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Simulation of Soil Settlement Using Plaxis for the Pekanbaru-Padang Toll Road Construction Project: A Detailed Analysis

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Abstract— Geotechnical issues often include settlement and soil bearing capacity, which serve as the foundation for toll roads. Each toll road is designed with specific loads and elevations, which sometimes cannot be supported by the consolidation of the existing soil due to the soft soil characteristics. Soil improvement methods such as replacement (soil material replacement) and preloading are commonly used to enchace the shear strength of soft soils. This analysis aims to evaluate and compare the amount of consolidation settlement analytically using modeling in Plaxis 2D with a very fine mesh type, using settlement plate data from the field. The analysis compares the amount of consolidation settlement through Plaxis 2D modeling with a very fine mesh type and field settlement plate data. From the analysis the consolidation time using Plaxis 2D modeling is found to be 149 days, while the settlement time field data is 39 days. The consolidation settlement obtained from the plaxis 2D model with a very fine mesh is 0.056 meters, whereas the settlement from the field data is 0.416 meters, with a percentage difference of 86.53%. It can be concluded that the significant difference between the field data and the Plaxis 2D analysis results is due to the lack of data available for each soil layer.

Keywords: Consolidation, Replacement, Preloading, and Plaxis.

1. Introduction

Rapid economic growth in cities cannot be separated from crucial problems. These problems include the increase in the movement of goods and services to the city center which causes a high number of vehicles crossing the road and leads to traffic congestion [1]. An example is the cities in the Pekanbaru-padang. The enhancement of land transportation infrastructure includes the implementation of toll road construction [2]. The operation of toll roads aims to improve the efficiency of distribution services to support the growth of the economy, particularly in areas with high levels of development. With the existence of toll roads, it is expected that a spillover effect will occur, thereby enhancing the economic growth of the regions traversed by the road [3-4].

The Pekanbaru-Padang Toll Road project is a strategic initiative designed to enhance connectivity between two major cities on Sumatra Island. The primary objectives of this project are to reduce travel time, alleviate traffic congestion, and support regional economic growth[5]. The project is divided into five work zones with varying lengths: Zone 1 is 3 km, Zone 2 is 5 km, Zone 3 is 6 km, Zone 4 is 6 km, and Zone 5 is 4.7 km, making the total length of the toll road approximately 24.7 km. Soil tests conducted across the different zones reveal tha most of the project area is underlain by soft soil with high moisture content[6]. This can be seen on the distribution map of soft soil in the following Figure 1.

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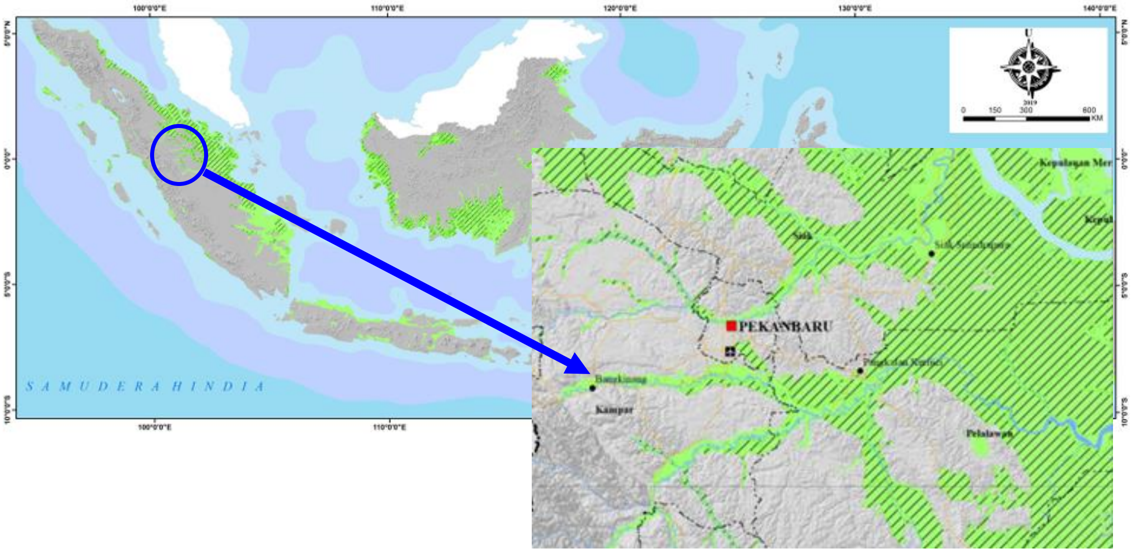

