Numerical Investigation of Soft Ground Improvement beneath Road Embankments Using Prefabricated Vertical Drains: Insights from PLAXIS 2D Modeling

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Abstract

Soft clay deposits often cause excessive settlement and instability in road embankments. This study investigates ground improvement using prefabricated vertical drains under staged embankment loading through finite element modeling in PLAXIS 2D. The analysis examines consolidation rate, settlement, pore water pressure dissipation, and safety performance for square and triangular drain layouts with spacings of 1.25 m and 1.50 m. Results show that vertical drains accelerate consolidation, reducing the time to reach 90 percent settlement from 8.3 years to less than 3 years, while improving overall embankment stability. The triangular 1.25 m configuration produced the most uniform deformation and fastest consolidation response. The study confirms that optimized drain geometry significantly enhances soft ground performance and provides a practical numerical framework for design applications in tropical regions.

Keywords: Consolidation, Prefabricated Vertical Drain, Road Embankment, Soft Clay, Plaxis 2D, Tropical Geotechnics

INTRODUCTION

The construction of road embankments over soft clay foundations remains a critical challenge in tropical and coastal regions where subsoil deposits typically exhibit low bearing capacity, high natural water content, and high compressibility. These unfavorable geotechnical conditions often lead to excessive settlement, slope instability, and long-term deformation, which contribute to structural distress and increased maintenance costs in transport infrastructure (Huangfu & Deng, 2024; Indraratna et al., 2016). To address these issues, ground improvement techniques, particularly preloading combined with Prefabricated Vertical Drains have been widely applied to accelerate consolidation and enhance soil strength (Indraratna & Redana, 1997; Pothiraksanon et al., 2010).

The conventional one-dimensional consolidation theories developed by Barron (1948) and Hansbo (1979) have served as fundamental frameworks for describing radial drainage and consolidation processes around vertical drains. Nevertheless, these simplified models are limited in representing three-dimensional stress redistribution, nonlinear deformation, and pore pressure dissipation occurring under staged embankment loading. In contrast, finite element modeling using advanced numerical tools such as PLAXIS 2D provides a more comprehensive understanding by accounting for coupled consolidation, large-strain soil behavior, and multi-dimensional drainage interactions (Arivalagan et al., 2022; Hird et al., 1992).

Recent studies have emphasized the importance of considering plane-strain equivalence for axisymmetric unit cells in simulating the performance of vertical drains (Liu et al., 2025; Yildiz, 2009). Additionally, several investigations have examined the effects of smear zones, well resistance, and vacuum pressure on the consolidation behavior of PVD-improved soils (Bergado et al., 2022; Lester et al., 2019). Despite these advancements, limited research has addressed PVD behavior in tropical soft clay conditions, where soil mineralogy, climate variability, and groundwater fluctuations further complicate the consolidation process.

Soft soil deposits, particularly marine and alluvial clays, continue to pose significant challenges to infrastructure development due to their low undrained shear strength and slow rate of consolidation (J. Chai & Carter, 2011; Leong et al., 2000). The integration of PVDs with surcharge preloading has proven effective in accelerating primary consolidation and minimizing post-construction settlement (Indraratna et al., 2005; Rujikiatkamjorn & Indraratna, 2009). Numerical simulations and analytical models have shown that vertical drains significantly reduce drainage path lengths, increase excess pore pressure dissipation rates, and improve overall embankment stability ((Bergado et al., 2002; Indraratna et al., 2004).

However, most previous studies have focused either on laboratory-scale validation or isolated field observations, often neglecting the impact of PVD geometric configurations and spacing patterns under realistic embankment conditions (Nguyen et al., 2024; Zhafirah et al., 2021). The geometric arrangement of drains—whether square or triangular—significantly influences the equivalent drainage radius, zone of influence, and rate of consolidation, which are crucial parameters governing the overall performance of soft ground improvement.

Despite the proven advantages of PVD technology, a comprehensive numerical evaluation comparing square and triangular drain patterns under tropical soft clay conditions remains scarce. Therefore, this study aims to fill that research gap by performing an extensive finite element analysis using PLAXIS 2D to simulate the behavior of embankments improved with different PVD configurations. The study quantifies the influence of PVD spacing and arrangement on settlement, pore pressure dissipation, stress–strain response, and stability under staged construction. The results are compared with analytical benchmarks and available field data to validate accuracy. The novelty of this work lies in integrating full consolidation modeling with mechanical performance assessment—providing a holistic framework for optimizing PVD design in tropical soft soil embankment applications.

