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STABILITY ANALYSIS OF ROAD BODY EMBANKS AGAINST SLOPE DECLINE AND SLOPE INCREMENT USING FEM ON ROADS JUNCTION BYPASS TOLL ROAD – PEKANBARU

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Abstract

Soft soil is characterized by low bearing capacity and high degree of compressibility, which could potentially cause ground subsidence and slope instability in road construction. This study aims to analyze the stability of a road embankment and predict the magnitude of soil consolidation settlement in the Junction Bypass–Pekanbaru Toll Road Construction Project at STA 203+850. The methods employed were Terzaghi's one-dimensional consolidation method and numerical modeling using the finite element method (FEM). To determine which method more accurately represents actual field conditions, the calculated settlement values were compared with settlement plate monitoring data. The results showed that the consolidation settlement calculated using Terzaghi's method was 0.328 m, whereas the finite element analysis yielded a settlement of 0.171 m. These results were compared with the settlement plate measurement of 0.222 m, indicating that the finite element method produced a settlement prediction closer to the actual field conditions. The slope stability analysis resulted in a factor of safety of 1.94 using Culmann's method and 1.04 using the finite element method. Therefore, the finite element method provides a settlement prediction that more closely represents field conditions, while the embankment slope remains in a critical stability condition.

Keywords: Soft soil, Land subsidence, Consolidation, Slope stability (Safety factor)

INTRODUCTION

The provision of arterial roads plays a vital role in stimulating the development and balance of the national economy. This role is realized by increasing interconnectivity between regions while facilitating the movement of goods and services. Therefore, road infrastructure must be built with strong and stable bearing capacity to support traffic loads and ensure the safety and comfort of road users. In Indonesia, many areas have expansive clay soils that are at risk of volume deformation due to fluctuations in water content. This condition requires technical intervention in design and construction to maintain road structural integrity and prevent damage.

Soft soil is a type of soil that requires careful intervention due to its physical characteristics, namely minimal bearing capacity, low shear strength, low permeability, and very high degrees of shrinkage and swelling, resulting in massive and long-term consolidation settlement. If the existence of soft soil is not identified and tested comprehensively, this condition can cause instability and long-term land settlement , which risks threatening the integrity of the building above it. To estimate the magnitude of consolidation settlement that occurs, calculations can be carried out analytically applying scientific principles developed by Terzaghi (1946) .

Soil management in cases of land subsidence, particularly for embankments on road surfaces, involves various methods aimed at addressing the consolidation and settlement of soft soils to maintain the stability and bearing capacity of road construction. Generally, soil management in cases of land subsidence is carried out using a combination of accelerated consolidation methods such as preloading and geotextiles. This approach aims to reduce the risk of road damage due to land subsidence and increase the overall service life of the road structure.

Settlement plate is a tool commonly used in large construction projects such as toll road construction to ensure the stability and equality of the land before construction begins. To improve the soft soil at the field review location located at sta 203 + 850, several methods were used in the field such as the Fine Element Method (FEM), geotextile installation, and preloading . The settlement of soil consolidation on the embankment of the road body is interesting to study because soil with soft consistency and low permeability such as clay requires special attention.

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The process of consolidation and land subsidence takes a long time and is significant, so it requires in-depth analysis to anticipate its impact. Thus, based on the above background, the author is interested in discussing "Analysis of the stability of the embankment of the road body against settlement and slope using the finite element method on the Junction Bypass - Pekanbaru toll road sta 203 + 850".

LITERATURE REVIEW

Zahara (2008) studied the control of land subsidence due to embankment loads at bore log sample point no. BH-II (Area-II) in the Kualanamu Airport Project. The embankment construction phase is a crucial part of the physical implementation process. Embankment activities have the potential to trigger pore water flow in the soil, which triggers volume reduction, also known as consolidation. This consolidation-induced soil deformation risks disrupting long-term structural performance and, if excessive, can lead to structural failure. Therefore, an evaluation was conducted to determine the extent of land subsidence and the duration of consolidation completion. Calculations were implemented using the Plaxis device and manual computation based on Terzaghi's one-dimensional consolidation theory. The data used were obtained from soil parameters and reports on the Kuala Namu Airport Project. The embankment construction was carried out in four stages, with each layer approximately 4 meters thick, with a 100-day interval between embankment phases. Evaluation findings using the Plaxis device and manual computation indicate disparities in consolidation time and settlement magnitude . The Plaxis application results show a peak consolidation duration of 1,080 days with a settlement of 0.701 m. Meanwhile, manual calculations obtained a settlement of 0.739 m in a consolidation period of 1,398 days.

Alisha (2025) studied soil stability analysis using Plaxis-based geotextile reinforcement. The test was conducted based on the finite element method across the stages of data entry, calculation flow, and output results. The test output showed that the existing soil embankment had a safety factor of 1.81 for traffic loads and construction, which decreased to 1.77 when seismic loads were added. After the application of geotextiles, the safety factor value increased to 2.20, making the slope more stable. Meanwhile, the application of PVD only increased the safety factor to 1.83 in static conditions and 1.82 in seismic conditions. In terms of land settlement parameters, the unreinforced slope experienced a settlement of 0.3721 m, the slope reinforced using geotextiles experienced a settlement of 0.3691 m, and the slope with PVD increased by 0.3786 m. This conclusion indicates that geotextiles are more optimal for increasing slope stability and minimizing deformation compared to PVD, which is more intended to accelerate the flow of soil consolidation.