Figure 1. Distribution of soft soil

In Figure 1, it can be seen that the location being reviewed is in the green-colored area, which indicates that the area consists of soft soil [7]. This type of soil typically has high compressibility, low permeability, and low bearing capacity, making it unsuitable as a foundation for toll road construction without intervention[8-9]. Unimproved soft soil can lead to significant ground settlement, potentially damaging the toll road structure and posing safety risks to road users[10]. Settlement can be particularly severe if it occurs locally, causing uneven subsidence in certain areas. To address these issues, comprehensive soil improvement measures have been implemented[11]. These measures include a combination of soil replacement and preloading techniques[12]. Soil replacement involves removing the soft soil from the surface and replacing it with more stable material to a depth of 1.4 meters. Preloading is applied by adding a load of 1.4 meters on top of the improved soil. The purpose of preloading is to consolidate the soft soil layer by applying a pressure equal to or greater than the load that the soil will experience after construction is completed. This process accelerates the natural consolidation of the soil, allowing it to achieve the necessary strength before the toll road is constructed. The preloading causes compression of the soil layers below due to soil particle deformation, particle displacement, and the explusion of water or air from soil pores among other factors[13-15]. The compression resulting from preloading is crucial for ensuring the long-term stability of the toll road. Without adequate consolidation, soft soil may continue to settle after the toll road is built, potentially causing damage to the road structure and incurring high repair costs in the future[16]. Although soil replacemet and preloading are commonly used methods, this study will explore additional aspects. The primary focus of the research is to evaluate soil settlement using Plaxis 2D software with a very fine mesh[17]. Plaxis 2D is a finite element analysis software frequently used to model soil behavior under load. Simulations conducted with Plaxis 2D will be compared with field data to assess the accuracy of the model in predicting soil settlement[18-19]. The research will concentrate on the area around the borehole data or the sound test results at STA 47+100. Data from this location will be used to validate the Plaxis 2D simulation results and evaluate the effectiveness of the soil improvement methods applied. The study aims to provide deeper insights into soft behavior and the effectiveness of soil improvement techniques for future toll road projects, especially in areas with similar soil conditions.

2. Method

The research location is at the Pekanbaru-Padang Toll Road Project, specifically at STA 47+100, situated in Kampar Regency, Riau Province, Sumatra. Based on the geotechnical investigation conducted in the field, including sondir and boring tests, it has been determined that the area consists of soft soil that requires stabilization before the toll road construction can proceed. The soil conditions at this site necessitate improvements to ensure adequate stability and load-bearing capacity to support the Pekanbaru-Padang Toll Road Project. The project location map can be seen in Figure 2.

