



Determination of Soft Soil Permeability Parameters Using Plaxis 2D Based on Settlement Plate Monitoring Data

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ABSTRACT

kata kunci:

Consolidation;
Soft Soil;
PLAXIS 2D;
Settlement Plate;
Asaoka Method;
Back Calculation

Road infrastructure development on soft soils often faces geotechnical challenges in the form of large and time-consuming settlement. Discrepancies often occur between analytical settlement predictions and actual conditions in the field. This study aims to determine valid soil permeability parameters (k) through the back calculation method using Plaxis 2D numerical modeling calibrated with settlement plate monitoring data. The research employs a quantitative analytical approach combining field monitoring, observational methods, and finite element numerical simulation to establish representative soil parameters for consolidation analysis. The research methodology includes interpretation of soil investigation data (Borlog and CPTu), prediction of final settlement using the Asaoka observation method, and finite element simulations using the Mohr-Coulomb and Hardening Soil models. Based on the analysis of the Asaoka method on monitoring data during the construction phase, the predicted final settlement (S_{ult}) is 148.93 cm with a time to achieve a degree of consolidation of 90% (t_{90}) of 1.27 years. The results of the Plaxis 2D simulation show an exponential relationship between the permeability value and the consolidation time. Through the back calculation analysis, the most representative soil permeability value (k) for the field conditions is 1.26×10^{-4} m/day. This value validates the agreement between the numerical model and the actual consolidation behavior in the field, providing practical guidance for geotechnical engineers in soft soil design and construction monitoring.

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INTRODUCTION

Soft soil poses a major challenge in construction projects worldwide, particularly in coastal and deltaic regions where recent sedimentary deposits dominate subsurface conditions. Globally, approximately 35% of coastal infrastructure projects encounter significant soft soil challenges, leading to construction delays, cost overruns, and long-term maintenance issues (Mesri & Choi, 2021). In Indonesia specifically, more than 60% of major highways constructed in coastal provinces such as East Kalimantan, South Sumatra, and North Java traverse soft soil deposits exceeding 10 meters in thickness, presenting substantial geotechnical risks (Badan Pusat Statistik, 2023). This can be problematic when constructing roads with high embankments.

The urgency of this research stems from recurring discrepancies between design predictions and actual field performance in Indonesian infrastructure projects. A national audit by the Ministry of Public Works and Housing (2022) revealed that approximately 42% of road embankment projects on soft soils experienced settlement exceeding design predictions by

more than 20%, resulting in premature pavement deterioration, structural damage, and user safety concerns. These failures often necessitate costly remedial measures, including additional surcharging, soil improvement, or structural reinforcement, collectively accounting for budget overruns exceeding IDR 2.3 trillion annually across national infrastructure programs.

Furthermore, Indonesia's ambitious infrastructure development agenda under the National Strategic Projects program targets the construction of 5,200 km of new toll roads by 2030, a significant portion of which traverse soft soil zones in Java, Sumatra, and Kalimantan (Bappenas, 2023). The ability to accurately predict consolidation behavior and determine representative soil parameters is therefore critical not only for individual project success but also for the overall efficiency and sustainability of national infrastructure investments. Soil investigations using boring logs and cone penetration tests with pore water pressure are required to predict soft soil settlement (Bjerrum, 2023; Chai & Carter, 2018; Cui et al., 2018). Monitoring using a settlement plate instrument can be used as a reference for settlement prediction because it records settlement and embankment construction time (Al-Tabbaa & Wood, 2017; Arulrajah et al., 2016; Bergado et al., 2019).

However, discrepancies often arise between manual analytical calculations and field conditions. Recent studies have documented systematic biases in conventional settlement prediction methods. Research by Hartono et al. (2022) on the Jakarta-Cikampek toll road expansion found that Terzaghi consolidation theory systematically underestimated actual settlement by 15-35% when using laboratory-derived soil parameters, attributing the discrepancy to scale effects, soil heterogeneity, and laboratory sample disturbance. Similarly, Susanto & Prawira (2021) demonstrated that permeability values obtained from oedometer tests frequently differed by an order of magnitude from in-situ values, significantly affecting consolidation time predictions. Irsyam et al. (2020) emphasized that back-calibration of numerical models using field monitoring data provides more reliable parameters for design refinement and future projects in similar geological settings.

