Volume: 14 | Number: 01 | April 2025 | ISSN: 1907-4247 (Print) | ISSN: 2477-4863 (Online) | Journal Homepage: https://cantilever.id

Cantilever

Jurnal Penelitian dan Kajian Bidang Teknik Sipil

OPEN ACCESS

Research Article

Performance of Slab-on-Pile and Embankment Foundations in Soft Clay under Subsidence Conditions: A Case Study from Northern Java

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Received: 10 May 2025, Accepted: 12 July 2025, Published: 22 July 2025

Abstract

The northern coast of Java is a critical economic corridor in Indonesia but faces severe geotechnical and environmental challenges, including erosion, flooding, and land subsidence. In the Semarang–Demak Plain, land subsidence is a major concern due to thick, compressible clay deposits and shallow groundwater, which pose significant risks to infrastructure stability. The Semarang–Demak Toll Road, connecting Semarang City and Demak Regency, was constructed using two foundation systems: slab-on-pile and embankment with prefabricated vertical drains (PVD). At the interchange between Pantura Road and the toll road, a slab-on-pile foundation was selected to address high settlement risks. This study evaluates and compares the performance of both foundation types using one-dimensional analysis and two-dimensional finite element analysis (FEA). The results show that the slab-on-pile system experienced settlements of 0.519 m (one-dimensional analysis) and 0.775 m (FEA), while the embankment with PVD resulted in significantly higher settlements of 2.533 m (one-dimensional analysis) and 1.038 m (FEA). The slab-on-pile foundation also achieved a shorter consolidation period and a higher safety factor. These findings confirm the effectiveness of the slab-on-pile system in minimising settlement and improving long-term performance under challenging soil conditions. The study underscores the importance of selecting appropriate foundation strategies in subsidence-prone coastal areas and provides practical insights for infrastructure planning and geotechnical design in similar environments.

Keywords: *Finite element analysis, Land subsidence, Prefabricated vertical drains, Settlement analysis, Slab on pile.*

1. INTRODUCTION

Geotechnical challenges in coastal areas, particularly those involving soft ground conditions, pose significant risks to infrastructure development and sustainability [1], [2], [3]. These challenges are especially critical in countries like Indonesia, the world's largest archipelagic nation, comprising approximately 17,508 islands with a coastline of about 91,363.65 km and a total land area of roughly 1.90 million square kilometres [4]. Indonesia's extensive coastal zones offer considerable strategic and economic value, supporting vital sectors such as fisheries, maritime transport, manufacturing, and tourism. However, these regions are increasingly exposed to complex and interrelated environmental problems, including shoreline erosion, marine pollution, recurrent flooding, tidal inundation, and progressive land subsidence. These geohazards are often exacerbated by rapid urbanisation, high population density, and unsustainable exploitation of natural resources [5]. As a result, managing geotechnical risks in coastal environments has become a pressing concern for engineers, planners, and policymakers aiming to ensure long-term resilience and functionality of infrastructure systems [6].

Among Indonesia's many coastal regions, the north coast of Java has drawn particular attention due to its dense population, industrial concentration, and severe geohazards. Several studies have documented the widespread occurrence of coastal erosion, tidal flooding, and land subsidence, especially in low-lying urban and peri-urban zones [7], [8]. These phenomena have adversely affected urban coastal regions, causing structural damage to buildings, deterioration of road infrastructure, and increased disaster risk, all of which threaten long-term sustainable development.

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DOI: https://doi.org/10.35139/cantilever.v14i1.463

One of the most pressing geotechnical concerns in this region is land subsidence, which significantly exacerbates the impacts of other hazards such as tidal flooding, saline intrusion, and stormwater inundation. The subsidence rate along the north coast of Java ranges from 1 to 20 cm/year [9], making it one of the most affected coastal zones in Southeast Asia. In the Semarang–Demak Plain, subsidence rates are particularly high, ranging between 0.9 and 8.4 cm/year [7], [10]. This phenomenon results from both natural processes, such as sediment compaction and tectonic activity, and anthropogenic drivers, including excessive groundwater extraction, uncontrolled land development, heavy surface loads, and reclamation projects. The cumulative effects of these forces have made the region especially vulnerable to infrastructure failures and service disruptions.

Infrastructure projects in subsiding areas like Semarang–Demak require specialised geotechnical solutions. Traditional shallow foundations are often unsuitable due to the deep soft clay layers and high water table. Previous research has proposed several countermeasures, including prefabricated vertical drains (PVD) to accelerate consolidation, deep soil mixing, micro piles, and slab-on-pile that bypass compressible soils [1], [3], [11], [12]. While these approaches have shown varying degrees of success, there remains a lack of comparative, site-specific analysis of their performance in Java's coastal subsidence zones.