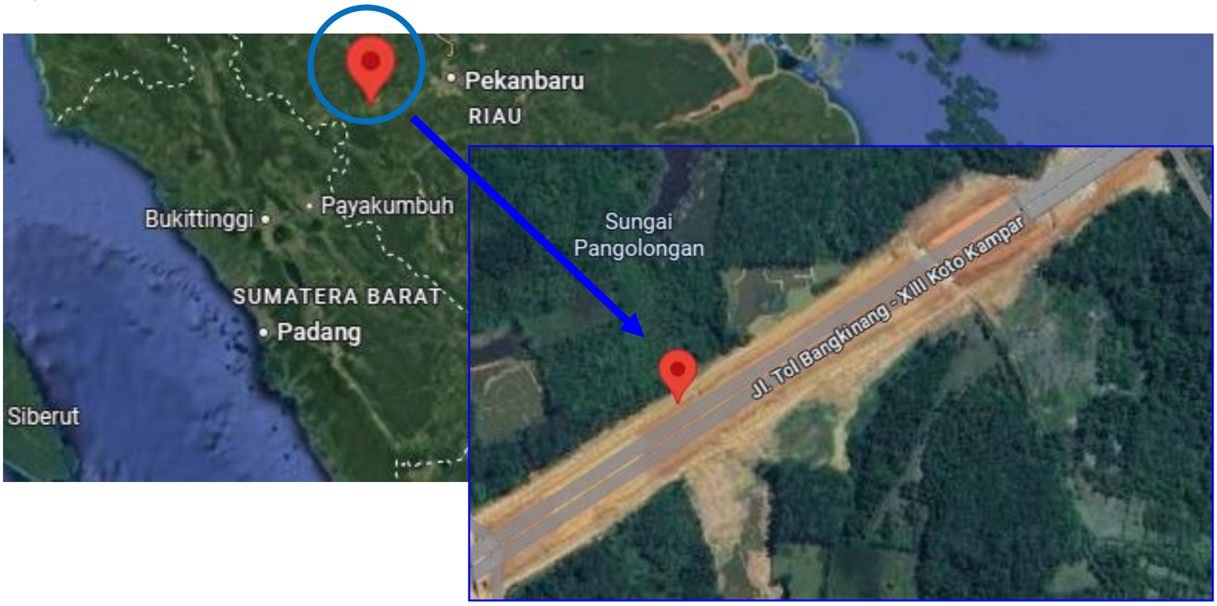

Figure 2. The Project Location Map

His study utilizes a combination of the Replacement and Preloading methods for soil consolidation analysis, along with numerical modeling using Plaxis 2D. Geotechnical data, including soil physical and material properties, topographic information, and construction loads, are collected as the basis for the analysis. The replacement method involves replacing soft soil with more stable material, while Preloading is applied to accelerate the consolidation process by applying temporary loads. Modeling with Plaxis 2D is used to predict soil behavior during consolidation, including soil settlement and stress distribution. The results of the modeling are then validated with field data, and an evaluation is conducted to assess the effectiveness of these methods in accelerating consolidation and ensuring soil stability under construction loads.

Figure 3. The Plan For Replacement And Preloading 47+100

From the above Figure 3 in the planning of the Replacement and Preloading methods, there are several soil layers, including existing soil, a Replacement layer, embankment for the mainroad, and embankment for preloading. The existing soil consists of there layers obtained from cone penetration test (CPT) data. The first layer, from the surface level (elevation 0) to a depth of 3.2 meters, is clay soil. The second layer, between 3.2 and 6 meters, is silty clay, and the thrid layer, form 6 to 10 meters, is sand. In the Replacement layer, the material used is silty sand with a depth of 1.4 meters from the ground surface. The CPT data can be seen in Table 1.

Tabel 1. CPT data

Depth	C (kg/cm^2)	C+F (kg/cm^2)	Soil ID	Depth	C (kg/cm^2)	C+F (kg/cm^2)	Soil ID
0	0	0	Clay				
0,2	0	0	Clay	5,2	63	82	Silty Clay
0,4	2	3,5	Clay	5,4	42	64	Silty Clay
0,6	2	3,5	Clay	5,6	24	40	Silty Clay
0,8	2	3	Clay	5,8	38	52	Silty Clay
1	2	3	Clay	6	88	104	Silty Clay
1,2	2	3	Clay	6,2	102	114	Sand
1,4	3	5	Clay	6,4	108	118	Sand
1,6	3	5	Clay	6,6	122	144	Sand
1,8	4	6	Clay	6,8	139	162	Sand
2	4	6	Clay	7	134	163	Sand
2,2	3	5	Clay	7,2	136	164	Sand
2,4	3	5	Clay	7,4	142	172	Sand
2,6	4	6	Clay	7,6	150	182	Sand
2,8	4	6	Clay	7,8	128	152	Sand
3	5	7	Clay	8	106	122	Sand
3,2	7	9	Silty Clay to Clay	8,2	142	165	Sand
3,4	12	15	Silty Clay	8,4	156	184	Sand
3,6	32	35	Silty Clay	8,6	148	173	Sand
3,8	46	54	Silty Clay	8,8	162	188	Sand
4	64	78	Silty Clay	9	184	200	Sand
4,2	72	86	Silty Clay	9,2	234	250	Sand
4,4	76	90	Silty Clay	9,4	238	250	Sand
4,6	66	78	Silty Clay	9,6	250	250	Sand
4,8	63	75	Silty Clay	9,8	250	250	Sand
5	63	78	Silty Clay	10	250	250	Sand

For the mainroad embankment, with a height of 4.58 meters, and the preloading embankment, with a height of 1.4 meters, the material used is CBM soil. The consolidation test data will use the Mohr-Coulomb model with correlations to the N-SPT values[20]. The existing soil layers are categorized into two types: some layers exhibit undrained behavior, while others show drained behavior. Two types of replacement soil are used: silty sand with more than 60% sand content and granular soil (a mixture of coarse sand and gravel). Additionally, the original soil will be modeled based on data from the SO-47+100 ivestigation.