The Plaxis calculation output shows that the safety factor has exceeded the regulatory standard threshold of 1.4. The largest deformation was recorded in the 2 m embankment with original soil and geotextile conditions, namely 1.785 during construction, 1.452 after construction, and a settlement of -0.038 m. These findings provide an overview of the safety and settlement levels of various embankments, providing a comprehensive picture of the stability and performance of the road embankment structure. Surbakti (2021) studied soft soil settlement analysis by combining analytical and finite element methods. This study aimed to estimate the actual land subsidence in the field using the Terzaghi formula and finite element methods, both in 2D and 3D contexts. The projected land subsidence according to the Terzaghi method was -6.218 meters, while the output of the finite element method applying Plaxis 2D produced -6.404 meters and Plaxis 3D recorded a value of -6.218 meters. In contrast, field monitoring using a settlement plate instrument showed a settlement of -6,320 meters. Therefore, it can be concluded that the estimated consolidation settlement using the 3D Plaxis simulation is closer to the actual field results than the 2D Plaxis simulation and Terzaghi's analytical method.

Michael (2020) conducted research on the design of Prefabricated Vertical Drains (PVDs) to determine effective patterns and spatial arrangements for accelerating the consolidation time of soft soil layers. The settlement study was analyzed using Terzaghi's one-dimensional consolidation theory, the finite element method, and the Asaoka method for existing field data. The consolidation time was calculated by determining the time factor (T_v) at each time interval, then transformed into the vertical direction consolidation degree (U_v) using the Casagrande and Taylor approaches. The test results showed that without the use of PVDs, the time required to achieve a 90% consolidation degree was 48,300 days. After the intervention of triangular patterned PVDs plus 1.2 m spacing between PVDs, the duration to achieve a 90% consolidation degree was dramatically compressed to only 110 days, while field analysis data using the Asaoka method resulted in a time of 102 days for a similar consolidation degree. This study proves that the calculation of the time factor (T_v) based on Terzaghi's one-dimensional consolidation theory can be applied consistently to project both natural settlement rates and accelerated settlements through soil engineering methods. Wardani (2022) studied the stability analysis of road slope embankments utilizing geotextile reinforcement based on the Plaxis program. Tests were carried out using the finite element method on original soil embankments with varying heights of 2 m, 4 m, 6 m, 8 m, 10 m, 12 m, and 14 m. Simulations were carried out under construction and post-construction conditions, taking into account structural, vehicle, and earthquake loads. Embankments are classified as safe if they have a safety factor exceeding 1.3 . Results The analysis results show that embankments with a height of 2 m to 10 m have met the safety requirements. However, for embankments with a height of 12 m and 14 m, the safety factor value is still below the required limit so that the slope is not stable. Therefore, additional geotextile reinforcement is carried out. After being reinforced with geotextiles, the safety factor value increases so that the embankment slope becomes more stable both during construction and post-construction. These results indicate that the use of geotextiles is effective in increasing the safety factor and stability of embankment slopes. Pratama (2023) studied the consolidation analysis applying the preloading method and Prefabricated Vertical Drain (PVD) on the Pekanbaru–Padang Toll Road Construction Project. The combination of preloading and PVD is an effective method to increase the shear strength capacity of soft soil layers. This investigation aims to compare the magnitude of land subsidence using the finite element method of Plaxis 2D simulation based on mesh density to the STA 46+950 field settlement plate data, plus comparing the settlement output from Plaxis 2D finite element modeling with a coarse type of 0.8647 m.

METHOD

Research Location

The location chosen to conduct the research was the toll road project . Bypass-Pekanbaru at STA 203+850 (CL). The location of this work is in Kampar Regency, Pekanbaru, Riau Province, as can be seen in Figure 3.2 below :

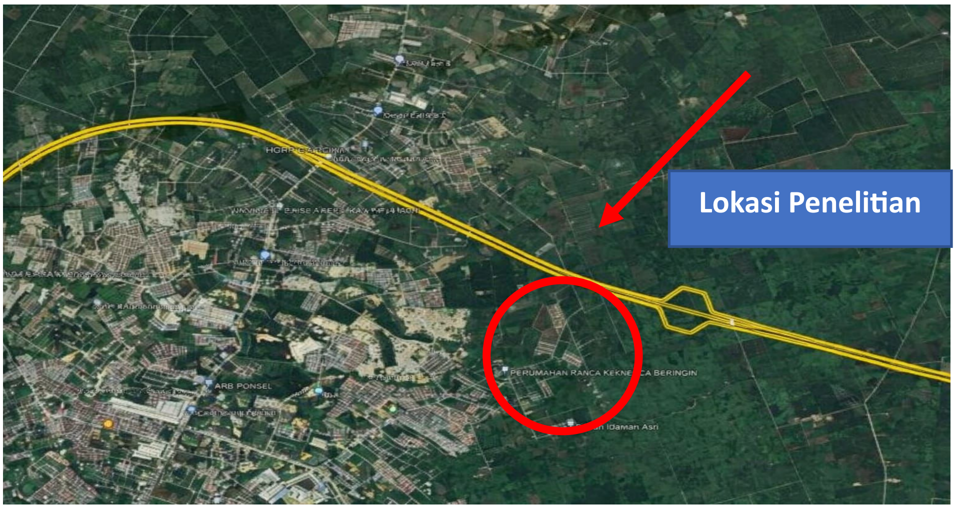

Figure 1Location of the Pekanbaru Bypass Toll Road Research Project
Source: Google Earth (2026)

Method of collecting data

The data collection methods that will be used in this research are:

1. Literature study
   Literature studies are conducted to provide understanding as a theoretical basis by studying various references such as books, scientific journals and previous research related to embankment stability, land settlement, and finite element methods.
2. Documentation Study
   The documentation study was conducted by collecting secondary data from the Junction Bypass – Pekanbaru Toll Road construction project documents. This data includes soil investigation data, soil parameters, and road embankment geometry data .

Research Steps

a. Stage First :
   Collecting various types of literature in the form of books and scientific papers related to this research.
b. Second stage:
   Collect data that will be used in analysis. The data used is bore log, cross main road section STA 203+850, and STA 203+850 CL settlement plate data.
c. Third stage:
   Analysis of land subsidence (consolidation) according to Terzaghi, using analytical methods.

d. Fourth stage:
   Make conclusions and suggestions from the research.