Given these challenges, the development of resilient infrastructure in the Semarang–Demak Plain demands foundation systems that can minimise long-term settlement while maintaining structural integrity under complex loading and drainage conditions. In particular, transport infrastructure such as toll roads is highly sensitive to vertical deformation. Excessive settlement can lead to pavement cracking, drainage system failure, slope instability, and even total roadway collapse, potentially resulting in significant economic losses and risks to human safety, particularly in areas intersecting major transportation corridors such as the Pantura Road.

This study evaluates the foundation design strategies adopted for the Semarang–Demak Toll Road, with a focus on the interchange between the Pantura Road and the new toll alignment (Figure 1). The foundation systems assessed in this research include a slab-on-pile foundation, which transfers vertical loads to deeper, more competent soil layers and effectively bypasses soft clay deposits, and an embankment with PVD, which accelerates primary consolidation by shortening drainage paths in low-permeability soils.

By comparing the settlement behaviour and structural performance of these two approaches, this research aims to identify the optimal design strategy for infrastructure development in highly compressible, subsiding coastal zones. The analysis includes both one-dimensional and finite element models, with results calibrated to geotechnical field data from 31 boreholes in the project area. The objective of this paper is to provide a comparative evaluation of slab-on-pile and embankment with PVD systems in mitigating land subsidence and ensuring long-term serviceability of critical road infrastructure. The findings are expected to contribute to better-informed planning and design practices for geotechnical engineering in coastal environments, particularly in regions experiencing rapid subsidence due to urbanisation and environmental change.

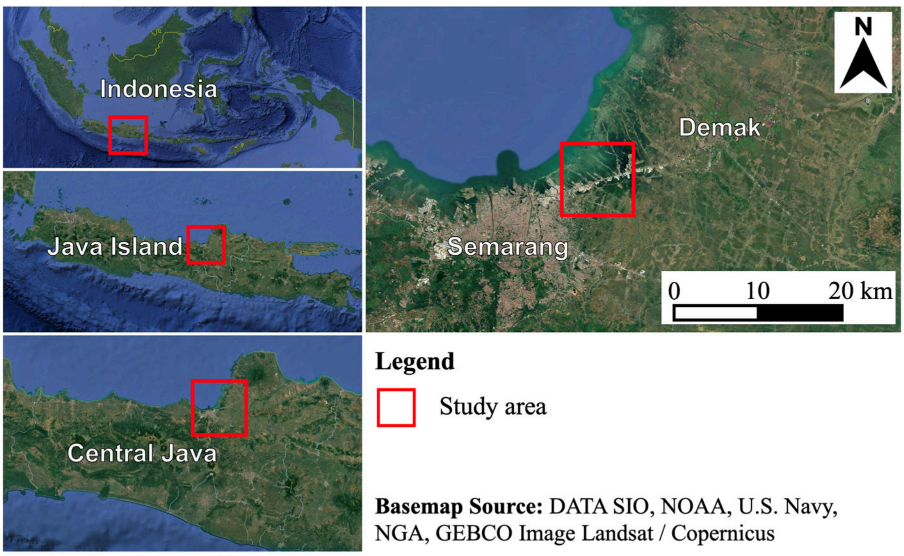

Figure 1. Location of the study area at the intersection between the Pantura Road and the Semarang–Demak Toll Road, Central Java, Indonesia (modified from [13]).

DOI: https://doi.org/10.35139/cantilever.v14i1.463

2. METHOD

This study employs a combination of geological characterisation, site-specific geotechnical investigation, and analytical modelling to evaluate settlement performance under two foundation systems: slab-on-pile and embankment with PVD. The methods are divided into three parts: an overview of the geological conditions in the Semarang–Demak Plain, a description of the study location and data sources, and the analytical procedures used to assess settlement behaviour.

2.1. Geological Condition

The Semarang–Demak Plain is a coastal lowland located in northern Java, encompassing the cities of Semarang and Demak. Geologically, this region is dominated by Quaternary alluvial deposits (Qa), which overlie older formations such as the Bulu Formation (Tmb) and the Damar Formation (QTd), as shown in Figure 2. These Quaternary sediments were formed through prolonged sediment transport, deposition, and consolidation processes, influenced by marine transgressions and regressions since the Late Pleistocene [10]. As a result, the northern part of the plain is characterised by low-lying coastal terrain, gradually transitioning into hilly areas in the south.