Table 2. Material Soil Parameters Model STA 47+100

Type of Soil	Elevation (m)	Thickness (m)	Properties	Soil Model
Clay	0 – 3.2	3.2	Drained	Mohr-Coulomb
Silty Clay	3.2 – 6	2.8	Drained	Mohr-Coulomb
Sand	6 – 10	4	Undrained	Mohr-Coulomb

Laboratory tests, including physical properties tests and consolidation tests, were conducted to obtain the necessary data for input into the Plaxis program. These tests provided the parameters such as unit weight (γ), saturated unit weight (γ_sat), modulus of elasticity (E), Poisson's ratio (υ), cohesion (c_ref), internal friction angle (∅), and coefficients of soil permeability in both the vertical (k_x) and horizontal (k_y) directions. The results from these laboratory tests were used to determine the soil properties required for accurate modeling in Plaxis. Additionally, the lambda compression index (λ*) was calculated using the provided formula, and the kappa compression index (κ*) was computed using a separate formula. These parameters, obtained from laboratory testing, are summarized in Table 2, and the calculated values are shown in Table 3.

Table 3. Data Entered Into The Plaxis Program

Description	**Unit**	**Material Properties STA 47+100**				
		Embankment	**Silty Sand**	**Clay**	**Silty Clay**	**Sand**
Material Model	**-**	**Mohr-Coulomb**	**Mohr-Coulomb**	**Mohr-Coulomb**	**Mohr-Coulomb**	**Mohr-Coulomb**
Depth	**Mtr**	**5.98 – 0**	**0 – 1.4**	**1.4 – 3.2**	**3.2 – 6**	**6 – 10**
Drainage Type	**-**	**Drained**	**Drained**	**Undrained**	**Drained**	**Drained**
γ_unsat	kN/m^3	17	16	16	17	18
γ_sat	kN/m^3	18	17	17	18	19
E	kN/m^2	10030	30000	10000	50140	323300
v (nu)		0.30	0.30	0.30	0.30	0.30
c_ref	kN/m^2	29.2	15.5	15.5	29.2	29.2
φ (phi)	º	40	30	0	90	90
Ψ (psi)	º	0	0	0	0	0
λ* (lambda)		-	-	-	-	-
κ* (kappa)		-	-	-	-	-
k_x	m/day	0.0005	0.0005	0.0005	0.0005	1
k_y	m/day	0.0005	0.0005	0.0005	0.0005	1
Layer Name	Preloading		1	2	3	4

In the Plaxis modeling, input parameters for the soil to be modeled are required. These soil parameters, obtained from laboratory test results as shown in Table 2 and Table 3, will be entered into the Plaxis program.

3. Result and Discussion

Based on the cone penetration test (CPT) results, soil replacement will be carried out at the STA 47+100 location. The replacement will be conducted from an elevation of 0 a depth of-1.4 meters. The CPT results indicate a total soil depth of 10 meters. Details of the soil layers that need to be replaced can be found in Table 4.

Table 4. Details Of The Soil Layers

Layer	**Description**
Layer 1	(CBM Fill) Mainroad 4.58 m + Preloading 1.4 m = 5.98 m
Layer 2	Replacement 1.4 m
Layer 3	Clay 1.8 m
Layer 4	Silty Clay 2.8 m
Layer 5	Sand 4 m

3.1 Calculations with Plaxis 2D

In the calculation using Plaxis, the modeling type applied is Plane Strain with 15 nodal point. The cross-section considered is 100 meters, and the mesh type used is medium. Generally, there are three types of geometric modeling in Plaxis: Axisymmetric, which is applied to symmetric structures such as single-pile foundations; Plane Strain, which is commonly used for long structures like retaining walls and is selected for this study; and Plane Stress, typically used for edge plates. The calculations in Plaxis 2D are carried out through sereval specific steps.

