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Analysis of Lateral Shifting of Slab on Pile on Soft Soil in Coastal Area

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ABSTRACT

This study discusses the settlement and lateral displacement of piles on a toll road built on saturated soft soil in a coastal area. The case study focuses on the point where the off-ramp and main road meet, with soil conditions dominated by very soft clay to a depth of ±58 m (N-SPT <10), meaning the piles function primarily as friction piles. Soil data from the BH-03 drill were processed through N-SPT correction, consistency grouping, and compressibility parameter correlation to obtain input for numerical modeling. The modeling was done using PLAXIS 2D under plane strain conditions, with the Soft Soil model for clay and Mohr–Coulomb for non-cohesive soil. Construction stages included 2.5 m of backfilling, two years of consolidation, and the installation of new piles near existing piles. The results showed that the vertical settlement of the pile tip from the numerical model was 3.9 cm, closely matching the analytical calculation results (3.07–3.66 cm), which is still within the SNI 8460 serviceability criteria. However, the lateral displacement reached 5–5.7 cm, exceeding the SNI limit of <2.5 cm. Horizontal displacement contours revealed a 6.3–10.1 cm soil shift toward the outside of the slope during new pile construction, indicating that long-term consolidation, embankment slope geometry, and seabed slope are the main causes of lateral deformation.

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INTRODUCTION

Infrastructure development such as toll roads in Indonesia faces diverse geotechnical challenges, particularly in coastal areas dominated by alluvial deposits. These geological conditions result in the distribution of soft soils with high plasticity and compressibility, increasing the potential for long-term settlement and the vulnerability of foundations to lateral shifts (Abija, 2023; Das, Islam, & Datta, 2025; Lu, Zhang, Shi, Jiang, & Lin, 2023; Ukwoma, Igwe, & Egbueri, 2024). To address these issues, the slab-on-pile (SOP) road foundation system is widely chosen because it can transfer loads to stiffer soil layers at depth. However, the performance of existing piles remains highly sensitive to changes in stress and loading conditions arising from surrounding construction activities (Elam & Björdal, 2020; Feng, Zhang, & Liu, 2020; Han Lin Wang, Chen, Cheng, Qi, & Cui, 2019).

Regionally, the presence of soft soils along the coast of Java Island has been documented through soft soil zoning maps compiled by relevant agencies, where coastal areas are indicated as zones with high compressibility potential and significant saturated clay layer thickness. These maps serve as an important reference in toll road route planning because they provide an initial overview of segments that have the potential to experience significant subsidence and require special foundation treatment (Cheng et al., 2024; Frid et al., 2025; Shi, Li, Chen, & Wang, 2018; Whiteley, Kelly, & Stewart, 2015). In the context of the Pesisir-X Project, the

section being studied is located in one of these soft soil zones, so the risk of subsidence and soil deformation has been identified since the planning stage.

Figure 1. Soft Soil Distribution Map
Source: Ministry of Energy and Mineral Resources, 2019

One common approach to reducing settlement on soft ground is the implementation of a slab-on-pile (SOP) system, in which the pavement is supported by a group of piles that transfer the load to a stiffer layer of soil at depth. In certain segments of the Pesisir-X Project, the SOP system was constructed on soft ground with embankments approximately 2.5 m above sea level that functioned as working platforms and as part of the approach. This configuration resulted in complex geometric conditions because the SOP piles were located relatively close to the embankment slope and were located in an area that was originally shallow water with a seaward slope (Barrie, Wang, Liang, & Qi, 2024; Rony, 2019; Su et al., 2020). Theoretically, the combination of embankments on soft ground, the embankment slope, and the piles' position near the slope could pose a risk of pile settlement and lateral shift in the pile group (Chen & Zhang, 2024; Varaksin & Apageo, 2016; Anhui Wang & Zhang, 2020; Feifei Wang et al., 2022).

The problem studied in this research originated from the construction history of the Pesisir-X Project. In the initial stage, a 2.5 m thick platform was piled above the sea to facilitate piling work with a slab on pile system. After the implementation of the first slab on pile was completed, another slab on pile construction was piled next to it after two (2) years, so that the soft soil under the embankment had the opportunity to experience medium-term consolidation. After this second piling, field observations were carried out which showed a lateral shift in the slab on pile area with a magnitude of approximately 5 cm, which was indicated by the displacement of road markings and barriers.