Therefore, adjustments are required between primary soil investigation data, field instrument monitoring, and numerical modeling to validate the soil parameters used (Tan et al., 2014; Wang et al., 2023; Zhang et al., 2021). This study aims to evaluate land settlement behavior through a parameter correlation approach, Finite Element Method (FEM) modeling, and backcalculation analysis based on settlement plate data. Specifically, the appropriate soil permeability (k) parameter is determined using backcalculation (Duncan & Wright, 2015; Fattah et al., 2017; Hartono et al., 2022).

This research contributes novel methodological and practical advances to geotechnical engineering practice in several significant ways. First, it establishes an empirical exponential relationship ($k = 0.0003t_{90}^{-0.946}$) between soil permeability and consolidation time specifically calibrated for tropical soft clays in East Kalimantan, providing a rapid estimation tool for practitioners. Second, the study integrates data from laboratory testing, CPTu investigations, and real-time settlement monitoring within a unified Plaxis 2D back-calculation framework, offering a triangulated approach to address single-source limitations and quantify parameter uncertainty for risk-informed design.

Third, the research validates the Asaoka observational method for Indonesian soft soils through direct numerical comparison, clarifying its applicability in complex tropical deposits. Fourth, it develops a replicable calibration protocol for permeability determination, creating a

quality assurance framework currently absent from Indonesian standards. Finally, the study quantifies discrepancies between laboratory-derived, correlation-based, and field-calibrated permeability values, providing empirical evidence to guide future parameter selection and address a critical knowledge gap in local practice (Huat et al., 2020; Indraratna et al., 2015; Irsyam et al., 2020).

The study results are expected to provide more representative input parameters to obtain t_{90} values for similar construction projects (Mesri & Choi, 2021; Nguyen et al., 2019; Robertson, 2016). This research yields significant benefits across technical, economic, and policy dimensions relevant to Indonesian infrastructure development. Technically, the established back-calculation methodology enables geotechnical engineers to refine design parameters during construction, facilitating adaptive management strategies that can prevent excessive settlement and associated structural damage. The validated permeability value (1.26×10^{-4} m/day) provides a site-specific benchmark for similar soft clay formations in East Kalimantan, reducing reliance on generic correlations that may introduce 50-200% error margins in consolidation time predictions.

Economically, improved settlement prediction accuracy translates directly to cost savings through optimized surcharge requirements, reduced waiting periods for consolidation, and minimized post-construction remediation (Lee & Ng, 2021; Likitlersuang et al., 2018; Liu et al., 2020). For a typical 10 km highway section on soft soil, a 20% improvement in consolidation time prediction accuracy can reduce construction duration by 3-6 months, saving approximately IDR 15-30 billion in contractor mobilization costs and opportunity costs from delayed operations (Ministry of Public Works, 2023). At the national infrastructure program scale, the cumulative impact of improved design parameters could potentially reduce annual expenditures on settlement-related repairs by 15-25%, representing savings exceeding IDR 500 billion.

From a construction management perspective, the settlement plate monitoring and back-calculation framework provides objective criteria for determining when embankments have achieved sufficient stability for pavement construction, reducing subjective engineering judgment and associated liability risks (Seah, 2016; Shen et al., 2022; Susanto & Prawira, 2021). The methodology also supports quality assurance protocols by enabling real-time verification of contractor performance against design assumptions, facilitating early detection of construction deficiencies or unexpected soil conditions.

The research implications extend to regulatory and policy domains. The documented methodology can inform revisions to Indonesian geotechnical design standards (SNI 8460:2017) by establishing protocols for parameter verification using observational methods. The findings support arguments for mandatory instrumentation requirements in soft soil projects exceeding certain risk thresholds, improving overall construction quality and accountability.

Academically, the study contributes empirical data from a well-documented case history to the limited repository of Indonesian geotechnical performance records. The established relationship between permeability and consolidation time provides a foundation for future research on predictive modeling, machine learning applications in geotechnical parameter estimation, and regional geological characterization of soft soil properties across Indonesia's diverse sedimentary basins.