1. **Soil** At this stage, the soil modeling is carried out based on the soil layers obtained from the field cone penetration tests. The data or values are then input according to Table 2. The process of inputting soil layer data or setting material properties. The field conditions converted into the Plaxis program aim to translate the on-site construction stages into the program's workflow. The objective is to closely replicate the on-site execution in the program so that the responses produced by the program can be representative oh the actual field conditions. The modeling of the soil layers can be seen in Figure 4.

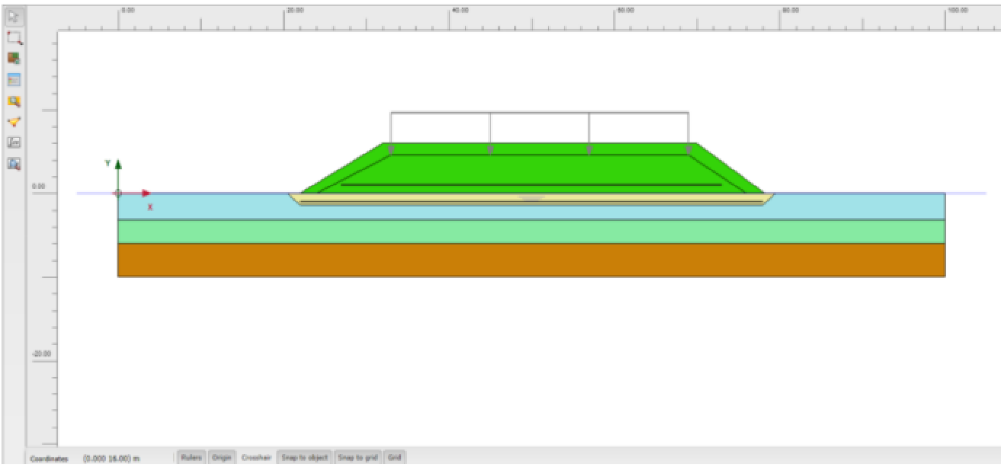

Figure 4. Soil Layer Modeling In Plaxis 2D

2. **Generate Mesh 2D** After all the soil geometry has been drawn and its properties have been input into the soil layers, the next step to define the boundary conditions and generate the mesh. In the process of setting boundary conditions, the consolidation boundaries of the analyzed structure will be determined. During the generate mesh phase, the entire structure is divided into smaller elements. The smaller the mesh size, the more accurate the calculations will be. For this study, a very fine mesh was used. The mesh selection can be seen in Figure 5.

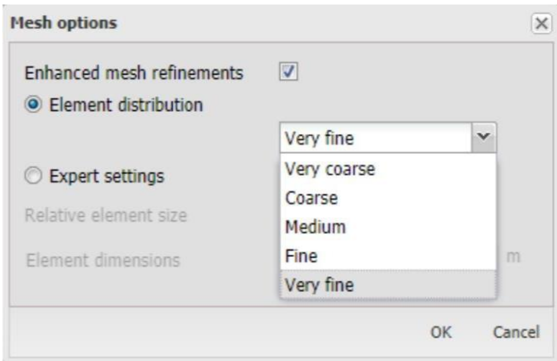

Figure 5. The Mesh Modeling Used

The calculations process in the Plaxis program involves dividing the entire construction into meshes. The smaller the mesh size, the more accurate the calculations, but the computation time will be longer. The results of the mesh generation with a very fine type. The generated mesh consists of 2.137 elements and 17.291 nodes.

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Table 5. The Generated Mesh Is of The Very Fine Type

PLAXIS Mesh Types	Mesh	
	Number Of Elements	**Number Of Nodes**
Very Fine	2.137	17.291

3. **Flow Condition** In this flow condition, the groundwater level at the study location will be calculated. For this study, the groundwater level is assumed to be at the same elevation as the current ground level. The pressure caused by the groundwater can be seen in Figure 6.