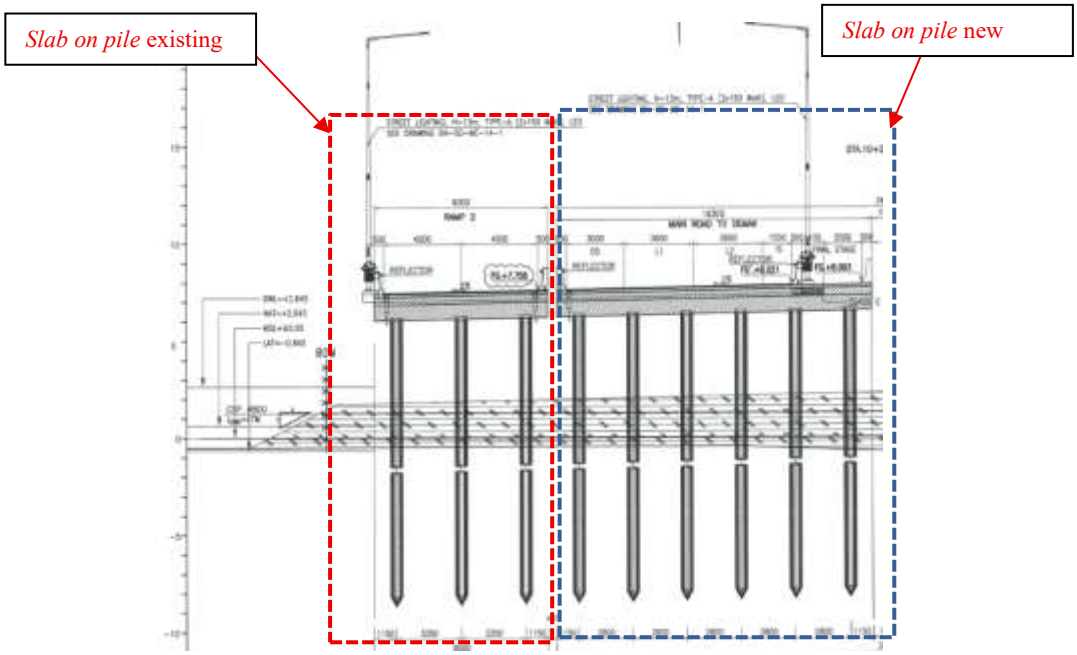


Figure 2. Cross section of Slab on Pile
Source: DED Coastal Project - X

While previous studies have extensively analyzed vertical settlement of pile foundations on soft soil, comprehensive investigations integrating staged construction, long-term consolidation, and adjacent pile installation effects on lateral displacement remain limited. The novelty of this research is the integration of detailed finite element modeling (using PLAXIS 2D) that explicitly simulates the multi-stage construction sequence—including initial platform embankment, a two-year consolidation period, and the driving of new adjacent piles—to analyze the coupled effect on both vertical and lateral movements of existing piles. This approach provides a more holistic understanding of soil-structure interaction in a complex, time-dependent coastal geotechnical setting.

The primary objective of this study is to identify the dominant causes of the observed lateral shifting of an existing slab-on-pile foundation by comparing field measurements, analytical calculations, and detailed numerical simulations. Specifically, it aims to: (1) model the staged construction and consolidation history using PLAXIS 2D, (2) quantify the contributions of embankment loading, consolidation, and new pile installation to the lateral displacement, and (3) evaluate the compliance of the calculated displacements with national design standards (SNI 8460:2017).

The benefits and implications of this research are twofold. Theoretically, it contributes to the body of knowledge on the lateral behavior of pile groups in soft soils under sequential loading, offering a validated modeling framework for similar problems. Practically, the findings provide actionable guidance for engineers in planning and designing slab-on-pile systems in coastal areas, such as recommending safe distances from embankment slopes, considering long-term consolidation effects in design, and implementing monitoring strategies to control lateral movements, thereby enhancing the safety and durability of infrastructure projects on soft soil.