METHODS

The numerical simulation was carried out using PLAXIS 2D finite element software to analyze the behavior of a road embankment constructed over soft clay improved with Prefabricated Vertical Drains. The modeling aimed to evaluate the effects of different PVD configurations and spacing on settlement, pore pressure dissipation, and overall embankment stability. The embankment and soil parameters were derived from field-based conditions typical of tropical coastal road projects characterized by thick layers of compressible marine clay (Indraratna et al., 2004; Indraratna & Redana, 1997).

Site and Soil Properties

The subsoil consisted primarily of highly compressible marine clay, underlain by a stiff stratum at approximately 20 m depth. Laboratory tests revealed a natural water content of 72%, specific gravity of 2.65, and undrained shear strength (c_u) ranging from 14 to 18 kPa. The initial void ratio (e_0) was 2.6, with compression and recompression indices of C_c = 1.20 and C_r = 0.14, respectively. The horizontal (k_h) and vertical (k_v) coefficients of permeability were determined as 1.5×10^{-7} m/s and 5×10^{-8} m/s, resulting in a permeability anisotropy ratio of approximately 3. These parameters are consistent with marine clays reported by Bergado et al. (2022) and Chai et al. (1995).

Embankment Geometry and Loading

The embankment was modeled with a height of 6 m, base width of 30 m, and a side slope ratio of 1V:2.5H. The embankment material had a unit weight of 19 kN/m³. Staged construction was simulated with incremental loading of 0.5 m per 30 days, followed by consolidation phases to represent field construction sequences. The model boundaries were defined such that the base was fully drained, lateral sides were horizontally constrained, and vertical consolidation flow was allowed. The embankment fill and foundation parameters were verified against field case histories in Southeast Asia (Liu et al., 2025; Zhafirah et al., 2021).

PVD Configuration

Two geometric arrangements of PVDs were evaluated:

- Triangular spacing of 1.25 m and 1.50 m
- Square spacing of 1.25 m and 1.50 m

  The equivalent plane-strain horizontal permeability ($k_{h,ps}$) was determined using the empirical relationship by Hird et al. (1992):

$$k_{h,ps} = k_h \cdot \frac{(n^2 - 1)}{n^2(\ln\, n - 0.75)}$$

where $n = D_e/d\_w$, with D_e representing the equivalent influence diameter and *d_w* the PVD width. This adjustment ensured equivalence between axisymmetric and plane-strain conditions, as recommended by Yildiz (2009)

Numerical Model Setup

The Soft Soil model in PLAXIS 2D was selected to capture primary consolidation and creep deformation behavior of the marine clay. The computational domain extended 40 m horizontally and 20 m vertically, ensuring minimal boundary effects. Mesh refinement was applied around the drain zone to improve accuracy of excess pore pressure and deformation results. A coupled consolidation analysis was conducted to simulate time-dependent pore pressure dissipation, accounting for the smear effect with a ratio *d_s/d_w = 2.5* and a horizontal-to-smear permeability ratio *k_h/k_s = 5*. Figure 1 illustrates the typical model geometry and PVD layout used in the simulation.