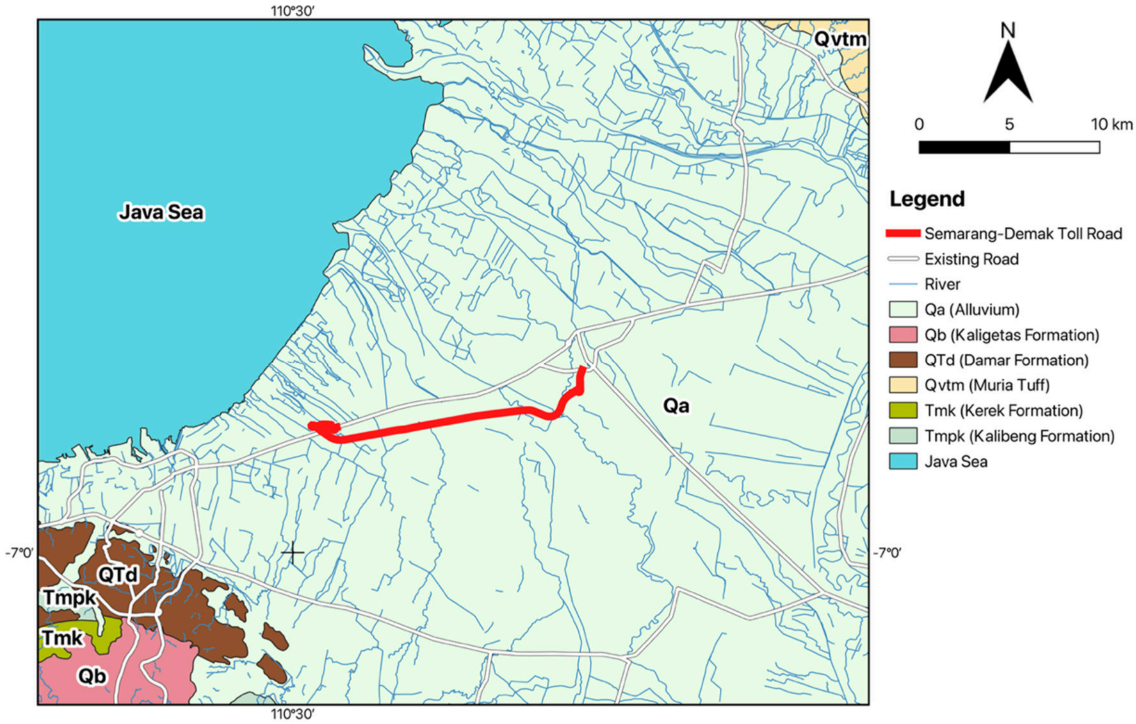

Figure 2. Geological map of the Semarang–Demak Plain, showing the alignment of the Semarang–Demak Toll Road in relation to local geological formations. (modified from [14], [15]).

Geophysical and geotechnical investigations in the region have revealed thick layers of normally consolidated soft clay, with boreholes extending up to 70 meters deep. These investigations show that soft clay deposits can reach depths of approximately 38 meters, with hard soils typically found below 40 meters. Shallow groundwater conditions, often reaching the surface, further complicate the geotechnical profile, contributing to soil behaviour that is highly susceptible to land subsidence. In some areas, particularly along the coast in Demak, land subsidence rates have been recorded at up to 2.2 cm/year [10] mainly due to natural compaction processes.

Such conditions pose significant challenges to infrastructure development and demand specialised foundation solutions to ensure long-term structural performance. The Semarang–Demak Toll Road project addresses these challenges by implementing two foundation techniques: the slab-on-pile system and embankments with PVD**.** This study evaluates the effectiveness of these two approaches under the prevailing soil and hydrogeological conditions.

2.2. Study Location

The assessment of the slab-on-pile and embankment foundation systems was conducted at the Semarang–Demak Toll Road Package 2 construction site, located in Sayung Lor, Demak Regency, Central Java Province, Indonesia. The specific study location is situated at the intersection of the Pantura Road and the Semarang–Demak Toll

DOI: https://doi.org/10.35139/cantilever.v14i1.463

Road, with the coordinates is 6°56'23.02"S and 110°30'54.11"E.

The data used in this study were obtained from detailed geotechnical investigation reports conducted along the project alignment. These included soil mechanical properties and penetration resistance data derived from 31 borehole locations, strategically distributed throughout the study area.

2.3. Settlement Analysis

Settlement performance was analysed for two foundation types: the slab-on-pile design and the embankment with PVD design. Two analytical approaches were employed: (1) one-dimensional analysis, and (2) FEA.

2.3.1. One-dimensional analysis

For the slab-on-pile design, Vesic's method [16] was used, which decomposes total settlement into three components: (1) axial deformation of the pile shaft, (2) point settlement due to tip resistance, (3) shaft settlement due to side friction. For the embankment with PVD system, Johnson's method [17] was applied, which estimates consolidation settlement by incorporating: (1) overburden pressure, (2) foundation load pressure, (3) surcharge pressure. The time rate of consolidation was further assessed using both the Casagrande logarithmic method [18] and Taylor's square-root-of-time method [19], allowing for a comprehensive evaluation of the consolidation behaviour and expected settlement duration under embankment loading.