Testing Method

Method Which implemented in study use theory consolidation one dimension, calculation degrees consolidation with method finite element based on data settlement plate. Data Which required For analysis originate from Laboratory results and field testing conducted on the project. There are several stages in the data analysis process carried out in this study, starting from analyzing the results of laboratory soil sample tests to calculating consolidation settlement data. The stages carried out in the research process are as follows:

1. Collection data properties land from results laboratory, data settlement plate STA 203+850 (CL), data stratification land from results boring BT- 46.
2. Calculation time And stages process decline Which taken from data .
3. settlement plate STA 203+850 (CL), start from beginning loading preloading and consolidation are achieved.
4. Calculation time And depth decline land (consolidation) with analytical methods.
5. Compare And analyze the results calculation with realization of the decline that occurred in the field .

Data analysis

Contains field data and explanations.

1. Data cross section main road STA 203+850.

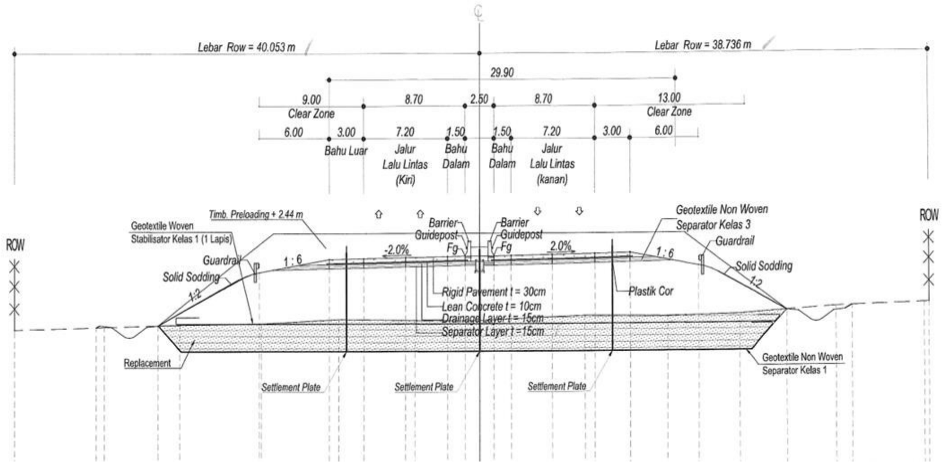

Figure 2Cross Section Data on STA 203+850
Source: Field Data

Data cross section as shown in Figure 3.3 is geometry body road along with layer bore log land Which The length of the road body is 29.90 meters, the width of the road body is 25.90 meters, the thickness of the replacement is 1.5 meters, the thickness of the embankment of the road body is 4.907 meters, and a preloading embankment of 2.4 meters thick is added , before the embankment of the road body is carried out. the road is being used to install settlement plates at ground elevation existing. Settlement plate used For know decline current In the field. The settlement plate is used to determine the actual subsidence in the field. The soil conditions around the field can be seen in Figure 3.4 as follows:

RESULTS AND DISCUSSION

Field Conditions and Soil Parameters

The analysis was conducted on the STA 203+850 CL road embankment on the Junction Bypass-Pekanbaru Toll Road project. The planned cross-section consists of a 1.50 m thick replacement, a 4.907 m high road embankment, and a 2.44 m thick preloading. Thus, the total height of the analyzed embankment is approximately 8.847 m. A settlement plate was installed at the existing ground elevation prior to the embankment work to record vertical movements during loading and consolidation.

Soil investigations revealed a surface layer of clayey sand and silty sand, followed by a compressible clay layer at a depth of approximately 4.0 to 15.2 m. The groundwater table is at a depth of approximately 2.5 m. This clay layer is the primary layer considered in the settlement analysis due to its low permeability and potential for consolidation due to the additional embankment load.

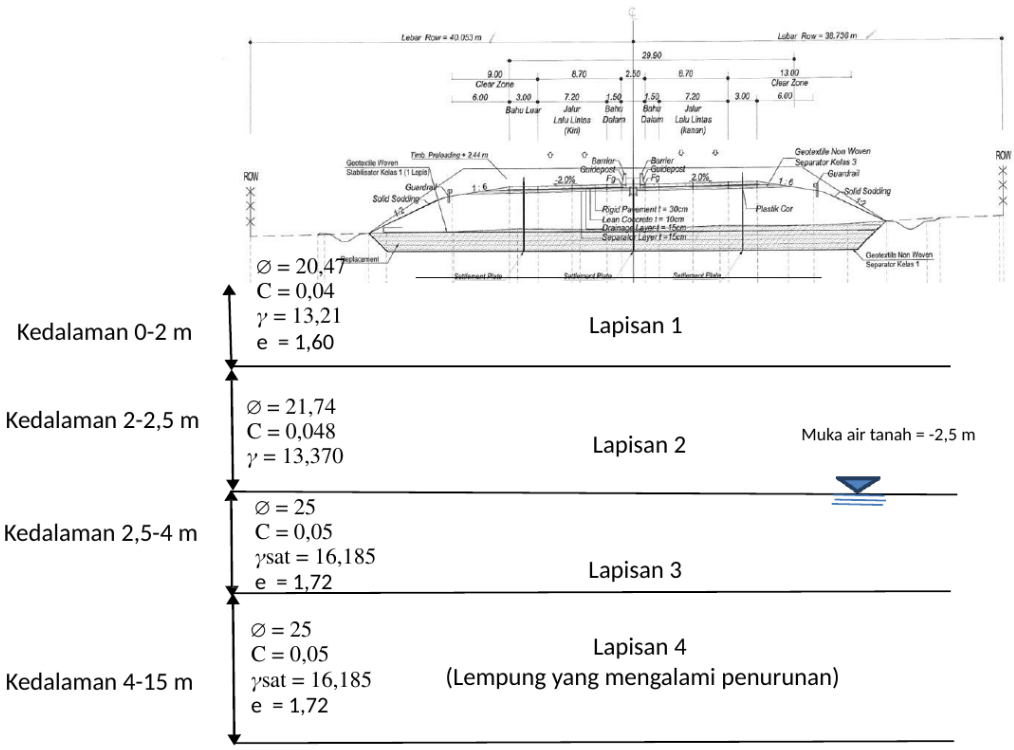

Figure 4 Soil layer stratification at STA 203+850 CL
Source: Project data (2026)