METHOD

Calculation of Pole Bearing Capacity

The bearing capacity of the piles in this study has dimensions with a diameter of 60 cm and compressive strength (fc'= 52 Mpa) calculated using the Meyerhof and Luciano Decourt method as follows:

$Q_p = Ap\ x\ Cu\ x\ Nc,\ \ Q_s = \alpha\ x\ Cu\ x\ \Delta L$ $Q_u = Q_p + Q_s$ (Meyerhof)

…(1)

Where Qp is the end capacity, Qs is the shear capacity, Cu is the undrained shear strength, Nc is the bearing capacity factor and ΔL is the length of the pile segment.

$Q_p = \alpha\ x\ Np\ x\ K\ x\ A_p,\qquad Q_s = \beta\ x\ \frac{N_s}{3} + 1\ x\ A_s$

$Q_u = Q_p + Q_s$ (Luciana Decourt)

…(2)

Where Np is the average N-SPT value at the base of the pile, K is the earth pressure correction factor and Ap is the pile tip area.

Pile Settlement Analysis

In the analysis of pile groups, an approach is carried out using the Boussinesq Method calculation, namely a stress distribution of 2V: 1H. In this approach, the pile group load is assumed to work through a fictitious raft at a depth of 2/3 of the pile length, and settlement is calculated from a combination of elastic settlement and soil consolidation under the raft (Tomlinson, 1994; Das, 2012).

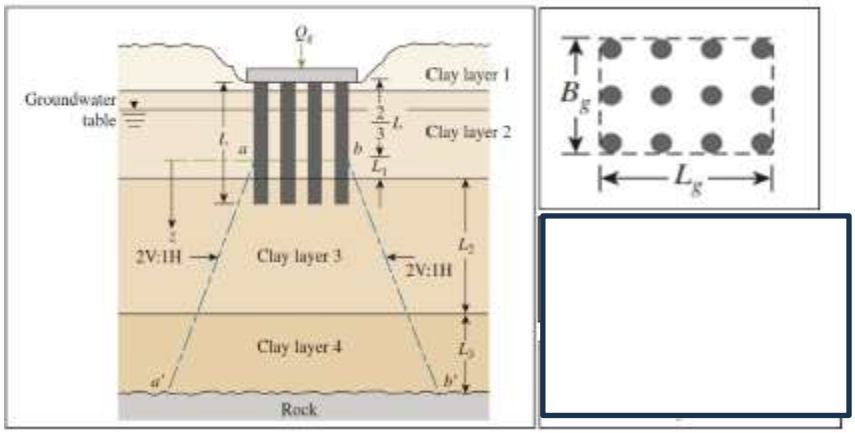


Figure 3. Illustration of Pole Group Voltage Distribution
Source: Das, 2012

The following is the equation for the addition of vertical stress ($\Delta\sigma$) to the layer below the fictitious raft:

$$\Delta\sigma' i = \frac{Q_g}{(B_g + z_i)(L_g + z_i)}$$

…(3)

Where Qg is the total load of the pile group, Bg and Lg are the width and length of the pile group area, and zi is the depth of the review point from the base of the fictitious raft. The Δσ'i value is then used to calculate the settlement using the 1D Terzaghi method. The formula using the *Terzaghi method* is as follows:

If $\sigma'_o + \Delta\sigma \leq \sigma_c'$ then,

$$Sc = \frac{Cs\ H}{1 + e_o} \log\left(\frac{\sigma'_o + \Delta\sigma}{\sigma'_o}\right)$$

…(4)

If $\sigma'_o + \Delta\sigma > \sigma_c'$ then,

$$Sc = \frac{Cs\ H}{1 + e_o} \log\left(\frac{\sigma_c'}{\sigma'_o}\right) + \frac{Cc\ H}{1 + e_o} \log\left(\frac{\sigma'_o + \Delta\sigma}{\sigma'_c}\right)$$

…(5)

Where Cs is the expansion index, Cc is the compression index, Δσ is the additional stress due to the embankment load and σ'c is the pre-consolidation stress.

The Poulos and Davis (1980) method is also used to analyze the settlement of grub piles, this approach is based on the theory of elasticity, with the following formula:

$S_1 = \frac{Q\ I}{Es\ d}$, (single pole)

$S_1 = S_1 x \sum_{j=1}^{n} (P_j \alpha_{ij})$ (for grub pole)

…(6)

Where Es is the modulus of elasticity of the soil, d is the diameter of the pile and I is the total displacement influence factor, S_1 is the settlement of a single pile under a unit load, n is the number of piles in the group, α_{ij} is the interaction factor between pile i and pile j, whose value depends on the ratio of the distance between piles to the diameter (s/d), the ratio of the length to the diameter (L/d) and the relative stiffness of the pile-soil (K).