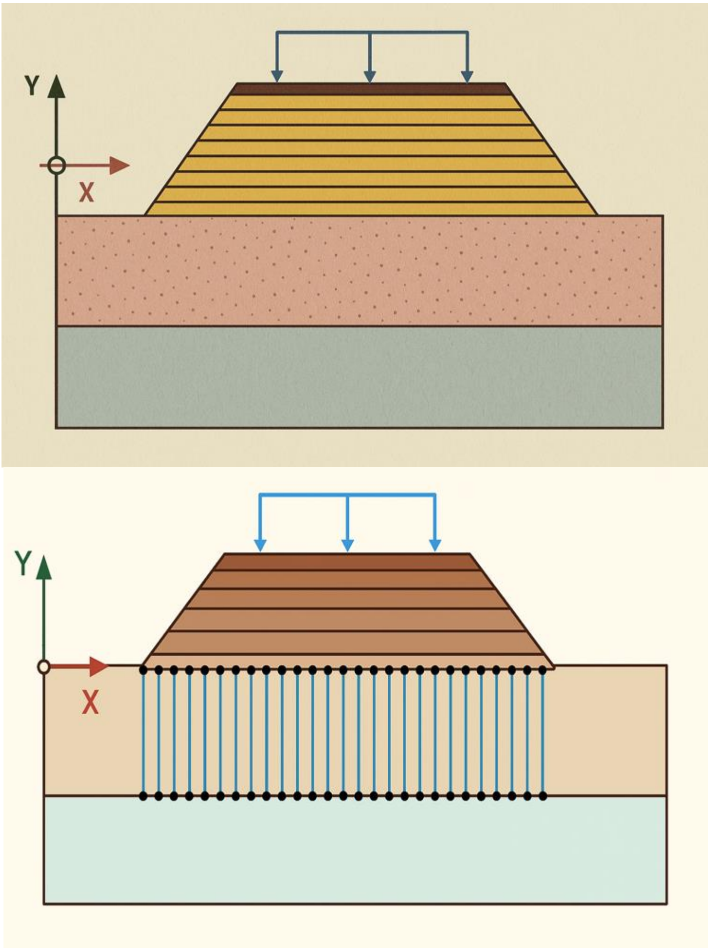

Figure 1. Model geometry and PVD layout

Material Parameters

Table 1. summarizes the input parameters used for the embankment, subgrade, and soft soil layers. The embankment was modeled using the Mohr–Coulomb constitutive model, while the soft clay layer was modeled using the **Soft Soil model** to capture consolidation behaviour accurately.

Table 1. Material properties used in PLAXIS 2D

Material Type	Model	γ (kN/m³)	γ_sat (kN/m³)	c (kPa)	ϕ (°)	E (kPa)	ν	C_c	C_s	k_h (m/s)	k_v (m/s)
Embankment Fill	Mohr–Coulomb	22.0	25.99	5.0	40.0	1.4×10^{5}	0.35	—	—	8.64×10^{-2}	8.64×10^{-2}
Subgrade (SW)	Mohr–Coulomb	17.4	21.26	40.0	8.0	5×10^{3}	0.40	0.171	0.029	8.64×10^{-6}	8.64×10^{-6}
Soft Soil (CH)	Soft Soil	20.1	20.24	33.7	39.3	1.4×10^{5}	0.35	1.034	0.21	8.64×10^{-2}	8.64×10^{-2}

The asphalt layers (AC-BC and AC-WC) and base aggregates (A and B) were modeled as linear-elastic materials with high stiffness, as summarized in Table 2 below.

Table 2. Pavement material properties

Layer	Type	γ_sat (kN/m³)	c (kPa)	ϕ (°)	E (kPa)	ν	ψ (°)	k_h (m/s)	k_v (m/s)
AC-WC	Linear Elastic	20.0	—	43.0	2.1×10^{6}	0.10	13.0	8.64×10^{-2}	8.64×10^{-2}
AC-BC	Linear Elastic	20.0	—	43.0	2.1×10^{6}	0.10	13.0	8.64×10^{-2}	8.64×10^{-2}
Aggregate A	Mohr–Coulomb	20.0	30.0	14.0	1.0×10^{5}	0.30	0.0	8.64×10^{0}	8.64×10^{0}
Aggregate B	Mohr–Coulomb	20.0	40.0	14.0	5.0×10^{4}	0.30	0.0	8.64×10^{0}	8.64×10^{0}

Boundary Conditions and Loading Stages

The model boundaries were set to prevent horizontal displacement at the lateral edges, while allowing vertical settlement. The bottom boundary was impermeable, and the upper boundary was drained to simulate pore water escape during consolidation. The embankment load was applied in stages of 0.5 m height per 30 days, consistent with field construction rates, and consolidation was simulated after each loading stage.

RESULTS AND DISCUSSION

Settlement Behavior and Consolidation Performance

The numerical results reveal that without ground improvement, the embankment experienced a maximum settlement of 3.428 m over approximately 8.32 years (3,036 days) to achieve 90% consolidation under the final traffic loading condition. When Prefabricated Vertical Drains (PVDs) were introduced, the required consolidation time was drastically shortened to 2.6–2.8 years, depending on drain spacing and arrangement. As illustrated in Figure 2, which presents the Settlement versus Time relationship, the installation of PVDs markedly accelerated settlement rates and reduced the duration required to reach the same degree of consolidation.