Table 1 Summary of soil stratification and parameters

Depth (m)	Soil type	γsat (kN/m³)	E (kN/m²)	k (m/day)	φ (°)	c
0-2	Clayey Sand (SC)	16,035	5,000	0.0001	20.47	0.040
2-4	Silty Sand (SM)	16,185	5,000	0.0001	21.74	0.048
4-15.2	Clay (CH)	16,185	5,000	0.000001	25.00	0.050
15.2-19.45	Sand	15,862	5,000	0.1	25.00	0.050

Elastic modulus and permeability parameters not available from field testing were determined based on the soil classification and N-SPT values in the reference tables used in the manuscript. This approach allows for modeling, but also presents a source of uncertainty when comparing predicted results with actual field conditions.

Decline Analysis with Terzaghi Method

Consolidation settlement was calculated using Terzaghi's one-dimensional consolidation theory for three loading stages. The existing soil layer before the settlement plate installation was treated as overburden pressure, while additional loads came from replacement, embankment, and preloading. The calculation results for each stage are presented in Table 2.

Table 2 Results of analytical settlement calculations

Loading stage	Height (m)	Additional stress (kN/m²)	Decrease (m)	Decrease (cm)
Replacement	1.50	21,780	0.0897	8.97
Road embankment	4,907	71,250	0.1795	17.95
Preloading	2.44	35,429	0.0592	5.92
Total	8,847	-	0.3284	32.84

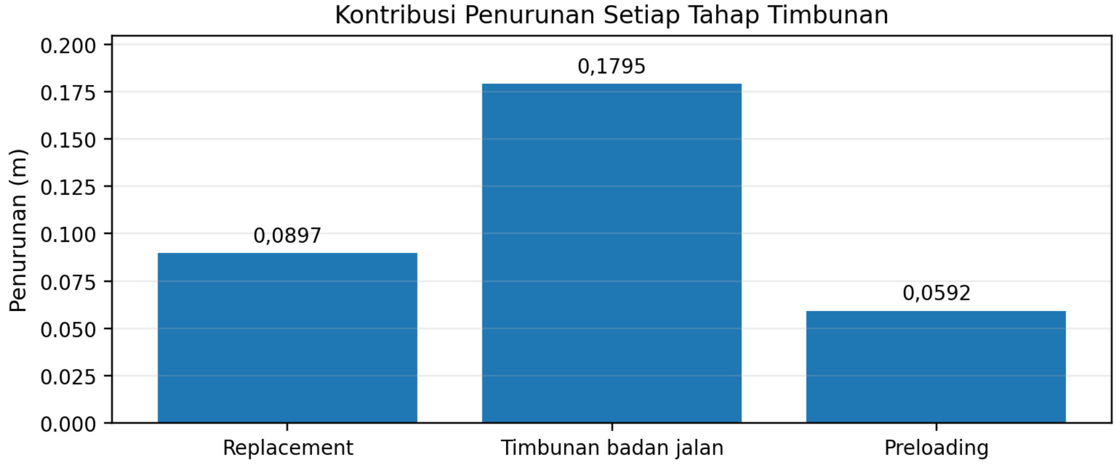

Figure 5 Contribution to settlement of each embankment stage

Source: Research results (2026)

The largest contribution to settlement comes from the roadbed embankment, amounting to approximately 0.1795 m, or more than half of the total settlement. Replacement contributes approximately 0.0897 m of settlement, while preloading contributes an additional 0.0592 m. Overall, the predicted settlement under fully consolidated conditions is 0.3284 m. This value is greater than the settlement recorded by the settlement plate. This difference should be understood as a consequence of analytical assumptions that simplify the soil conditions to one dimension and use representative parameters for layers that are not actually completely homogeneous. Analytical results remain important as estimates of long-term settlement limits, but they do not directly represent the stage of consolidation achieved during the monitoring period. The calculation summary can be expressed as S total = 0.0897 + 0.1795 + 0.0592 = 0.3284 m. This quantity is then used as a comparison against field data and FEM modeling results.

Settlement Plate Monitoring Results

Settlement plate monitoring was conducted for 125 days, from December 27, 2024, to April 30, 2025. Vertical movement increased gradually as backfilling progressed and then tended to level off at the end of the observation period. The final cumulative settlement recorded was 0.222 m (22.2 cm).