2.3.2. FEA using PLAXIS 2D

To complement the one-dimensional analysis, a two-dimensional FEA was conducted using PLAXIS 2D. This software enables a detailed simulation of soil–structure interaction and consolidation behaviour under varying loading and drainage conditions. The model was constructed using a 2D cross-section that represents the typical foundation profile, either slab-on-pile or embankment with PVD, with appropriate boundary conditions, such as vertical rollers on lateral boundaries and a fixed base. Soil stratigraphy was defined based on borehole data, incorporating soft clay layers, underlain by denser soils. The soft clay and stiffer layers were modelled using the Mohr-Coulomb model. Key material parameters used in the analysis included unit weight (γ), Young's modulus (E), Poisson's ratio (ν), cohesion (c), internal friction angle (φ), and permeability (k_x, k_y), where in this study we use the source of value parameters from laboratory tests and empirical correlations as detailed in Table 1. Drainage conditions were assigned according to the permeability of each soil layer and boundary assumptions. The construction process was simulated using PLAXIS's staged construction feature, and mesh refinement was applied, particularly in the pile and embankment zones, to enhance numerical accuracy.

The soil parameters used in the Mohr-Coulomb constitutive model were derived from a combination of direct laboratory test results and empirical correlations based on SPT values. For deeper hard clay layers beyond the depth of the borehole termination, parameter estimation was conducted using standard empirical correlations reported in the literature [20] due to limited site data.

In the PLAXIS 2D model, drainage boundary conditions were defined based on the permeability of the soil layers and the drainage assumptions typical for soft clay consolidation. Vertical drainage was simulated by assigning appropriate permeability coefficients in the vertical direction. Radial drainage through prefabricated vertical drains (PVD) was not simulated directly in PLAXIS 2D, but its effects were included in the one-dimensional analysis using the composite vertical-radial consolidation theory. Therefore, the PLAXIS analysis focuses primarily on vertical consolidation, and a comparison with the one-dimensional results provides a broader perspective on settlement behaviour.

Table 1. Source of Soil Parameters Used in PLAXIS 2D

Parameter	Symbol	Unit	Source of Value
Unit weight	γ	kN/m³	Laboratory test
Young's modulus	E	MPa	Empirical correlation (e.g., based on SPT N-values)
Poisson's ratio	ν	–	Assumed from literature for soft clay
Cohesion	c	kPa	Laboratory test
Internal friction angle	φ	°	Laboratory test
Permeability (horizontal)	k_x	m/day	Assumed: $k_x \approx 2$ to $3\ k_y$
Permeability (vertical)	k_y	m/day	Laboratory test (falling head method)

3. RESULTS AND DISCUSSION

This section presents the results of geotechnical characterisation, loading assumptions, and settlement analysis for two foundation types used in the Semarang–Demak Toll Road project: slab-on-pile and embankment with PVD. Both one-dimensional analysis and FEA using PLAXIS 2D were employed to assess settlement behaviour and foundation performance at the critical interchange location between Pantura Road and the toll road. Emphasis is placed on identifying the most effective foundation

DOI: https://doi.org/10.35139/cantilever.v14i1.463

system in minimising settlement and ensuring long-term structural stability under subsiding coastal conditions.

The PLAXIS 2D model used in this study was not validated against field measurements due to the unavailability of monitoring data, such as settlement plates or inclinometers, at the project site. Instead, the model parameters were derived from site-specific SPT and laboratory data. As such, this study assumes that the field investigation data represent the in situ conditions accurately. Although model validation was not performed, the analysis provides valuable insights into the relative performance of the two foundation systems. Future studies are recommended to include instrumented field data for model calibration and validation.

3.1. Soil Characteristics

In general, the soil characteristics along the Semarang-Demak toll road are dominated by highly compressible clay layers with thicknesses varying between 25 and 60 m [10]. The subsurface profile consists of various clay types, including very soft, soft, firm, stiff, very stiff, and hard clay. The thickness of each clay layer varies considerably along the alignment. In the interchange area, the soft clay layer exceeds 10 meters in thickness, and the groundwater table is located at a depth of approximately 8 meters. The stratigraphy of the study area was derived from borehole logs, including soil descriptions and N-SPT values obtained from site investigations. As shown in Figure 3, soft to very soft clay layers extend to a depth of approximately 30 meters, underlain by progressively stiffer and harder clays. The SPT data at STA 11+275 confirms low N-values (under 10 NSPT) within the upper 25 meters, indicating high compressibility and a significant potential for settlement within the active foundation zone.

