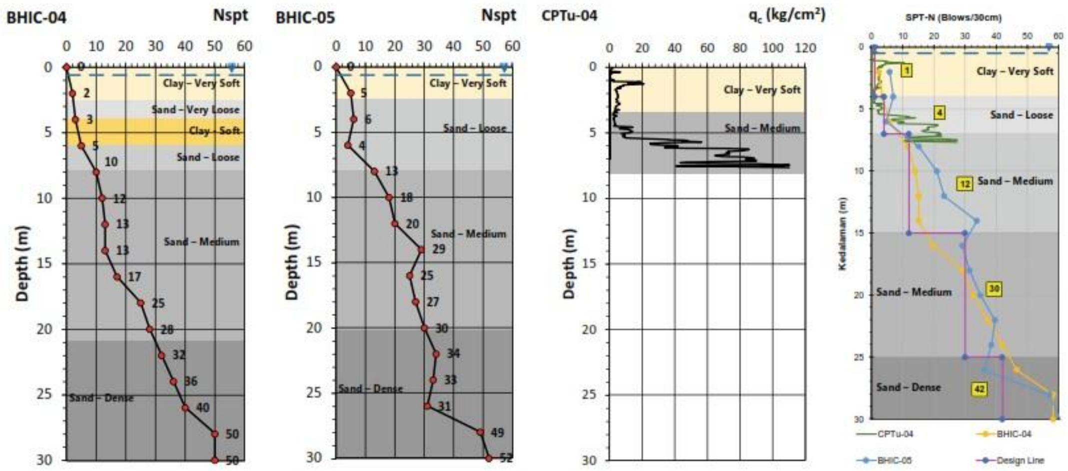

Fig. 3 Interpretation of soil investigation results

Table 1 Soil layer parameters

Depth			Nspt	Soil type	γ (kN/m³)		c′ (kPa)	φ′ (°)	E (kN/m²)	c_c	c_s	Kv (m/day)	Kh (m/day)
					Unsat	Sat							
0	–	4	1	Clay	15	16	0.6	24	300	0.84	0.17	7.55E−4	1.13E−3
4	–	7	4	Sand	16	17	1	27	3064	–	–	8.64E−1	1.73E+0
7	–	15	12	Sand	17	18	1	32	9192	–	–	8.64E−1	1.73E+0
15	–	25	30	Sand	18	19	1	39	22,980	–	–	8.64E−1	1.73E+0
25	–	30	42	Sand	19	20	1	42	32,172	–	–	8.64E−1	1.73E+0

3.3 Soil Parameters

Soil parameters for numerical modeling were derived from the interpretation of field test data. Each layer was classified according to depth and dominant soil type in order to determine its engineering properties. The interpretation of soil stratification served as the basis for defining the parameters of each layer. The planned soil profile is presented in Fig. 3 on the right. In the modeling, two constitutive models were applied: the Soft Soil Model for soft soils undergoing gradual consolidation, and the Mohr–Coulomb Model for stiffer soils or as a comparison for validation. The soil parameters were obtained from both field test results and empirical correlations based on soil type. Table 1 presents the soil parameters used in the analysis.

3.4 Road Embankment Stability and Settlement Modeling

Geotechnical modeling was carried out using Finite Element Method-based software to assess the performance of PVD + Preload and Vacuum Consolidation in reducing