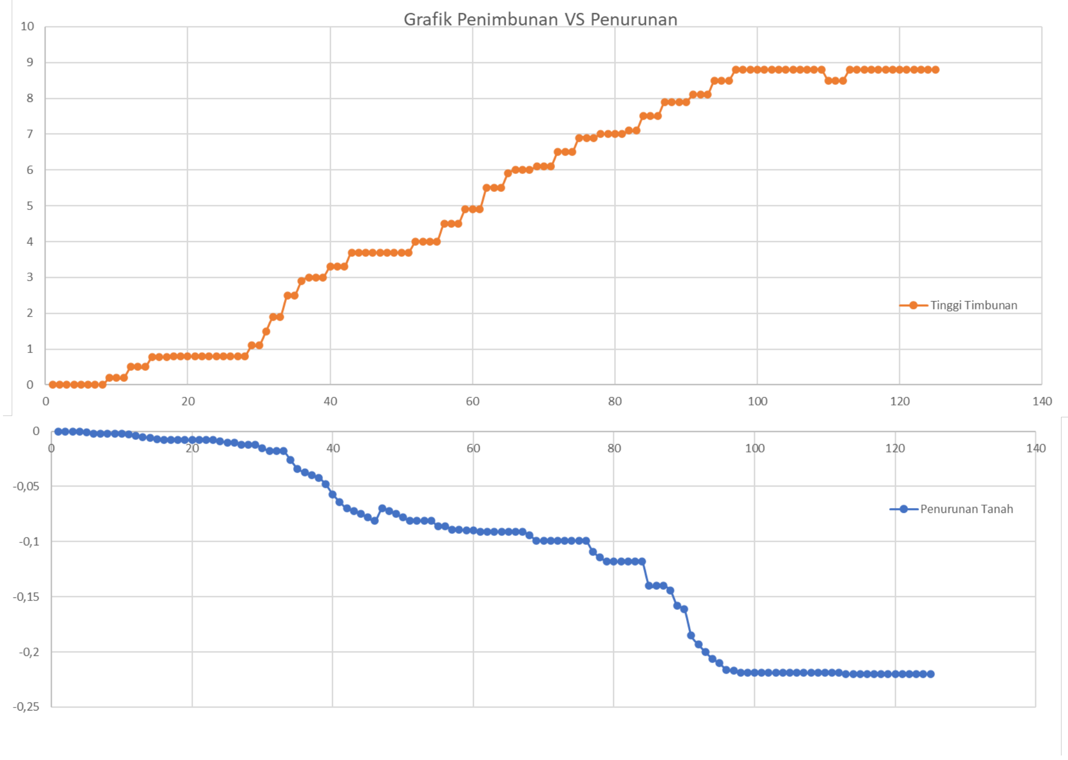

Figure 6 Graph of settlement plate monitoring results
Source: Processed project data (2026)

Table 3 Selected cumulative decline development

Day to	Cumulative decline (m)	Information
1	0,000	Initial conditions
39	-0.026	The decline is starting to increase
85	-0.140	Accumulation after loading
107	-0.185	Further improvements
125	-0.222	Final monitoring score

The curve shows that settlement does not occur immediately upon application of the load. Larger changes occur at certain loading phases, then the rate of settlement decreases as pore water pressure dissipation approaches steady state. The value of 0.222 m therefore represents the field response during the monitoring period, not the final settlement at 100 percent consolidation.

Compared to Terzaghi's prediction of 0.328 m, the field data was 0.106 m lower. The paper attributes this difference to three main factors: the analytical calculations assumed full consolidation, the unit weight used was the maximum condition, and the laboratory data did not necessarily represent the full range of soil layers at the study site.

Consolidation Time and Analytical Slope Stability

The consolidation time calculation uses a consolidated layer thickness of 4 m. Since drainage occurs upward and downward, the effective drainage path length is set at 2 m. With a time factor Tv90 of 0.848 and a consolidation coefficient Cv of 0.007 cm^2/second, the time to reach a degree of consolidation of 90 percent is estimated to be 56.084 days.

Table 4 Summary of consolidation and analytical stability results

Parameter	Mark	Interpretation
Thickness of the consolidation layer	4.0 m	Two-way drainage
Effective drainage path	2.0 m	H/2
Consolidation time 90%	56,084 days	Waiting period reference
Critical height of embankment	14,242 m	Greater than actual height
Actual height of embankment	7,347 m	Used in Culmann analysis
Culmann safety factor	1.94	Safe according to the minimum limit of 1.50

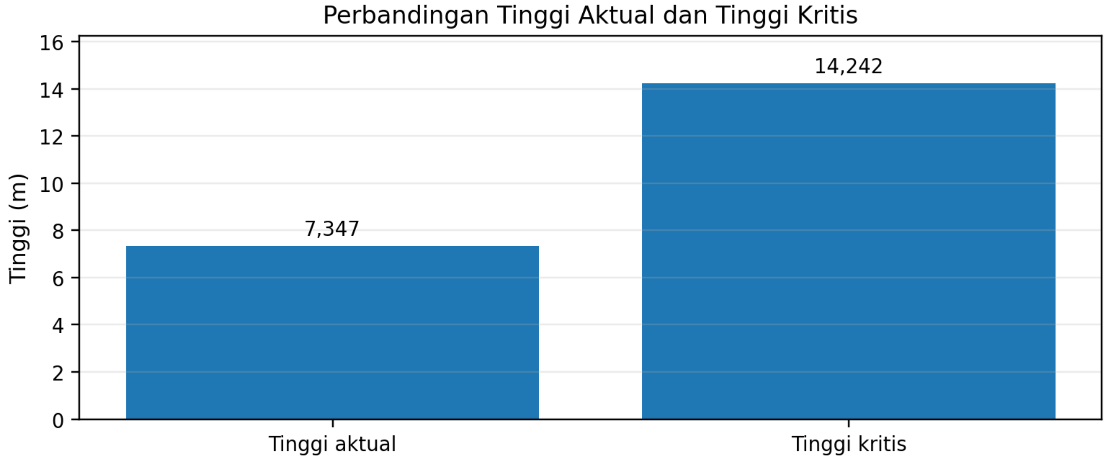

Figure 7 Comparison of actual height and critical height

Source: Research results (2026)

The 56-day estimate can be used as a baseline for determining the waiting period before the next construction phase. This value depends on the dual drainage assumption and laboratory-derived CV parameters, so verification through monitoring is still necessary to ensure that the settlement rate in the field is sufficiently low.

Slope stability was analytically calculated using the Culmann method. The critical height of 14,242 m compared to the actual height of 7,347 m yields a safety factor of 1.94. Based on the minimum threshold of 1.50 used in the study, the slope is considered safe against landslides according to the analytical approach.

Modeling with Finite Element Method

Numerical modeling was performed using Plaxis 2D with a plane strain approach and 15-node elements. The soil was modeled using the Mohr-Coulomb model based on the unit weight, elastic modulus, Poisson's ratio, cohesion, internal friction angle, and permeability of each layer. The groundwater table was placed at a depth of 2.5 m, according to the conditions used in the model.