Numerical Modeling

PLAXIS 2D is a computer program based on finite element method calculations that can be used for deformation analysis calculations, slope stability and groundwater flow behavior (Mahmud et al., 2023). Field conditions are modeled numerically with the PLAXIS program with the aim of implementing each construction stage in the form of a work model at each stage of input, analysis and output of the program, with the aim of approaching the stages of work implementation in the field with a computer model, so that a response is obtained that is close to the actual conditions in the field (Teguh et al., 2022)

The modeling geometry is arranged in such a way as to approach the actual conditions in the field, both in terms of embankment configuration, pile position, and soil stratigraphy. The soft soil layer is modeled with soft soil, where the compressibility parameters λ (lamdha) and κ (kappa) are obtained by converting the Cc and Cs values from laboratory tests. The non-cohesive soil layer is modeled with Mohr Coulum, with shear strength and deformation parameters taken from laboratory test results and relevant geotechnical correlations.

Table 1. Numerical Model Material Input

Material Type	Set Type	Model	Drainage Type
Very Soft Clay	Soil & Interfaces	Soft Soil	Undrained A
Soft Clay	Soil & Interfaces	Soft Soil	Undrained A
Stiff Clay	Soil & Interfaces	Soft Soil	Undrained A
Gravel	Soil & Interfaces	Mohr-Coulomb	Drained
Heap	Soil & Interfaces	Mohr-Coulomb	Drained
Pile head	Plate	Plastic	-
Concrete Spun Pile	Embedded Beams	Elastic	-

Source: Project soil data, processed

Load modeling was carried out following field data and conditions, structural loads above the pilehead such as slab loads, barriers, and asphalt pavement layers, were first calculated using the tributary area concept and entered into the PLAXIS modeling. The piles analyzed were existing piles as shown in Figure 4. Near the piles, new piles were driven which were suspected to be the initial trigger for the shift.

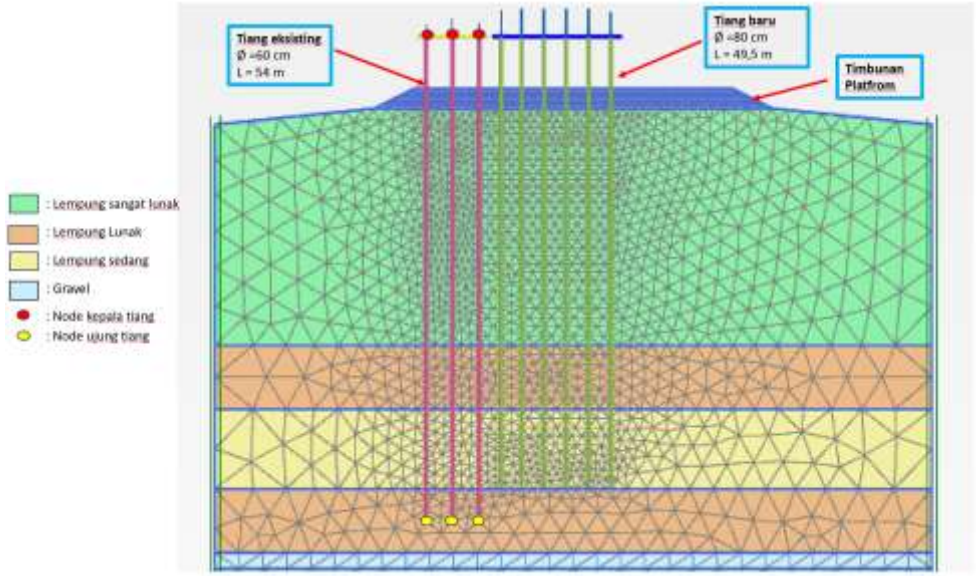


Figure 4. PLAXIS Modeling Geometry

Source: PLAXIS 2D modeling results, processed

The modeling also created review points in the form of nodes at the pile head and pile tip, which were used as control points to read the displacements in the pile. The soil layers were also modeled with consistencies according to field conditions, consisting of very soft clay, medium clay, soft clay, and gravel.