3.2. Loading of Toll Road

In this study, the toll road foundation structures are designed to support both traffic and construction loads. These loads are modelled as distributed surface loads acting uniformly on the road structure. The loading analysis for the Semarang–Demak Toll Road complies with the provisions of SNI 1725:2016 [21], which outlines the design criteria for bridge and elevated roadway loading. An estimated load of 120 tons per pile was applied in the analysis. Based on the road elevation, the corresponding distributed loads are 49.32 kN/m² for segments with heights less than 6 meters and 59.18 kN/m² for those with elevations greater than 6 meters, which lower elevation sections (< 6 m) experience lower surface loading compared to higher elevation sections (> 6 m), due to differences in structural fill and associated loads.

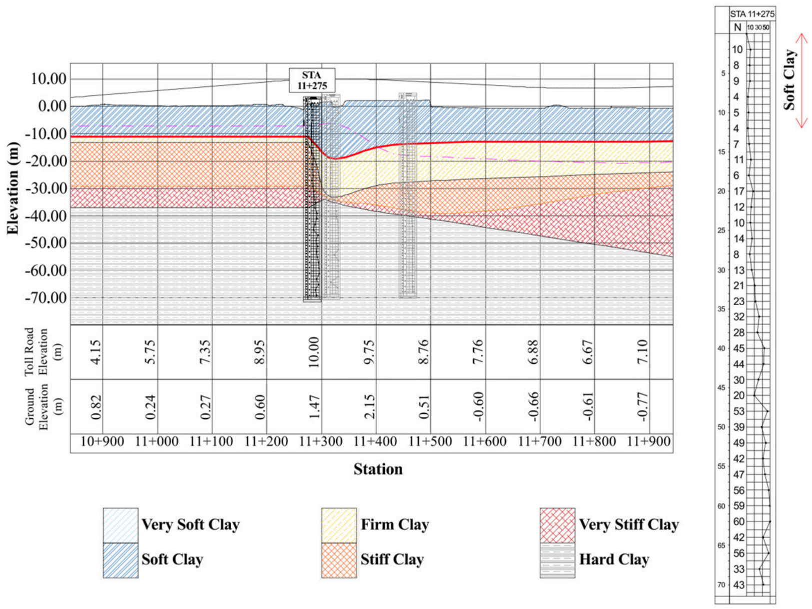

Figure 3. Soil stratigraphy and Standard Penetration Test (SPT) data along STA 10+900 to STA 11+900 at the Semarang–Demak Toll Road interchange.

3.3. Slab-on-Pile Foundation Analysis

The slab-on-pile model analysis includes two design configurations based on road elevation. For road sections with an elevation less than 6 meters, the pile spacing is 3.50 meters, as illustrated in Figure 4a. For sections with an elevation greater than 6 meters, the pile spacing is reduced to 2.80 meters, as shown in Figure 4b. These two configurations serve as the

DOI: https://doi.org/10.35139/cantilever.v14i1.463

basis for modelling and load estimation in the analysis of foundation performance.

3.3.1. One-dimensional analysis

The settlement analysis was performed using the method proposed by Vesic (1977), which divides total pile settlement into three components: settlement due to the axial deformation of the pile shaft (w_s), the settlement of the pile point caused by the load transmitted at the point (w_{pp}), and the settlement of the pile point caused by the load transmitted along the pile shaft (w_{ps}). The results of each component are summarised in Table 2.

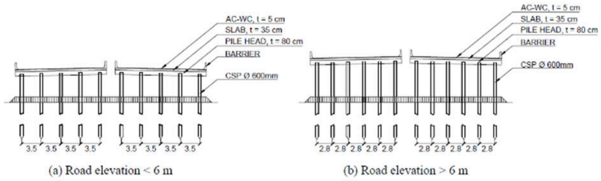

Figure 4 Slab-on-pile foundation configurations based on road elevation: (a) road elevation < 6 m with 3.50 m pile spacing; (b) road elevation > 6 m with 2.80 m pile spacing.

The single pile head settlement (w_{single}) was calculated using the method proposed by Vesic (1977), which involves summing three components of settlement: the axial deformation of the pile shaft (w_s), the settlement of the pile point caused by the load transmitted at the point (w_{pp}), and the settlement of the pile point caused by the load transmitted along the pile shaft (w_{ps}). The results of this calculation are summarised in Table 3. Furthermore, the group pile head settlement (w_{group}) was determined by applying a correction factor based on the ratio of the pile group width (B) to the individual pile diameter (d), in accordance with Vesic's recommendations. The group settlement results are presented in Table 4.

3.3.2. Finite element analysis

The slab-on-pile design modelling on the interchange area was carried out by modelling the analysis design in the same way as the design applied at the project site. The form of modelling and the results of modelling analysis are obtained and are presented in Figure 5. Based on the analysis result, the consolidation process lasts 8,995 days with the maximum settlement in coordinates (1.9;-6.5) of 0.7754 m, and the safety factor value of the settlement graph against the consolidation time is 2.05. The safety factors presented in this study were derived using the shear strength reduction (SSR) method available in PLAXIS 2D. This method systematically reduces the shear strength parameters (cohesion and friction angle) until the model reaches failure, thereby providing an estimate of the global factor of safety.