Table 5 Main configurations of the FEM model

Model components	Arrangement
Type of analysis	Plaxis 2D, plane strain
Element types	15-noded element
Material model	Mohr-Coulomb
Unit	m, kN, day
Construction stages	Excavation replacement, geotextile, replacement, road embankment, preloading, consolidation, safety factor
Main output	Vertical deformation, pore water pressure, and safety factor

Unlike one-dimensional calculations, FEM numerically represents embankment geometry, layer subdivision, construction stages, and deformation responses. All phases are activated sequentially so that stress changes and consolidation follow the sequence of fieldwork.

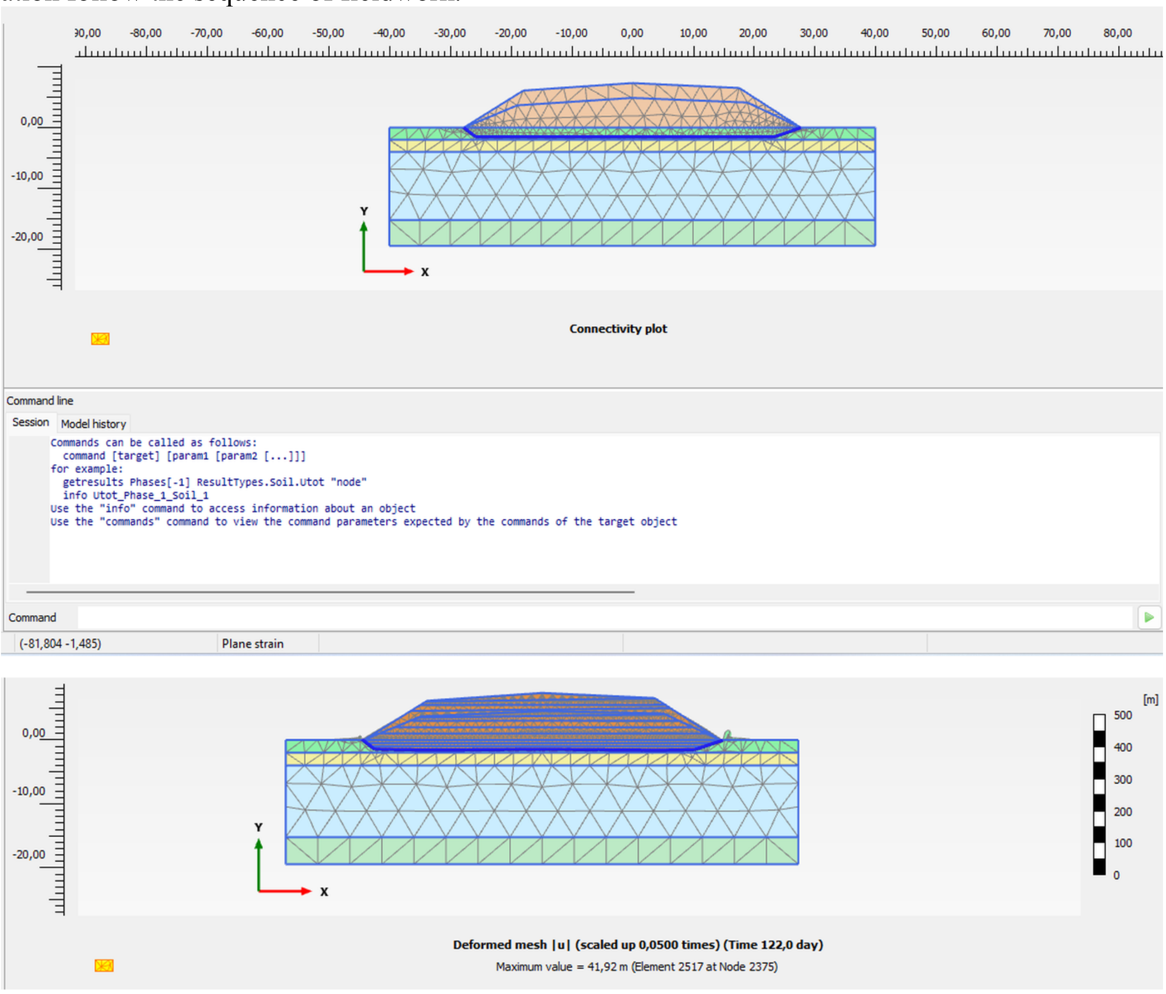

Figure 8 Generated mesh and deformed mesh in the FEM model
Source: Author's processed results (2026)

FEM Derivation Results

The vertical displacement output showed a maximum settlement of 0.171 m. This value is smaller than the settlement plate monitoring result of 0.222 m, but the difference is only 0.051 m. The percentage difference compared to the field data is approximately 22.97 percent.