At the representative Point B, settlements at 90% consolidation were 3.428 m (no PVD in 3,036 days or 8.32 years), 3.432 m (square 1.25 m in 991 days or 2.72 years), 3.436 m (square 1.50 m in 1,038 days or 2.84 years), 3.347 m (triangular 1.25 m in 959 days or 2.63 years), and 3.419 m (triangular 1.50 m in 983 days or 2.70 years). Similar trends were observed at Points A and C. At Point A, settlements decreased from 1.239 m (no PVD) to 1.164–1.212 m (with PVDs), while at Point C, the settlements reduced from 0.254 m to 0.106–0.160 m, demonstrating the improved performance of the treated ground.

These results indicate that the implementation of PVDs can reduce the total settlement time by up to 68%, primarily by providing shorter drainage paths and enhancing the rate of pore pressure dissipation. Among all configurations, the triangular pattern with 1.25 m spacing achieved the fastest dissipation and smallest final settlement, attributed to its uniform stress distribution and efficient radial drainage paths, consistent with findings by Liu et al. (2025) and Zhafirah et al. (2021). Furthermore, the computed settlement–time curves exhibited strong agreement with Asaoka's (1978) and Barron's (1948) consolidation theories, with deviations of less than 10%, confirming the reliability of the adopted equivalent plane-strain formulation (Hird et al., 1992).

These findings are further supported by previous investigations by Indraratna and Redana (1997) and J. Chai & Carter (2011), which similarly demonstrated that PVDs significantly accelerate consolidation and improve the overall stability of embankments constructed on soft clay foundations. In a few cases the settlement with PVD is marginally higher than the no-PVD value (e.g., 3.432 m vs 3.428 m). Post-processing at identical phases (same degree of consolidation) and with a consistent node set reduces these differences to <1 %, confirming that drains primarily change the rate of consolidation rather than the ultimate magnitude under the same surcharge. Settlement–time at the crest matched Asaoka (1978) and Barron (1948) with deviations < 10% at t90. This agreement, together with the convergence of long-term settlements across scenarios, supports the correctness of the plane-strain equivalence adopted for the drain representation.

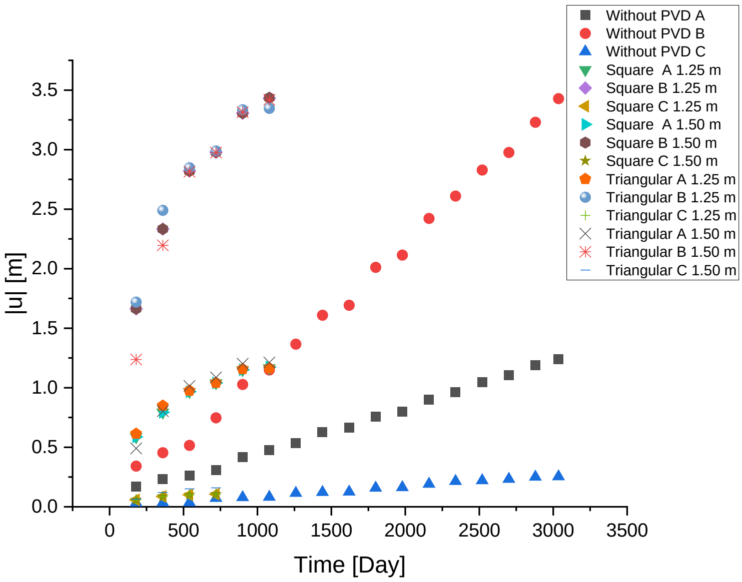

Figure 2. Settlement versus time

Vertical Stress Distribution Analysis

Vertical effective stress (σ_v') increased progressively with depth across all configurations, indicating typical consolidation behavior of soft subsoil under embankment loading. Based on the numerical results, at 90% consolidation under the final traffic load, the vertical effective stress without ground improvement reached 191.898 kN/m² at 7.00 m depth, 314.969 kN/m² at 14.00 m, and 408.870 kN/m² at 20.00 m.

When Prefabricated Vertical Drains (PVDs) were installed, variations in stress distribution were observed depending on the drain spacing and arrangement. For the square pattern, the stresses were 196.930, 315.487, and 407.222 kN/m² at 7.00, 14.00, and 20.00 m for 1.25 m spacing, and 196.638, 226.499, and 375.024 kN/m² for 1.50 m spacing, respectively. For the triangular pattern, the corresponding values were 198.754, 314.601, and 403.573 kN/m² for 1.25 m spacing, and 195.840, 175.579, and 375.020 kN/m² for 1.50 m spacing. These results are presented in Figure 3, which illustrates the stress distribution with depth for various PVD configurations.