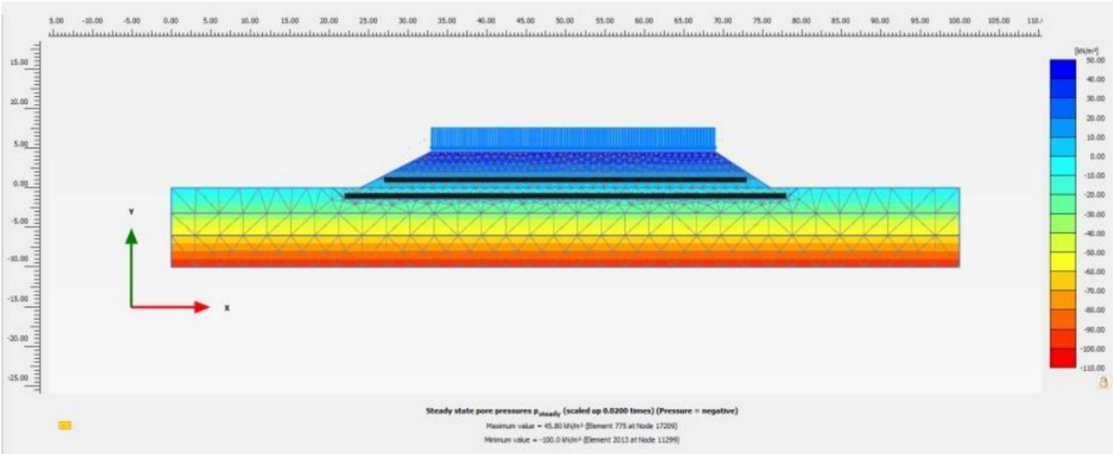

Figure 6. The Pressure Caussed By Groundwater Is a Maximum of 45.80 kN/m² and a Minimum of-100.0 kN/m²

4. **Staged Construction** The staged contruction phase is part of the calculation process. There are six calculation phases, and details of phases can be seen in Figure 7.

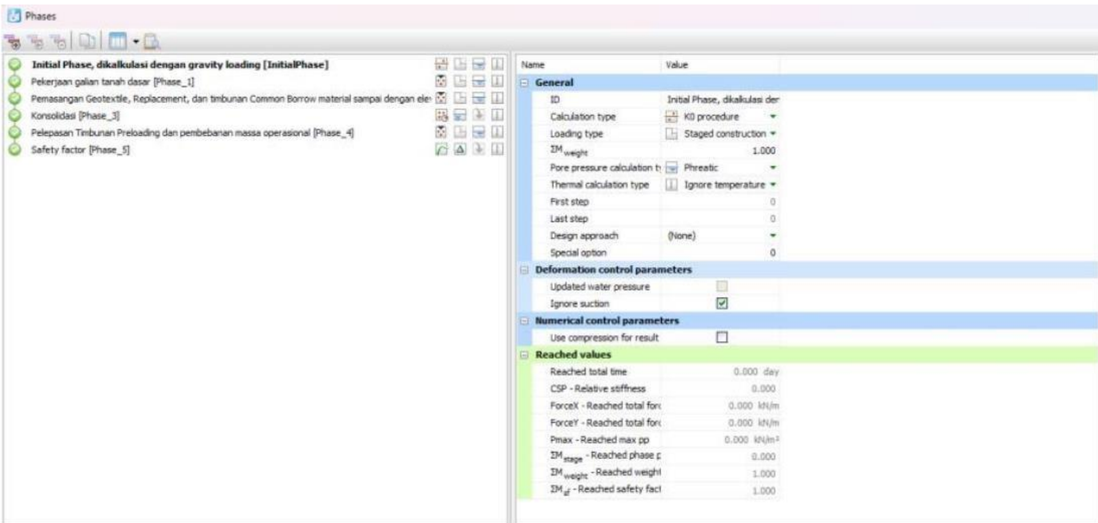

Figure 7. Calculation Phase

After completing the calculation phase, the next step is to determine the observation point (Point A). The location of Point A must correspond to the location of the settlement plate installation at STA 47+100, specifically at the base soil layer, to ensure accurate results. Point A is located at coordinates x = 51.27 m and y = 2.53 m in the Plaxis model. Differences in the observation point location can lead to errors in the analysis, as each location will experience different amounts of settlement and consolidation. The observation for this study can be seen in Figure 8, 9, and 10.