RESULTS AND DISCUSSION

Existing Land Data

The soil data used in this study is the drilling point from BH-03 which is the Coastal Toll Road Development Project - x, precisely at the meeting point of *Ramp off* and *main road.* Soil

investigation was carried out to a depth of 60m, then the test data was processed through several stages, namely correction of NSPT values, regrouping of soil types and consistencies, and checking the suitability of each parameter with the correlations of relevant soil parameters. Figure 5 shows the NSPT value profile of the BH-03 drilling test results used as a basis in this study.

Table 2. Summary of Existing Land Characteristics BH-03

	Very Soft Clay	Soft Clay	Medium Clay	Gravel
NSPT Correction	1.46	4.42	5.90	5.88
γ sat (kN/m ^{3})	16.37	18.3	17.54	18.00
σ' (kN/m ^{2})	109.94	298.80	339.30	472.00
toilet (%)	59.56	39.90	46.3	39.9
e	1.61	1.04	1.25	1.08
Sr (%)	100	100	100	100
Gs	2.68	2.7	2.68	2.68
LL (%)	87.42	76.70	97.5	-
PL(%)	32.79	28.53	32.49	-
PI (%)	28.53	48.18	65.01	-
Cc	0.358	0.471	0.612	-
CV (cm ^{2}/sec)	0.00050	0.00040	0.00030	-
Cs	0.126	0.125	0.176	-
Pc (kN/m ^{2})	85.24	216.61	298.53	235.47
Cu (kN/m ^{2})	18.70	26.5	50.0	-
c ' (kN/m ^{2})	12.4	27.4	33.3	-

Source: BH-03 borehole data, processed

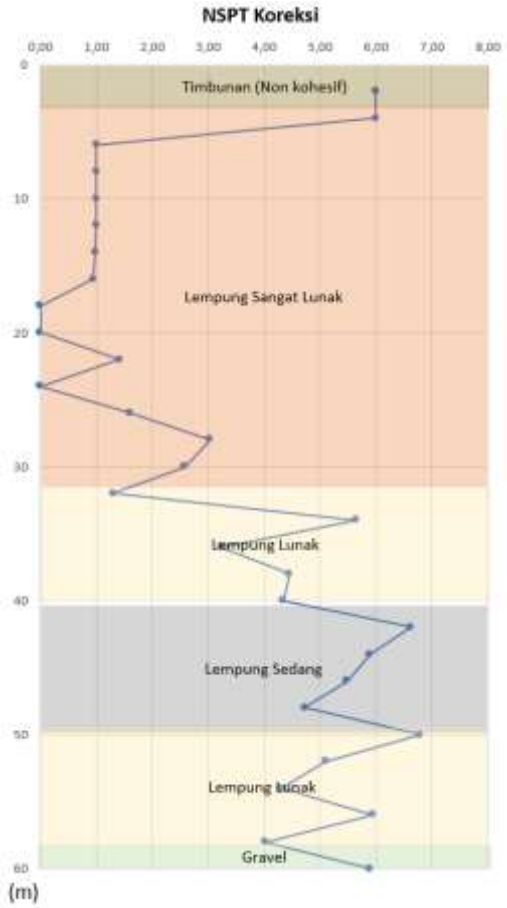


Figure 4. Stratigraphy of BH-03
Source: BH-03 borehole data, processed

Vertical Settlement of the Pole

In the consolidation section (vertical settlement), analytical calculations were performed on the settlement of the existing piles before modeling with PLAXIS 2D. The analytical calculations for the settlement of the group piles used the Raft method. The foundation yielded a settlement of 3.66 cm, while the Paulo and Davis method yielded a settlement of 3.07 cm. These results were then compared with numerical analysis using PLAXIS 2D, yielding a settlement of 3.9 cm. A summary of the settlement is presented in Table 3.

Table 3. Comparison of Total Reduction Results of Analytical and Numerical Methods

Review Point	Raft Foundation Analytical Methods (cm)	Paulo and Davis' Analytical Method (cm)	PLAXIS Numerical Method (cm)
Pole tip	3.66	3.07	3.9

The difference between the Raft foundation settlement is 3.66 cm, while the PLAXIS 2D numerical modeling is 3.90 cm so that the difference of 0.24 cm (7%) is an indicator of settlement in the slab on pile . The settlement that still appears in the numerical analysis is in line with the characteristics of the soil at the study site. The very thick compressible clay layer causes the consolidation process to take a long time, previous manual calculations show that in

a period of just two years the consolidation settlement has reached around 2.65 cm and secondary consolidation is still continuing.