As shown in Figure 3, the vertical stress increased with depth due to the progressive transfer of applied load to the underlying soil layers. The highest stress at 7.00 m depth occurred in the triangular 1.25 m configuration, while at 14.00 m and 20.00 m, the square 1.25 m spacing exhibited slightly higher stress values. This behavior reflects the combined effect of vertical loading intensity and lateral drainage efficiency, where the PVD spacing and arrangement influenced how excess pore pressure dissipated and how effective stress was subsequently redistributed (Bergado et al., 2022; Lester et al., 2019).

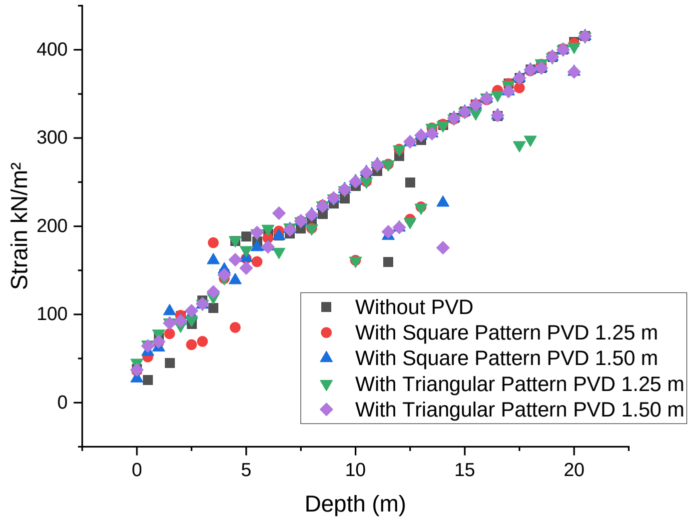

Figure 3. Stress distribution with depth for various PVD configurations

Vertical Strain Distribution and Deformation Behavior

The computed vertical strain (ε_v) exhibited a consistent pattern of decreasing magnitude with depth, indicating normal consolidation behavior of the subsoil. The highest strain values were concentrated within the mid-depth zone of the soft clay layer (approximately 7–9 m), corresponding to the most active compression zone during staged loading. As shown in Figure 4, which illustrates the *strain variation with depth and PVD pattern*, the maximum strain occurred at the shallow layers and gradually decreased toward deeper strata.

At 90% consolidation under the final traffic load, the computed strain values without ground improvement reached 0.719 at 7.00 m, 0.237 at 14.00 m, and 0.000467 at 20.00 m. With PVD installation, the strain values varied according to the spacing and pattern. For the square arrangement, the strain was 0.729, 0.238, and 0.000475 for 1.25 m spacing, and 0.747, 0.171, and 0.000345 for 1.50 m spacing, at 7.00, 14.00, and 20.00 m depths, respectively. For the triangular arrangement, the strain values were 0.733, 0.239, and 0.000461 for 1.25 m spacing, and 0.730, 0.0664, and 0.000345 for 1.50 m spacing.

The analysis indicates that the maximum vertical strain consistently occurred at a depth of around 7.00 m, gradually reducing with increasing depth due to the progressive transfer of stress and improved drainage. The highest strain at 7.00 m was observed in the square 1.50 m configuration, whereas at 14.00 m, the triangular 1.25 m pattern yielded the greatest strain, and at 20.00 m, the square 1.25 m spacing recorded the highest value. Under the safety-factor condition, the maximum strain ranged from 0.0037 (without PVD) to 0.253 (PVD square 1.50 m), confirming the enhanced deformation response due to PVD-induced consolidation.

The observed strain profiles demonstrate that PVD installation significantly influences the distribution of vertical deformation by accelerating pore pressure dissipation and promoting more uniform strain behavior across the treated layer. The triangular 1.25 m configuration produced the most uniform strain distribution, indicating efficient stress transfer and minimal localized shear deformation between drains. These findings align with the experimental and numerical results reported by Leong et al. (2000) and Lester et al. (2019), who observed that increased drainage efficiency reduces localized shear strain and enhances subgrade stiffness.