Table 2. Parameters and results of one-dimensional pile settlement analysis using Vesic's method [16].

Parameter	w_s	w_{pp}	w_{ps}	Unit
Q_b	553.24	-	-	kN
Q_s	3639.94	-	3639.94	kN
f_b	-	1956.67	-	kN/m^2
f_s	-	-	48.28	kN/m^2
f_c	30	-	-	MPa
z	-	-	40	m
d	0.6	0.6	0.6	m
L	48.53	-	-	m
A_b	0.28	-	-	m^2
α_s	0.50	-	-	
v_s	-	0.45	0.45	
I_{pp}	-	0.88	-	
I_{ps}	-	-	4.86	
E_p	25742.96	-	-	MN/m^2
E_s	-	17.64	17.64	MN/m^2
Result	0.016	0.047	0.006	m

Note:
Q_b = ultimate end bearing capacity
Q_s = ultimate skin friction
f_b = ultimate end bearing capacity per unit area
f_s = ultimate skin friction per unit area
f_c = concrete compression strength
z, d, L = pile depth, diameter, and length
A_b = area of end pile
α_s = adhesion factor
v_s = Poisson ratio of soil
I_{pp} = factor of load transmitted at the point
I_{ps} = factor of load transmitted along the pile shaft
E_p, E_s = modulus elasticity of pile, and soil

Table 3. Single pile head settlement calculation based on Vesic's method [16].

Parameter	Value	Unit
w_s	0.016	m
w_{pp}	0.047	m
w_{ps}	0.006	m
w_{single}	0.069	m

Table 4. Group pile head settlement calculation based on Vesic's method [16].

Parameter	Value	Unit
B	34.10	m
d	0.60	m
w_{single}	0.069	m
w_{group}	0.519	m

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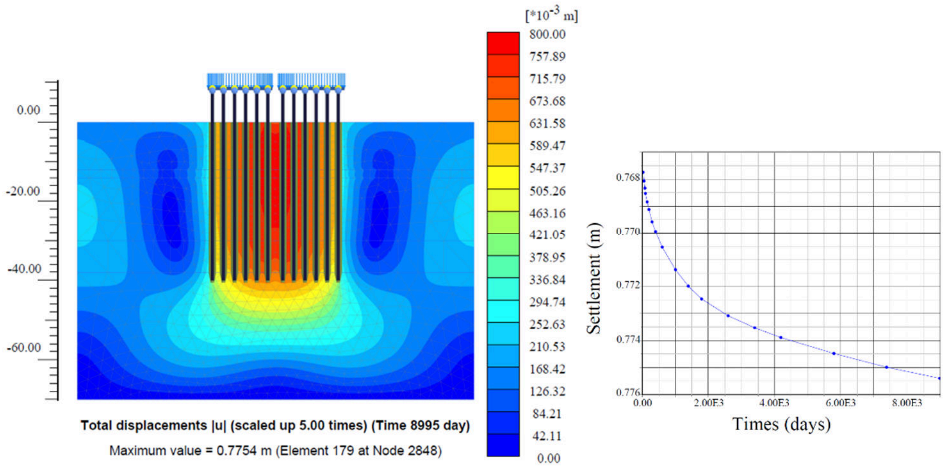

Figure 5. Finite element analysis results of the slab-on-pile foundation using PLAXIS 2D, showing (left) total displacement contours after 8,995 days and (right) settlement versus time curve. The maximum settlement is 0.7754 m.

Based on the results of the one-dimensional and finite element analyses, a difference in settlement values is observed. The settlement obtained from the one-dimensional analysis (0.519 m) is smaller than that from the finite element analysis (0.7754 m). This discrepancy arises from the fundamental differences in assumptions between the two methods. The one-dimensional analysis assumes uniform settlement across all piles, whereas the finite element analysis accounts for non-uniform distribution of loads and deformations resulting from service loads. Therefore, finite element analysis provides a more comprehensive representation and serves as a valuable complement to the one-dimensional analysis.

3.4. Embankment Foundation

The embankment analysis with PVD was conducted to estimate the consolidation time and settlement resulting from various triangular PVD spacing configurations. The type of PVD used in this study was the Kjellman drain [22], with a width of 100 mm and a thickness of 3 mm. The parameters used in the consolidation analysis are presented in Table 5.

3.4.1. One-dimensional analysis

The analysis without soil improvement was conducted to estimate the consolidation time and settlement behaviour of the soil in its natural condition. In this study, soil layers classified as firm clay or softer were identified based on the following criteria:

1) Clay with an N-SPT value ≤ 10
2) Clay with a cone resistance (q_c) ≤ 0.9 MPa

Based on these parameters, the thickness of firm or softer clay at the interchange location was determined to be approximately 14 meters. The consolidation time (t) for the unimproved soil was calculated using the drainage path length (H) corresponding to this thickness. The results of the calculation are illustrated in Figure 6, which presents the correlation between the degree of consolidation (U) and the consolidation time (t).