Lateral Displacement of *Existing Piles*

The lateral displacement of the existing piles was evaluated by comparing the results of PLAXIS 2D numerical modeling with field observation data. Monitoring data indicated that the pile cap experienced a horizontal displacement of approximately 5 cm toward the embankment slope. Conventional analytical approaches to consolidation generally only describe one-dimensional settlement, so lateral displacement predictions are not calculated analytically and are more accurately obtained through numerical modeling.

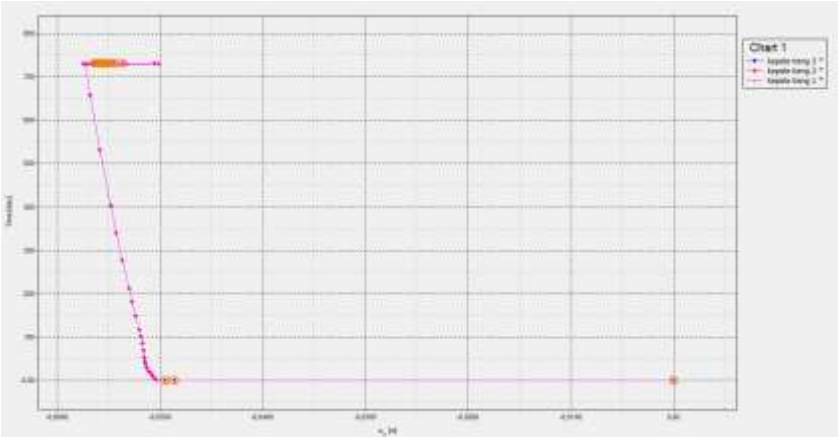


Figure 5. Lateral displacement of the pile head

Source: PLAXIS 2D analysis results, processed

Figure 5 shows a graph of lateral displacement of the pile head against time. It can be seen that when the consolidation period was given for 2 (two) years, the displacement occurred up to 5.7 cm. After the 2 (two) years of consolidation, construction work was carried out on 6 new piles around it and a displacement occurred, but it was reduced to 5.6 cm as evidenced by the lateral displacement graph above.

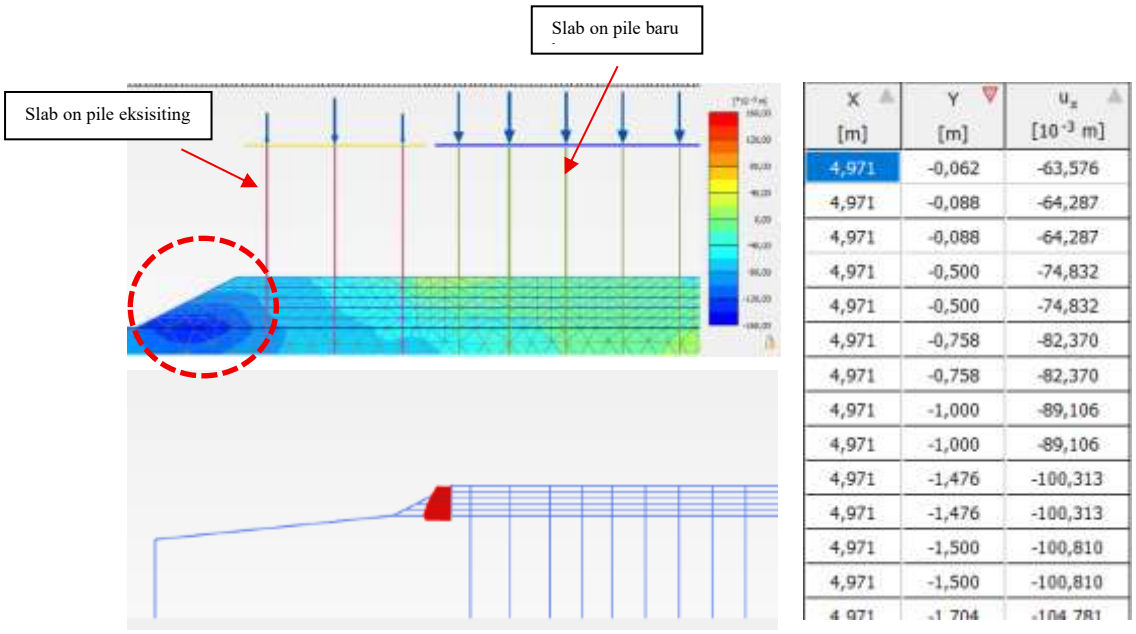
Table 4. Comparison of Total Reduction Results of Analytical and Numerical Methods