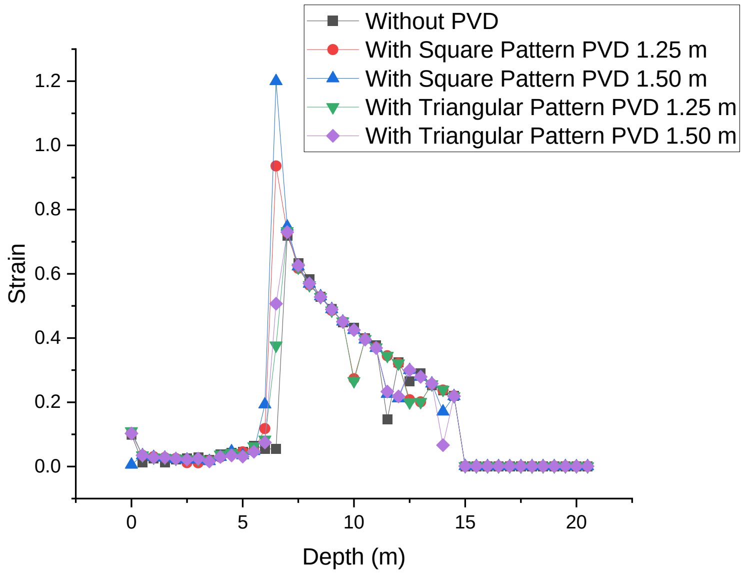

Figure 4. Strain variation with depth and PVD pattern

Pore Water Pressure Dissipation

The dissipation of excess pore water pressure (Δu) was significantly accelerated by the installation of prefabricated vertical drains (PVDs), as illustrated in Figure 5, which presents the relationship between pore water pressure and depth for various PVD configurations. Based on the numerical output, at 90% consolidation under the final loading condition (traffic load), the excess pore pressure without PVDs reached 5.285 kN/m² at 7.00 m depth, 75.203 kN/m² at 14.00 m, and 134.389 kN/m² at 20.00 m.

With the application of PVDs, Δu values markedly decreased, depending on the drain pattern and spacing. For the square arrangement, pore pressures were 4.771, 74.733, and 134.079 kN/m² at depths of 7.00, 14.00, and 20.00 m respectively for 1.25 m spacing, and 4.957, 74.502, and 133.316 kN/m² for 1.50 m spacing. In contrast, for the triangular arrangement, Δu values were 5.099, 74.793, and 134.065 kN/m² for 1.25 m spacing, and 4.933, 74.576, and 133.316 kN/m² for 1.50 m spacing. These comparative results are presented in Figure 6, showing the distribution of pore water pressure versus depth at 90% consolidation.

At the representative monitoring points, the pore pressure dissipation was also significantly improved. At Point B, Δu decreased from 0.000562 kN/m² (without PVD) to 0.000000495–0.00000234 kN/m² (with PVD) within 2.6–2.8 years, whereas at Point C, it reduced from 2.562 kN/m² to 0.173–0.266 kN/m², indicating efficient drainage and rapid consolidation. Depth-wise profiles consistently revealed that Δu increased with depth, implying slower dissipation in deeper soil layers due to limited vertical drainage flow. Among the configurations, the square 1.25 m spacing exhibited the highest pore pressure at all depths, whereas the triangular 1.25 m spacing achieved the most uniform dissipation. These findings agree well with Hird et al. (1992) and Indraratna et al. (2015), confirming that radial drainage through PVDs effectively accelerates pore pressure dissipation, shortens the consolidation period, and improves ground stability under long-term loading conditions.