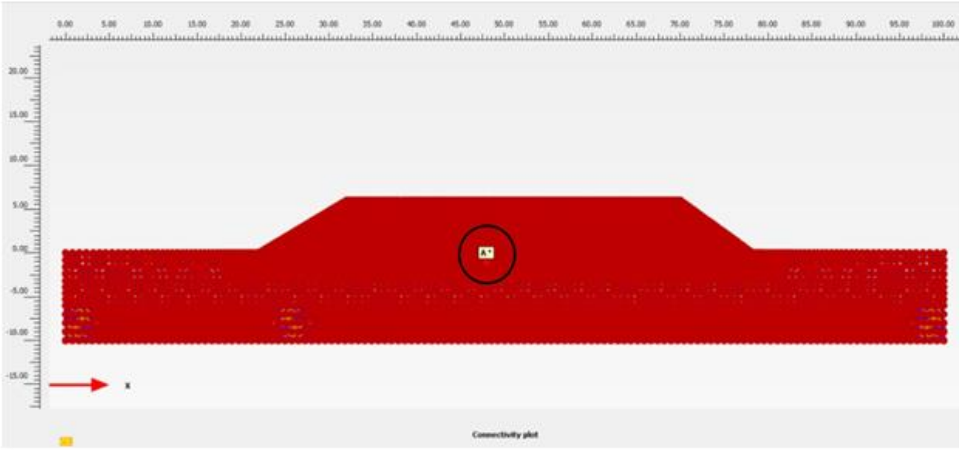

Figure 8. Analysis Review Point A

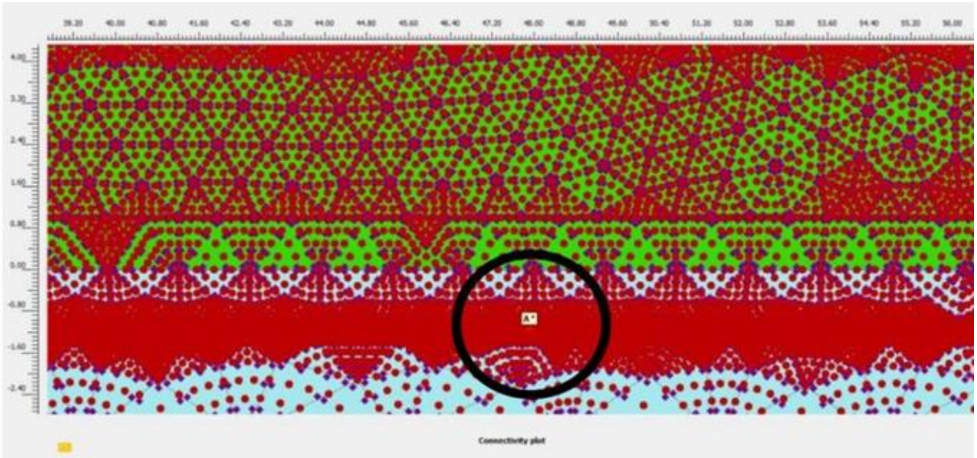

Figure 9. Analysis Review Point A

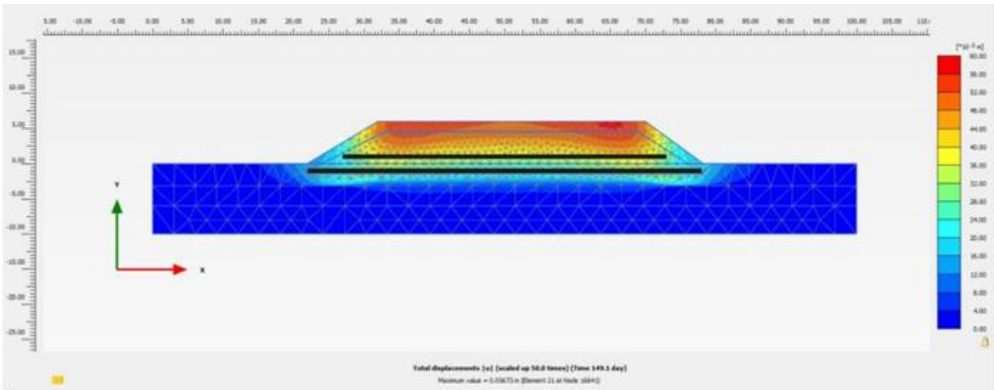

Figure 10. Total Displacement

After completing the calculation stage in Plaxis, the output results will show the vertical settlement occurring in the STA 47+100 area with the type of mesh used, as indicated in Table 6.