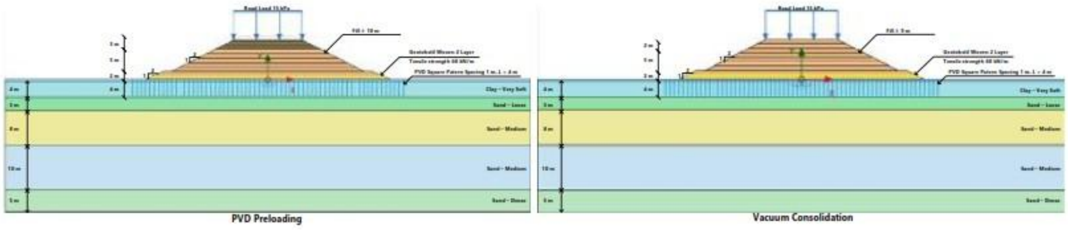

Fig. 4 Modeling PVD preloading and vacuum consolidation

Table 2 Construction stages and implementation time

PVD preloading			Vacuum consolidation		
Construction stage	Embankment height (m)	Construction time (days)	Construction stage	Embankment height (m)	Construction time (days)
Instal PVD	–	3	Instal PVD	–	3
Fill phase 1–9	9	63	Vacuum ON	–	7
Fill phase 10	10	14	Fill phase 1–8	8	56
Waiting time	–	21	Vacuum OFF	–	1
			Fill phase 9	9	14
Total construction time		101	Total construction time		81

settlement and enhancing embankment stability. The modeling was conducted on the road cross-section at STA 1 + 950, which represents the location with the highest embankment elevation of approximately 7 m. For the PVD + Preload method, the embankment was modeled at 10 m, consisting of 7 m of planned embankment and an additional 3 m surcharge, serving both as preloading and for elevation equalization with the surrounding area. In the case of Vacuum Consolidation, the embankment height was modeled at 9 m (7 m planned embankment + 2 m surcharge), with similar functions for elevation adjustment and soil densification. Figure 4 illustrates the modeling scheme for both methods.

In both methods, two layers of geotextile with a tensile strength of 60 kN/m were applied, along with PVD installed at 1 m spacing and 4 m depth. This configuration was intended to accelerate the consolidation process and ensure embankment stability during construction. Table 2 presents the comparison of construction stages and duration for each method.

4 Result and Discussion

After the modeling was completed according to the geometric configuration, material properties, and construction stages of each method, the evaluation was conducted based on two main criteria: embankment stability and ground settlement. Regarding stability, the modeling results indicated that the Vacuum Consolidation method achieved higher safety factor values than PVD + Preloading, both under short-term and long-term conditions. This finding suggests that the application of vacuum pressure provides better slope stability in soft soil conditions similar to those at the study site. Table 3 summarizes the post-operational safety factor values. Figure 5 illustrates the slip surface of the embankment slope, while Fig. 6 compares the safety factor values at each construction stage.

Meanwhile, in terms of settlement, the Vacuum Consolidation method also demonstrated better performance. Both at 1 and 10 years after operation, the resulting settlement was smaller compared to the PVD + Preloading method. This finding

Table 3 Recapitulation of safety factor values under short-term, and long-term conditions

Type criteria		Criteria	PVD + preloading	Vacuum consolidation
Safety factor	Short-term	1.35	1.45	2.12
	Long-term	1.5	1.53	2.13

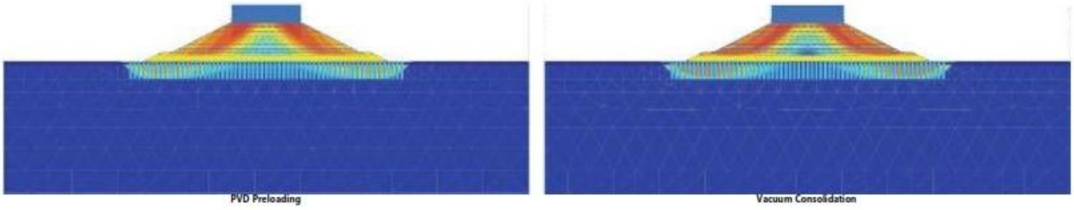

Fig. 5 Estimated slope stability based on modeling results

Fig. 6 Comparison of construction time against factor of safety values

Table 4 Recapitulation of embankment settlement

Type criteria		Criteria (cm)	PVD + preloading (cm)	Vacuum consolidation (cm)
Residual embankment settlement	1 year	2	1.38	0.76
	10 years	10	1.39	0.78

confirms that the vacuum method is more effective in accelerating soft soil consolidation and minimizing long-term settlement. Table 4 presents the magnitude of post-operational settlement at both 1 and 10 years.