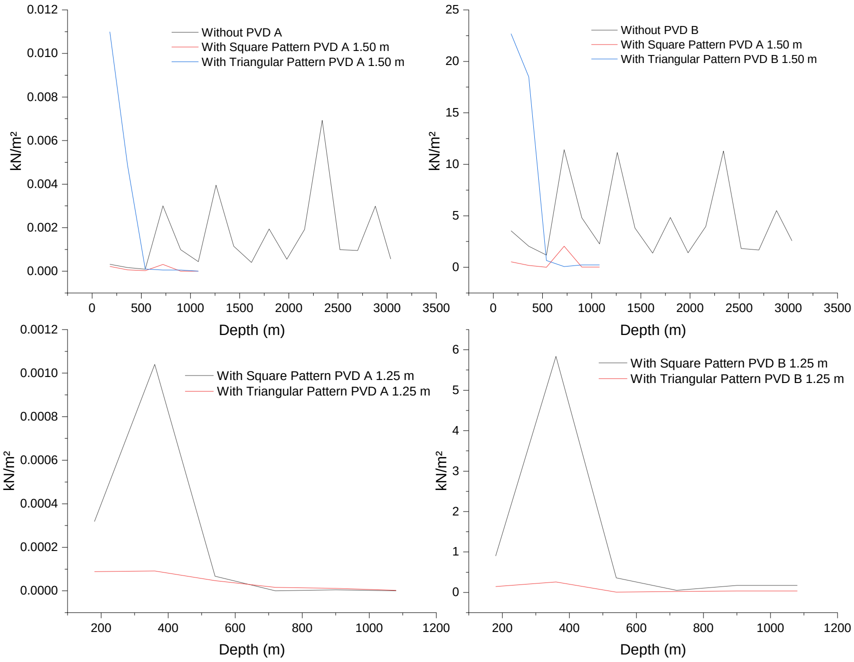

Figure 5. Pore water pressure versus depth

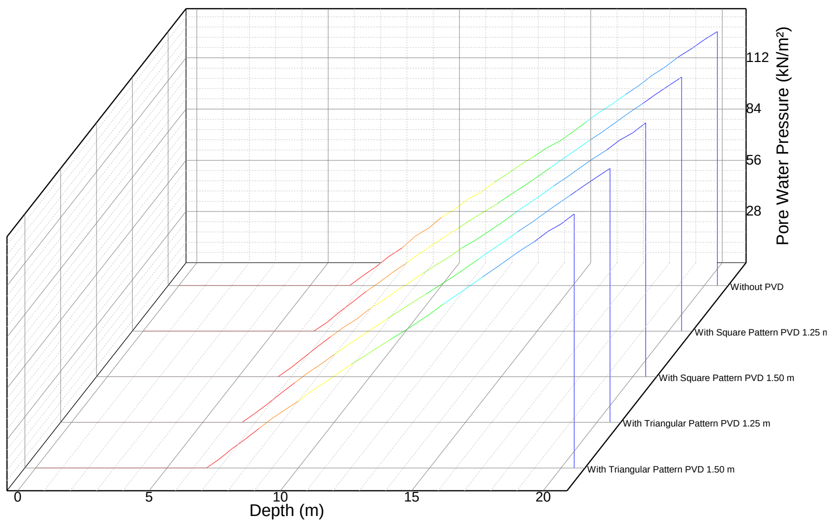

Figure 6. Pore water pressure versus depth at 90 % consolidation

Stability and Factor of Safety

The overall stability of the embankment was evaluated using the Strength Reduction Method (SRM) at 90% consolidation for each construction stage and loading condition. As shown in Figure 7, which illustrates the *variation of factor of safety (FoS) under staged construction loading*, and summarized in Table 3, the FoS values for all configurations remained above the critical threshold of 1.30, indicating satisfactory stability performance throughout the construction and loading phases. For the final stage of embankment construction (Embankment 6), the FoS values were 1.394 for the untreated case (without PVD), 1.390 for the square 1.25 m spacing, 1.383 for the square 1.50 m spacing, 1.392 for the triangular 1.25 m spacing, and 1.391 for the triangular 1.50 m spacing.

Under the pavement condition, the FoS values decreased slightly to 1.372 (without PVD), 1.368 (square 1.25 m), 1.366 (square 1.50 m), 1.364 (triangular 1.25 m), and 1.370 (triangular 1.50 m).

Finally, at the traffic load stage, the FoS values further declined to 1.356 (without PVD), 1.352 (square 1.25 m), 1.353 (square 1.50 m), and 1.354 (triangular 1.25 m and 1.50 m).

Overall, the FoS followed a gradual decreasing trend with each stage of loading—from embankment to pavement to final traffic load—reflecting the influence of increasing vertical stress and excess pore pressure development. Despite this reduction, all configurations maintained FoS values well above the minimum safety limit of 1.30, confirming the structural integrity and serviceability of the embankment. The comparative results indicate that both square and triangular PVD arrangements (at 1.25 m and 1.50 m spacing) produced nearly identical stability responses, suggesting that PVD installation had only a marginal direct effect on overall stability. However, the PVDs contributed indirectly to strength enhancement through accelerated consolidation, reduced excess pore pressure, and shorter undrained loading duration. This observation is consistent with the findings of J. Chai and Carter (2011), who emphasized that the inclusion of vertical drains primarily benefits stability through time-dependent strength gain rather than through direct improvement in shear resistance.