Table 6. The Generated Mesh Is Of The Very Fine Type

PLAXIS Mesh Types	Mesh		Settlement (m)
	Number Of Elements	Number Of Nodes	
Very Fine	2.137	17.291	0.056

According to the results in Table 6, the settlement obtained from the Very Fine mesh type is 0.056 m. in contrast, the measured settlement on-site at STA 47+100 is 0.416 m.

3.2 Discussion

The consolidation settlement duration obtained from the analysis using Plaxis 2D with a combination of the Replacement and preloading methods, utilizing a very fine mesh type, show a field consolidation time of 39 days. However, the Plaxis 2D model estimates a consolidation time of 149 days, resulting in a difference of the 110 days. This discrepancy is due to complete field data, leading to the use of N-SPT value correlation to supplement the analysis as show in Table 7.

Table 7. Comparison of Settlement Between Plaxis 2D and Settlement Plate Data at STA 47+100

	Settlement Plate STA 47+100	**Plaxis 2D Mesh Very Fine**
Settlement (Days)	39 Days	149 Days
Difference Between Predicted and Field Settlement at STA 47+100 (Days)		110 Days

There is a discrepancy between the field results and the predicted settlement at STA 47+100, where the settlement recorded by the settlement plate in the field was 0.416 m. A difference of 0.36 m was found when compared to the settlement predicted by Plaxis 2D, which was 0.056 m. This difference is due to the laboratory data not fully representing all soil layers in the field, necessitating the use of correlations when inputting parameters into Plaxis. The consolidation analysis using the combination of the Replacement and Preloading methods with Plaxis 2D modeling, utilizing a very fine mesh type, showed a field settlement of 0.416 m, while the Plaxis 2D prediction was only 0.056 m. The difference of -0.36 or -86.53% was caused by incomplete field data, leading to the use of N-SPT correlation to compensate. The percentage difference is presented in Table 8.

Table 8. Comparison of Plaxis 2D Settlement with Settlement Plate Data at STA 47+100

	Settlement Plate STA 47+100	**Plaxis 2D Mesh Very Fine**
Settlement (m)	0.416 m	0.056 m
Difference Between Predicted and Field Settlement at STA 47+100 (m)		-0.36 m
Percentage Difference in Settlement (m)		-86.53%

The discrepancy between the field results and the predicted settlement at STA 47+100 can be attributed to several factors, as described in the research findings:

a. Incomplete Representation of Soil Layers in Laboratory Data. The laboratory data used for the Plaxis 2D modeling did not fully capture the heterogeneity of the soil layers in the field. In practice, soil profiles can vary in terms of composition, structure, and other properties that may not be entirely reflected in laboratory samples. This limitation can lead to inaccuracies when these lab-based parameters are used in numerical simulations.
b. Use of Correlations to Compensate for Incomplete Data. Due to the lack of complete field data, the researchers had to rely on correlations, such as the N-SPT (Standard Penetration Test) correlation, to estimate certain soil parameters for the Plaxis model. These correlations, though useful, can introduce a degree of uncertainty as they are approximations based on empirical relationships that may not account for all site-specific conditions.

c. Modeling Assumptions and Mesh Resolution. The modeling was carried out using the Replacement and Preloading methods with a very fine mesh type in Plaxis 2D. While a fine mesh enhances the resolution of the model, it may also amplify discrepancies if the underlying soil data or parameters are inaccurate. Additionally, the modeling assumptions regarding soil d. behavior during consolidation may not fully represent real field conditions, such as the influence of varying moisture content, soil stress history, and other dynamic factors.
d. Field Conditions vs. Modeling Assumptions. Field settlements are influenced by complex factors, including soil heterogeneity, loading conditions, and other site-specific variables that might not be accurately captured in the model. The field data, obtained using a settlement plate, may reflect local variations and conditions not accounted for in the numerical simulation.

4. Conclusion

The conclusion of this discussion reveals a significant discrepancy between the consolidation time calculated using Plaxis 2D and the field observations. The Plaxis 2D model estimates a cosolidation time of 149 days, while field results indicate 39 days, resulting in difference of 110 days. Additionally, the difference in settlement of 0.36 meters or -86.53% between the field (0.416 meters) and the Plaxis 2D prediction (0.056 meters) suggets that laboratory data may not fully represent all soil layers, highlighting the need for correlating N-SPT values. This discrepancy emphasizes the necessity for more comprehensive field data to improve the accuracy of predictive models and ensure a more accurate representation of field conditions.

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