The time of consolidation (t) was estimated using methods proposed by Casagrande [18] and Taylor [19], which involved calculating the time factor (T_v) obtained based on the value of the degree of consolidation (U). The results of the calculation are presented in Figure 6. The settlement analysis method by Johnson [17] was applied by modelling the soil profile as a series of layers, each with a thickness of 2 meters. Settlement calculations were conducted based on the midpoint of each layer. The results of the analysis are presented in Table 6.

Table 5. Parameters used in the consolidation analysis of the embankment foundation with PVD

Parameter	Value	Unit
H	14	m
U	90%	
C_v	0.93	m^2/year
C_h	1.85	m^2/year
a	100	mm
b	3	mm

Note:
H = flow length
U = degree of consolidation
C_v = consolidated coefficient in vertical
C_h = consolidated coefficient in radial
a = width of PVD
b = thick of PVD

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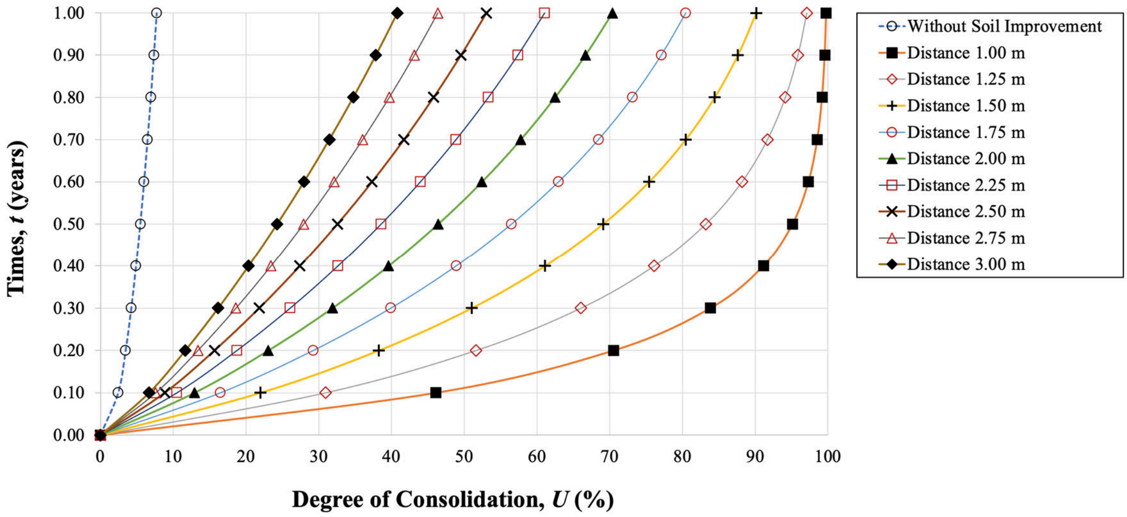

Figure 6. Relationship between the degree of consolidation (U) and consolidation time (t) for various PVD spacings compared to unimproved soil

Table 6. Consolidation settlement calculation results for each soil layer based on Johnson's method [17]

Layer	Depth	e_0	C_c	p_0	$\Delta\sigma_z$	ΔS_c
	m	-	-	kN/m^2	kN/m^2	m
1	2	1.790	0.686	15.107	205.914	0.573
2	4	1.790	0.686	30.215	205.914	0.439
3	6	1.790	0.686	45.322	205.914	0.366
4	8	1.790	0.686	60.430	202.979	0.314
5	10	1.790	0.686	65.962	200.044	0.298
6	12	1.790	0.686	71.495	197.110	0.283
7	14	1.764	0.659	77.151	194.175	0.260
S_c						2.533

3.4.2. Finite element analysis

The embankment design modelling on the interchange area was carried out by modelling the analysis design in the same specification as the design applied at the project site. The form of modelling and the results of modelling analysis are obtained and presented in Figure 7. Based on the analysis result, the consolidation process lasts for 10,880 days with the maximum settlement in coordinates (0.224;12.1) of 1.038 m, and the safety factor value of the settlement graph against the consolidation time is 1.44. The safety factors presented in this study were derived using the shear strength reduction (SSR) method available in PLAXIS 2D. This method systematically reduces the shear strength parameters (cohesion and friction angle) until the model reaches failure, thereby providing an estimate of the global factor of safety.

The settlement results from both the slab-on-pile and embankment foundation designs were evaluated using one-dimensional analysis and FEA. For the slab-on-pile foundation, the one-dimensional analysis yielded a settlement of 0.519 m, while the FEA resulted in a slightly higher settlement of 0.775 m. In contrast, the embankment foundation exhibited significantly greater settlement values. The one-dimensional analysis estimated a settlement of 2.533 m, whereas the FEA indicated a smaller value of 1.038 m.