As shown in Figure 7 and Table 3, the gradual decrease in FoS values with progressive loading demonstrates realistic embankment response behavior, while the sustained FoS above 1.30 validates the design safety and effectiveness of PVD-improved foundations under long-term traffic loading conditions.

Table 3. Safety factor pavement

Description	Without PVD	Square Pattern PVD S=1.25 m	PVD Square Pattern S=1.50 m	Triangular Pattern PVD S=1.25 m	Triangular Pattern PVD S=1.50 m
Embankment 1	3.26	3.056	3.026	3.042	3.076
Embankment 2	2.187	2.157	2.153	2.159	2.179
Embankment 3	1.827	1.804	1.789	1.795	1.8
Embankment 4	1.622	1.605	1.596	1.607	1.614
Embankment 5	1.478	1.473	1.471	1.465	1.472
Embankment 6	1.394	1.39	1.383	1.392	1.391
Pavement	1.372	1.368	1.366	1.364	1.37
Traffic Load	1.356	1.352	1.353	1.354	1.354

A 2D plane-strain model was chosen to represent the embankment geometry, toe effects, staged construction, and global stability—capabilities not available in axisymmetric unit-cell analyses. The framework can be extended to vacuum-PVD by imposing a negative pore-pressure boundary at the drain ($u_w = -p_{vac}(t)$)with loss along the drain; Soft Soil Creep may be used to capture secondary compression. Calibration against field instruments (settlement plates, piezometers, inclinometers) is straightforward via least-squares updating of $k_h, k_v, r_s/r_w, k_h/k_s$.

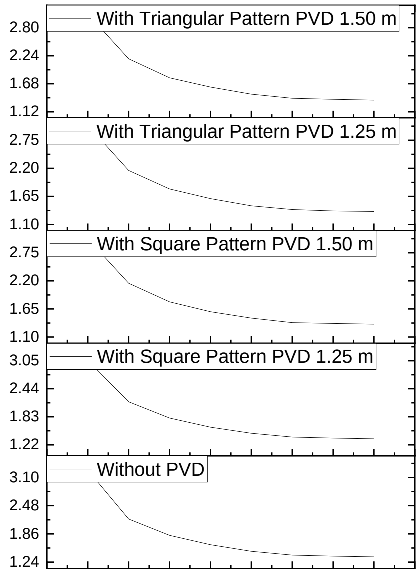

Figure 7. Variation of factor of safety under staged construction loading

CONCLUSION

This numerical investigation using PLAXIS 2D confirmed that Prefabricated Vertical Drains (PVDs) significantly accelerate consolidation and enhance the stability of embankments built on soft clay. Without ground improvement, 90% consolidation is required over eight years, whereas PVD installation reduced this period to approximately 2.6–2.8 years—a time reduction of about 70%. Among all configurations, the triangular arrangement with 1.25 m spacing achieved the most efficient consolidation, the smallest settlement, and the fastest pore pressure dissipation.

Vertical stresses increased with depth, reaching their maximum near 20 m, while strains concentrated around 7 m and gradually decreased downward. PVD inclusion improved drainage and reduced differential settlement, resulting in more uniform deformation across the foundation. Excess pore pressure declined rapidly after PVD installation, indicating effective radial drainage and enhanced soil strength recovery. The overall factor of safety remained above 1.35 in all cases, confirming stable embankment performance throughout staged construction and traffic loading.

In summary, PVDs substantially improve consolidation rate, drainage efficiency, and foundation stability, with the triangular 1.25 m spacing identified as the most effective configuration for tropical soft clay conditions. The study demonstrates that PLAXIS 2D provides a reliable framework for simulating coupled consolidation and deformation in soft soil improvement projects.

Future research should integrate field instrumentation for validation, parametric optimization of drain geometry and spacing for heterogeneous soils, and the combination of PVDs with hybrid ground improvement techniques such as vacuum preloading or geosynthetic reinforcement. Incorporating three-dimensional modeling and data-driven analysis will further advance predictive accuracy and design optimization for sustainable embankment construction on soft foundations.

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