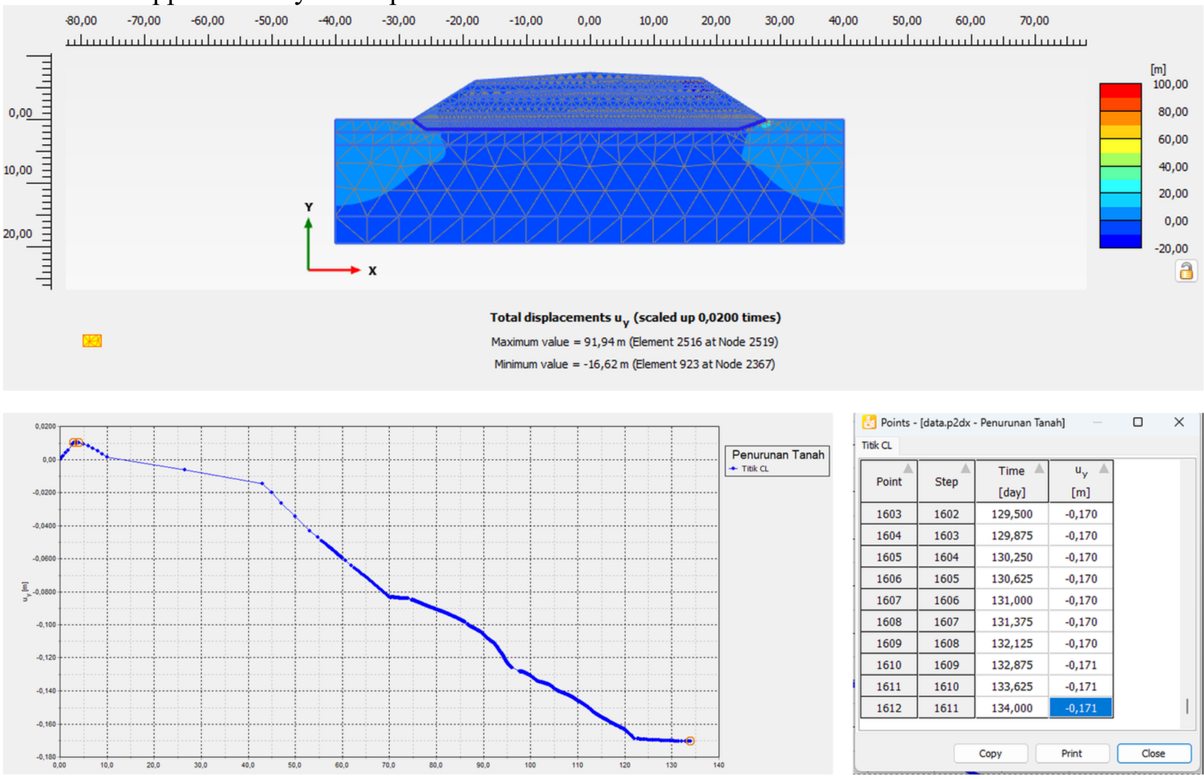

Figure 9 Contours, curves, and settlement output in Plaxis 2D

Source: Author's processed results (2026)

The FEM settlement curves show increasing deformation during the construction and consolidation stages, then approaching a steady state at the end of the simulation. This pattern is consistent with the trend in the settlement plate data, although the final model values are still below the observed values. Compared to the Terzaghi method, the FEM predictions align more closely with actual conditions. Terzaghi yields a difference of 0.106 m, or 47.75 percent, while FEM yields a difference of 0.051 m, or 22.97 percent. Based on this comparison, FEM provides a more representative settlement estimate for the study site. However, the closeness of the results does not mean the model is completely free from uncertainty. The modulus and permeability values of some layers are determined through assumptions based on soil classification. Parameter calibration using longer monitoring data can improve model accuracy.

FEM Slope Stability Results

Slope stability analysis in Plaxis was performed using the safety factor phase after all construction and consolidation stages were activated. The FEM results yielded a safety factor of 1.04. This value is significantly lower than the 1.94 obtained by the Culmann method and indicates that the slope is in critical condition according to the numerical model.

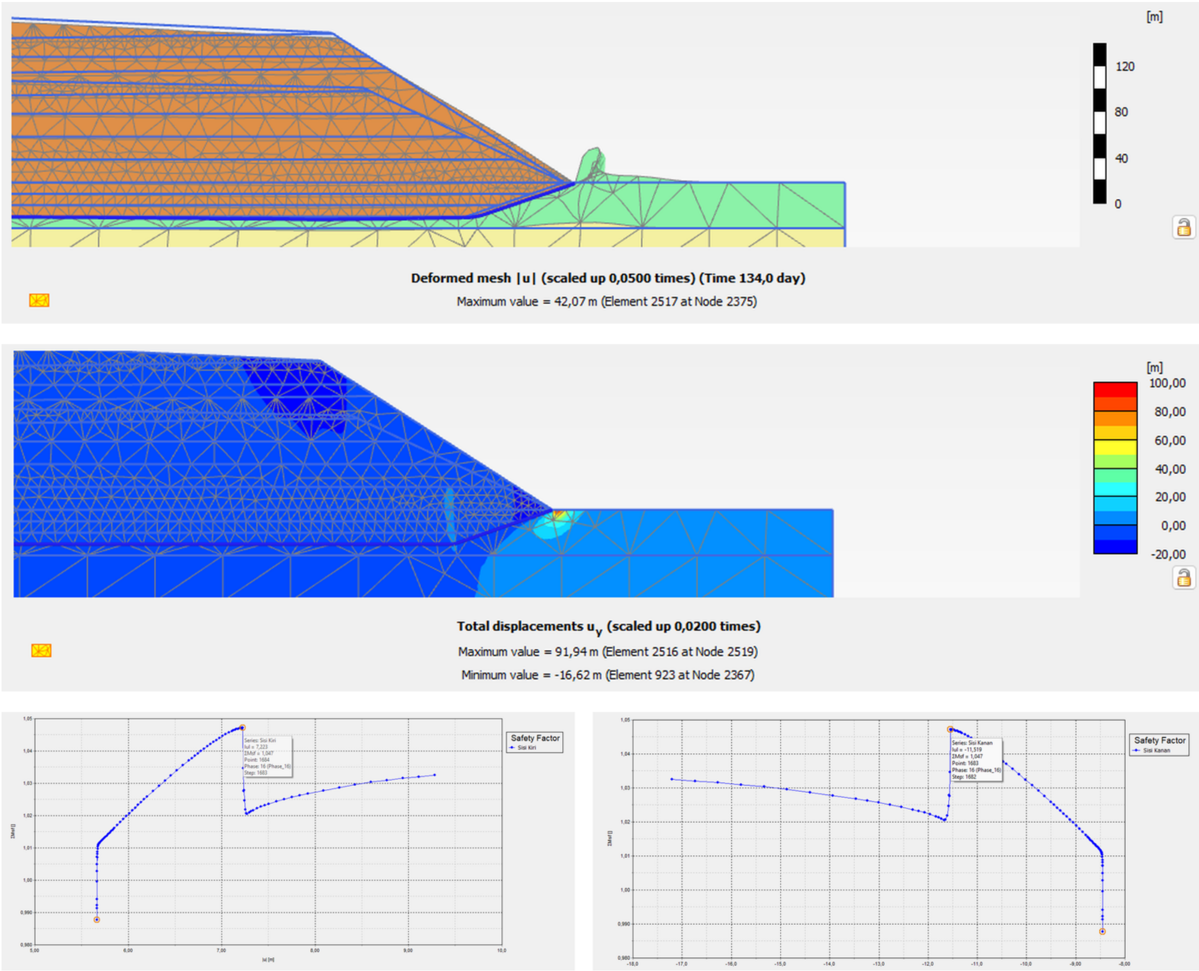

Figure 10 FEM slope deformation, displacement, and safety factor curves

Source: Author's processed results (2026)