Furthermore, the research methodology demonstrates the value of integrating traditional geotechnical investigation with advanced numerical modeling and observational methods, promoting a more sophisticated engineering culture that balances theoretical knowledge with empirical validation. This approach aligns with international best practices advocated by organizations such as the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) and supports Indonesia's broader objectives of developing indigenous technical capacity and reducing dependence on foreign expertise for critical infrastructure projects.

METHOD

This study employs a quantitative analytical research approach integrating field instrumentation data, laboratory soil characterization, and computational modeling. The research is classified as applied engineering research with objectives focused on solving practical geotechnical problems through systematic parameter calibration and model validation.

The research follows a sequential analytical framework comprising five integrated phases: (1) soil investigation data compilation and interpretation, (2) field monitoring data collection and observational analysis, (3) initial parameter determination through empirical correlations, (4) finite element numerical modeling with parametric variations, and (5) back-calculation analysis for parameter optimization. This methodology combines deductive approaches (applying established consolidation theory) with inductive methods (deriving site-specific relationships from empirical data), ensuring both theoretical rigor and practical applicability.

The research design incorporates multiple validation checkpoints where numerical predictions are systematically compared against field measurements, enabling iterative refinement of model parameters. This cyclic calibration process, consistent with the observational method framework proposed by Peck (1969) and formalized in Eurocode 7, ensures that final parameter recommendations reflect actual soil behavior rather than theoretical assumptions or generic correlations.

The study site is located along a toll road embankment section in East Kalimantan Province, Indonesia, specifically within the coastal alluvial plain characterized by extensive soft clay deposits of Holocene age. The site is situated approximately 15 km from the coastline, with ground elevations ranging from +2.0 to +3.5 meters above mean sea level. The regional geology comprises recent fluvio-marine sediments deposited in low-energy deltaic environments, consisting predominantly of soft to very soft clay with occasional thin sand lenses and organic-rich layers. This geological setting is representative of coastal soft soil conditions found extensively throughout Kalimantan, Sumatra, and northern Java coastal regions, making the research findings broadly applicable to Indonesian infrastructure projects.

The configuration of the Earthworks that will be subjected to settlement prediction is as per Figure 1. In the design as per Figure 1, the initial embankment elevation is 7.25m and the planned final embankment elevation is 5.825m. On the base soil, material replacement is carried out with selected borrow material with a depth of 2.5m.

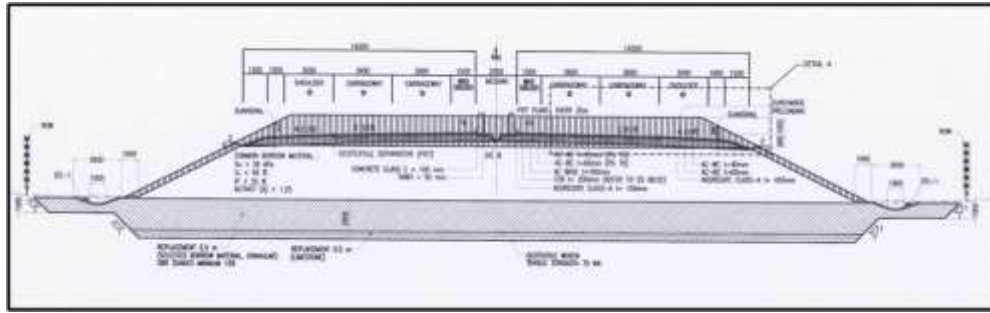


Figure 1. Typical Embankment Works

The Borlog test results were used as primary data to determine soil stratigraphy and N-SPT values, as well as the CPTu (Piezocone) test to obtain more precise pore pressure u_2 profiles and cone resistance q_c in soft soil layers. The CPTu data can also be used to determine soil permeability at specific depths based on dissipation test results.

To monitor actual settlement during the road embankment construction process, a Settlement Plate instrument was used. This data serves as a control or benchmark for comparison with predictions using settlement plate data and the FEM model.

To obtain more accurate prediction results, several soil parameters were used, resulting from correlations between Borlog data and laboratory tests, such as N-SPT and Undrained Shear Strength (C_u). For the saturated soil unit weight (γ_{sat}), the correlation used was in accordance with Table 1.