Review Point	Consolidation 2 years (cm)	Construction of 6 New Pillars (cm)	Difference (cm)
Masthead	5.70	5.4	-0.1

Source: PLAXIS 2D analysis results, processed

The results of the PLAXIS numerical analysis above are in line with actual conditions in the field, where the observation results show lateral shifts of the *existing piles.* approximately ± 5 cm towards the embankment slope. Therefore, it can be said that the PLAXIS model used is capable of representing the magnitude of the lateral displacement of the *existing piles* that is suitable for use as a reference in the analysis. In addition to the shift data on the pile head, there

is also a shift in the lateral slope of the embankment during the construction of the new pile as shown in Figure 6.



X [m]	Y [m]	u_x [10^{-3} m]
4,971	-0,062	-63,576
4,971	-0,088	-64,287
4,971	-0,088	-64,287
4,971	-0,500	-74,832
4,971	-0,500	-74,832
4,971	-0,758	-82,370
4,971	-0,758	-82,370
4,971	-1,000	-89,106
4,971	-1,000	-89,106
4,971	-1,476	-100,313
4,971	-1,476	-100,313
4,971	-1,500	-100,810
4,971	-1,500	-100,810
4,971	-1,704	-104,781

Figure 6. Lateral displacement on *the cross section* of the embankment slope
Source: PLAXIS 2D analysis results, processed

Figure 6 shows the horizontal displacement contours in the cross-section near the embankment slope along with the values u_x for several soil elements. The zone circled in red indicates outward soil movement, with values $u_x$ranging from – 0.063 to 0.101 m, or approximately 6.3 to 10.1 cm . This pattern indicates that the embankment load not only causes vertical settlement due to consolidation, but also causes lateral deformation , so that the displacement of the existing pile is a combination of soft soil consolidation and soil mass movement in the embankment body.

Evaluation of Eligibility Criteria According to SNI

Evaluation of the structural and geotechnical feasibility of foundation design is a crucial step that requires a comparison between the results of numerical analysis and the limit criteria set by technical standards. Based on the provisions applicable in Indonesia, the results of vertical settlement and lateral displacement of the foundation are evaluated with SNI 8460-2017 concerning Geotechnical Design requirements, which are summarized in Table 4 below.

Table 5. Comparison of PLAXIS Numerical Results with SNI

Parameter	Analysis results (cm)	SNI-8460 Limits (cm)	Information
Vertical End Drop	3.9	16.5	Still below SNI limits
Lateral displacement of pile head	5.4	< 2.5	Greater than SNI limits

Source: PLAXIS 2D analysis results and SNI 8460:2017

Based on the comparison in Table 4, the results of the numerical analysis show that the vertical settlement of the pile tip (3.9 cm) is still far below the maximum limit permitted by SNI

8460 of 16.5 cm, indicating that the bearing capacity and total settlement of the foundation system have been resolved. However, the calculation results indicate a significant problem in the lateral displacement of the pile head of 5.4 cm, where this value exceeds the SNI tolerance limit of less than 2.5 cm.

CONCLUSION

Based on the analysis, recommendations for managing lateral shifts in toll road foundations on thick, consolidating soft coastal soils emphasize accounting for long-term consolidation effects and slope gradients as primary triggers. Piles should be positioned at a safe distance from embankment edges—especially over sloping seabeds—to reduce soil mass movement impacts on pile caps, with layout adjustments or stiffer elements added in critical zones for enhanced stability. Platform embankments require geotextile reinforcement alongside standard soil materials. For future research, investigators could quantify optimal pile-to-slope distances and geotextile specifications through parametric 3D finite element modeling (e.g., PLAXIS 3D) calibrated against field monitoring data from Indonesian coastal projects.