These differences highlight two important observations. First, the slab-on-pile design consistently produced lower settlement values across both methods, confirming its effectiveness in mitigating ground deformation in soft soil conditions. Second, the variations between the one-dimensional and FEA results emphasise the importance of analysis methodology. The one-dimensional method assumes uniform load distribution and simplified soil behaviour, while FEA incorporates complex interactions between loads, geometry, and varying soil properties. As such, FEA offers a more realistic representation of field conditions and is especially useful in capturing the non-uniform nature of deformation under embankment loading.

Overall, the slab-on-pile foundation demonstrated superior performance in minimising settlement, and the use of both analysis methods provides a more comprehensive understanding of foundation behaviour in the Semarang–Demak subsiding coastal plain.

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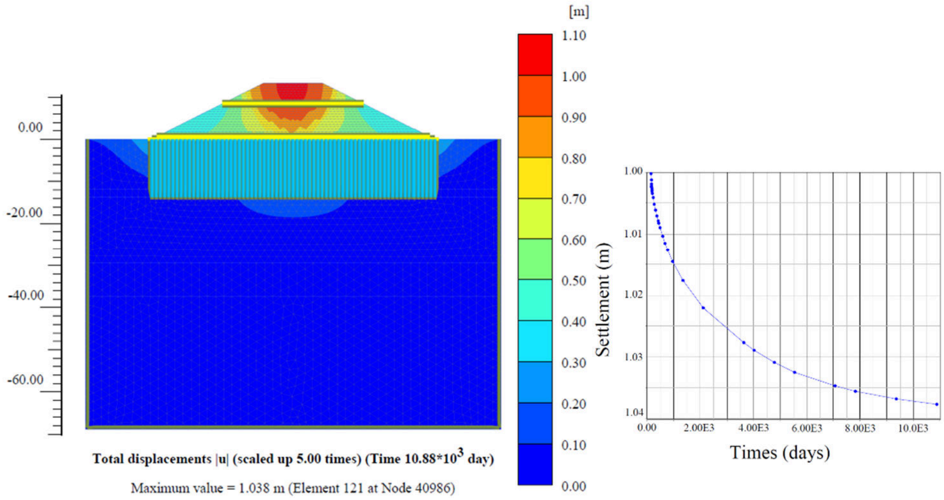

Figure 7. Finite element analysis results of the embankment foundation using PLAXIS 2D, showing (left) total displacement contours after 10,880 days and (right) settlement versus time curve. The maximum settlement is 1.038 m (Element 121 at Node 40986)

4. CONCLUSION

This study evaluated the performance of two foundation systems, slab-on-pile and embankment with PVD, under the challenging geotechnical conditions of the Semarang–Demak Plain, a coastal region characterised by thick soft clay layers and ongoing land subsidence. The comparison was conducted using both one-dimensional analytical methods and two-dimensional finite element modelling (PLAXIS 2D).

The slab-on-pile design demonstrated superior performance in terms of minimising settlement, accelerating consolidation, and maintaining structural stability. It resulted in settlement values of 0.519 m (one-dimensional) and 0.775 m (FEA), a safety factor of 2.051, and a consolidation period of 8,995 days. In contrast, the embankment with PVD design yielded higher settlement values, 2.533 m (one-dimensional) and 1.038 m (FEA), a lower safety factor of 1.441, and a longer consolidation time of 10,880 days.

The slab-on-pile foundation showed higher settlement in the FEA compared to the one-dimensional method due to the detailed simulation of interaction effects between the pile group and soil. In contrast, the embankment with PVD showed lower settlement in the FEA because radial consolidation was not simulated directly, resulting in a more conservative (slower) estimation of settlement progression.

These findings indicate that the slab-on-pile system is more suitable for critical infrastructure in regions with deep soft soils and high subsidence rates. It offers enhanced long-term performance and the potential to reduce maintenance costs by minimising residual settlement.

The PLAXIS model simulated vertical consolidation but did not directly model radial drainage from PVDs. This limitation may lead to an underestimation of accelerated consolidation in the embankment model. Nevertheless, this study was limited to two-dimensional analyses and idealised design conditions. The PLAXIS 2D model was not calibrated using field monitoring data such as settlement markers or inclinometer readings due to unavailability. Therefore, future research is recommended to incorporate instrumented field measurements for model calibration and validation. Additionally, future studies should include three-dimensional modelling and life-cycle cost assessments to support broader implementation.

ACKNOWLEDGEMENTS

The authors would like to thank PT PP (Persero) Tbk for providing the necessary data for this research and the Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada, for supporting the authors in carrying out the Semarang-Demak toll road project research.

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