The significant difference between the two methods indicates that the stability results do not yet provide a good agreement. The Culmann method assesses the safety of slopes based on the comparison of critical and actual heights, while the FEM takes into account the numerical response of the soil layers and construction stages. Because the FEM results approach the failure limit, slope conditions need to be treated with caution in engineering evaluations.

Discussion

A comparison of the three approaches reveals a clear pattern. The Terzaghi method predicts greater settlement than field data, while the FEM predicts smaller settlement. Although neither method matches the monitoring results, the FEM prediction's distance from the settlement plate is smaller.

Table 6 Comparison of reduction results

Approach	Decrease (m)	Difference to the field (m)	Difference (%)	Interpretation
Settlement plate	0.222	-	-	Actual data
Terzaghi	0.328	0.106	47.75	Larger than actual data
FEM Plaxis 2D	0.171	0.051	22.97	Closest to actual data

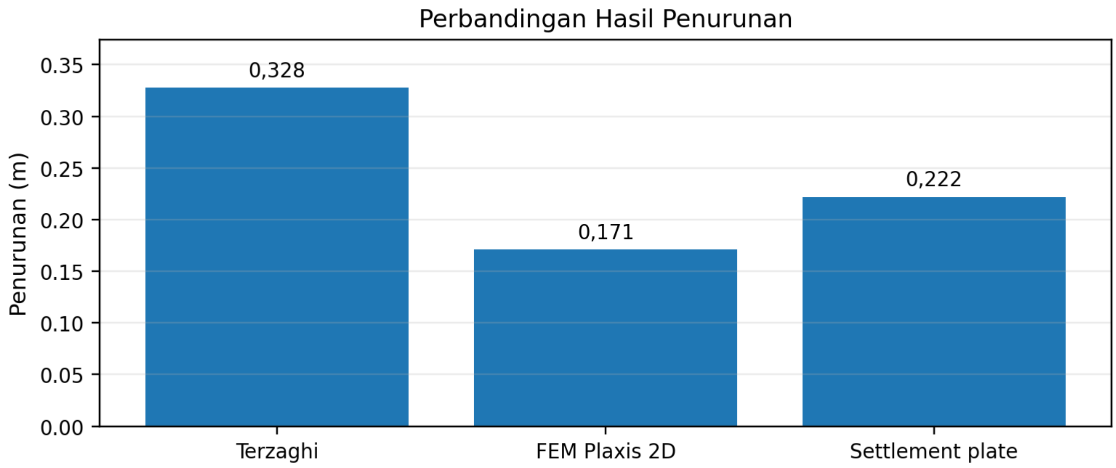

Figure 11 Comparison of the results of the reduction
Source: Research results (2026)

Terzaghi's higher predictions can be explained by the assumption of 100 percent consolidation, the use of maximum unit weight, and the limitations of laboratory data in representing the full range of soil layer variations. In contrast, FEM structures soil response based on geometry, loading stages, and interactions between layers. These characteristics make FEM results more closely approximate monitoring conditions, although the final values are still lower than those of the settlement plate. These results align with research by Surbakti (2021), which showed that Plaxis modeling can produce settlement estimates that closely match field observations, and Zahara (2008), who found differences between manual calculations and numerical modeling in consolidation analysis. These findings underscore the importance of comparing analytical and numerical predictions with field instruments.

Regarding slope stability, the conclusions of the two methods differ. A Culmann value of 1.94 indicates a safe condition, while a FEM value of 1.04 indicates a critical condition. This discrepancy means that stability results cannot be assessed solely from a single approach. Evaluations should prioritize more conservative conditions, especially when the numerical safety factor is very close to 1.00. Overall, FEM is a more representative method for predicting settlement at the study site because it produces results closest to the settlement plate. However, FEM results also indicate that slope stability remains critical. Therefore, settlement monitoring, lateral movement assessment, and re-evaluation of soil parameters are still necessary before the embankment is declared safe for the next construction phase.

CONCLUSION

Based on the results of analysis and calculations of field data and laboratory data, the following conclusions can be drawn:

1. The magnitude of land subsidence that occurred using the analytical method based on Terzaghi's one-dimensional consolidation theory was 0.328 meters, and the difference with the actual in the field was 0.106 m with a total embankment height of 8.84 meters.
2. The magnitude of the potential reduction in land subsidence that occurs based on Finite Elements Method (FEM) using Plaxis 2D is 0.171 meters, and the difference with the actual in the field is 0.05 m with a total embankment height of 8.84 meters.
3. The recommended method of choice among the two methods mentioned above is the finite element method, as it is more representative in predicting land subsidence in road embankments on soft soils. In addition to providing results that approximate actual conditions, this method also depicts soil and structural behavior more accurately and precisely.
4. The calculation of the slope safety factor using the Culmann method yielded a safety factor (FK) of 1.94, indicating that the embankment slope is safe from potential landslides. This value is obtained from the comparison between the critical height of the embankment of 14.242 meters and the actual height of the embankment of 7.347 meters. Meanwhile, the results of the finite element method analysis produced a safety factor of 1.04, indicating a critical condition and much lower than the analytical value.

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