REFERENCES

Abija, F. A. (2023). Ground variation, geotechnical uncertainties and reliability of foundation design for sustainable building infrastructures with case histories. *Journal of Material Sciences and Engineering Technology*.

Barrie, A., Wang, C., Liang, F., & Qi, W. (2024). Experimental investigation on the mechanism of local scour around a cylindrical coastal pile foundation considering sloping bed conditions. *Ocean Engineering*.

Chen, T., & Zhang, G. (2024). Centrifuge modeling of pile-supported embankment on soft soil base for highway widening. *Soils and Foundations*.

Cheng, Z., Xie, Z., Wei, M., Peng, Y., Du, C., Tian, Y., & Song, X. (2024). Review of sensor-based subgrade distress identifications. *Italian National Conference on Sensors*.

Das, S., Islam, M. S., & Datta, A. K. (2025). Design of embankment on soft ground conditions. *Open Journal of Civil Engineering*.

Elam, J., & Björdal, C. G. (2020). A review and case studies of factors affecting the stability of wooden foundation piles in urban environments exposed to construction work. *International Biodeterioration & Biodegradation*.

Feng, R. F., Zhang, Q. Q., & Liu, S. W. (2020). Experimental study of the effect of excavation on existing loaded piles.

Frid, M., Helman, A., Sharf, D., Frid, V., Elias, W., & Blumberg, D. G. (2025). An integrated study of highway pavement subsidence using ground-based geophysical and satellite methods. *Applied Sciences*.

Lu, C., Zhang, X., Shi, B., Jiang, J., & Lin, Z. (2023). Deformation in settlement and grouting remediation of thickened larger-diameter metro shield tunnel in soft soil: A case study. *Case Studies in Construction Materials*.

Mahmud, A. I., Said, L. B., & Alifuddin, A. (2023). Modeling of soil slip plane using PLAXIS 2D in post-disaster management of the Salaonro–Pompanua section, Soppeng Regency. *Flyover Journal*, 2(2), 76–85.

Ministry of Energy and Mineral Resources. (2019). *Map of soft soil distribution in Indonesia*.

Ministry of Energy and Mineral Resources.

Rony, M. S. I. (2019). Design rationale for shore pile and steel bracing system for deep excavation.

Shi, Y. J., Li, M. G., Chen, J., & Wang, J. H. (2018). Long-term settlement behavior of a highway in land subsidence area. *Journal of Performance of Constructed Facilities*.

Su, L., Wan, H. P., Luo, Y., Dong, Y., Niu, F., Lu, J., Ling, X. Z., Elgamal, A., & Arulmoli, A. (2020). Seismic performance assessment of a pile-supported wharf retrofitted with different slope strengthening strategies. *Soil Dynamics and Earthquake Engineering*.

Teguh, R., Rusbandi, R., Sudiadi, S., Novita, D., & Mardiani, M. (2022). Implementation of the PLAXIS application in the civil engineering study program, faculty of engineering, Tridinanti University, Palembang. *Fordicate*, 1(2), 124–132.

Ukwoma, I. P., Igwe, O., & Egbueri, J. C. (2024). Multidimensional characterization of problematic soils linked to foundation and building failures in parts of Southeast Nigeria. *Modeling Earth Systems and Environment*.

Varaksin, S., & Apageo. (2016). Ground improvement vs. pile foundations?

Wang, A., & Zhang, D. (2020). Lateral response and failure mechanisms of rigid piles in soft soils under geosynthetic-reinforced embankment. *International Journal of Civil Engineering*.

Wang, F., Shao, J., Li, W., Wang, Y., Wang, L., & Liu, H. (2022). Study on the effect of pile foundation reinforcement of embankment on slope of soft soil. *Sustainability*.

Wang, H. L., Chen, R. P., Cheng, W., Qi, S., & Cui, Y. (2019). Full-scale model study on variations of soil stress in geosynthetic-reinforced pile-supported track bed with water level change and cyclic loading. *Canadian Geotechnical Journal*.

Whiteley, R. J., Kelly, R. B., & Stewart, S. B. (2015). Case studies of geophysical imaging for road foundation design on soft soils and embankment risk assessment. *Exploration Geophysics*.