5 Conclusion

The analysis revealed that the Vacuum Consolidation method consistently outperformed PVD + Preloading in both settlement and stability aspects. For post-operational settlement, Vacuum Consolidation produced significantly smaller values, with 0.76 cm compared to 1.38 cm at 1 year, and 0.78 cm compared to 1.39 cm at 10 years. In terms of stability, the safety factor values were also higher for Vacuum Consolidation, reaching 2.12 in the short term and 2.13 in the long term, whereas PVD + Preloading only achieved 1.45 and 1.53, respectively. Furthermore, total subsidence during consolidation was lower with Vacuum Consolidation (1.9 m) than with PVD + Preloading (2.1 m), reflecting better control over soil deformation. Another drawback of the PVD + Preloading method is the need for a larger embankment volume, which not only increases the risk of instability but also prolongs construction time and requires more auxiliary materials such as geotextile.

References

1. Aini IA, Maulana EI, Santoso HT (2023) Evaluasi Metode Perbaikan Tanah Lunak dengan Preloading Kombinasi PVD-PHD pada Proyek Pembangunan Jalan Tol Semarang-Demak Paket II. Bentang J Teoritis Terapan Bidang Rekayasa Sipil 11:21–36. https://doi.org/10.33558/bentang.v11i1.4622
2. Ahsan AD, Yanti G, Megasari SW (2021) Analisis Penurunan Tanah Menggunakan Metode Vacuum Consolidation Dengan Variasi Jarak Pemasangan PVD. J Konstr 13:54–68
3. Hardiyatmo H (2002) Mekanika Tanah I. Gadjah Mada University Press
4. Siska HN, Yakin YA (2016) Karakterisasi Sifat Fisis dan Mekanis Tanah Lunak di Gedebage
5. Pratama ES, Wulandari TE (2024) Analisis Konsolidasi Menggunakan Preloading dan Prefebricated Vertical Drain (PVD) Pada Proyek Pembangunan Jalan Tol Pekanbaru—Padang. J Tekn Sipil UBL 1:26–40
6. Hamdhan IN, Rahmanisa NL (2023) Pemodelan Perbaikan Tanah Lempung Lunak Menggunakan Vacuum Preloading. J Mitra Tekn Sipil 6:775–786
7. Das BM, Sobhan K (2014) Principles of geotechnical engineering, 8th edn. Cengage Learning
8. Robertson PK (2010) Interpretation of cone penetration tests—a unified approach. Can Geotech J

9. Putra CE, Chaidir D, Makarim A (2020) Analisis Alternatif Perbaikan Tanah Lunak dan Sangat Lunak Pada Jalan Tol. J Mitra Tekn Sipil 3:1137–1150. https://doi.org/10.24912/jmts.v3i4.8382
10. Shendy SG (2023) Metode Perbaikan Tanah dengan Prefabricated Vertical Drain (PVD) Pada Jalan Tol Serpong-Balaraja Seksi 1B. J Mitra Tekn Sipil 6:321–332. https://doi.org/10.24912/jmts.v6i2.21695
11. Indraratna B, Rujikiatkamjorn C (2011) Soft soil stabilization using vacuum and vertical drains
12. Sastrawinata SA (2020) Studi Pengaruh Material Geosintetik Dalam Distribusi Beban Kerja Pada Konstruksi Jalan di Atas Tanah Lunak. J Mitra Tekn Sipil 3:59–68. https://doi.org/10.24912/jmts.v3i1.7055
13. Badan Standardisasi Nasional (2017) SNI 8460:2017: Persyaratan perancangan geoteknik
14. Apriadi D, Barnessa RA, Marsa NAI (2019) Finite element study of vacuum preloading and prefabricated vertical drains behavior for soft soil improvement. J Tekn Sipil 26:189–194. https://doi.org/10.5614/jts.2019.26.3.1