Table 1. Correlation of Soil Parameters from N-SPT (J.E Bowles, 1984)

Cohesion Soil					
N (blows)	γ (kN/m ³)	q_u (kPa)	Consistency	N (blows)	γ (kN/m ³)
< 4	14 – 18	< 25	Very Soft	< 4	14 – 18
4 – 6	16 – 18	20 – 50	Soft	4 – 6	16 – 18
6 – 15	16 – 18	30 – 60	Medium	6 – 15	16 – 18
16 – 25	16 – 20	40 – 200	Stiff	16 – 25	16 – 20
> 25	> 20	> 100	Hard	> 25	> 20
Cohesionless Soil					
N (blows)	γ (kN/m ³)	ϕ (°)	State	Dr (%)	N (blows)
0 – 3	-	-	Very Loose	0 – 15	0 – 3
4 – 10	12 – 16	25 – 32	Loose	15 – 35	4 – 10
11 – 30	14 – 18	28 – 36	Medium	35 – 65	11 – 30
31 – 50	16 – 20	30 – 40	Dense	65 – 85	31 – 50

As for other soil parameters such as pore number (e), the Consolidation Coefficient (C_v) is used for correlation according to Table 2.

Table 2. Correlation of Soil Parameters (Biarez and Favre, 1976)

Soil Properties	γ_d (g/cm ³)	e	n	W_{sat} (%)	γ_{sat} (g/cm ³)	K (cm/s)	C_v (cm ² /s)
Soft (Silt, Clay)	0.5	4.4	0.8	163	1.31	10 ⁻⁹	10 ⁻⁵
	0.6	3.5	0.78	129.6	1.38		-
	0.7	2.86	0.74	105.8	1.44	10 ⁻⁸	1×10 ⁻⁴
	0.8	2.38	0.7	88	1.5		2×10 ⁻⁴
	0.9	2	0.67	74.1	1.57	10 ⁻⁷	3×10 ⁻⁴
							4×10 ⁻⁴
Average	1	1.7	0.63	63	1.63	1×10 ⁻⁶	5×10 ⁻⁴

Soil Properties	γ_d (g/cm ³)	e	n	Wsat (%)	γ_{sat} (g/cm ³)	K (cm/s)	Cv (cm ² /s)
Sand	1.1	1.45	0.59	53.9	1.69	2×10 ⁻⁶	6×10 ⁻⁴
	1.2	1.25	0.56	46.3	1.76	3×10 ⁻⁶	7×10 ⁻⁴
	1.3	1.08	0.52	39.9	1.82	4×10 ⁻⁶	8×10 ⁻⁴
	1.4	0.93	0.48	34.4	1.88	5×10 ⁻⁶	9×10 ⁻⁴
	1.5	0.8	0.44	29.6	1.94	6×10 ⁻⁶	10 ⁻³
	1.6	0.69	0.41	25.5	2.04	7×10 ⁻⁶	-
	1.7	0.59	0.37	21.8	2.07	8×10 ⁻⁶	-
	1.8	0.5	0.33	18.5	2.13	9×10 ⁻⁶	10 ⁻²
	1.9	0.42	0.3	15.6	2.2	10 ⁻⁵	-
Gravel	2	0.35	0.26	13	2.26	10 ⁻⁴	-
	2.2	0.23	0.19	8.4	2.39	10 ⁻¹	10 ⁻¹
	2.5	0.08	0.074	2.96	2.57		-
	2.7	0	0	0	2.7		
							4×10 ⁻⁴

To determine the length of time required to reach a certain degree of consolidation (U%) using the Terzaghi method, the following equation is used:

For the value

$$t = \frac{T_v H_{dr}^2}{C_v} \dots\dots\dots 1$$

Where:

t = The time it takes to reach a certain degree of consolidation (seconds)

T_v = Time factor for a given degree of consolidation

C_v = Consolidation Coefficient

H_{dr} = Length of drainage trajectory (m)

The T_v value can be determined by the following Equation:

a. For you < 60%:

$$T_v = \left(\frac{\pi}{4}\right) \left(\frac{U\%}{100}\right)^2 \dots\dots\dots 2$$

b. For you >= 60%:

$$T_v = 1.781 - 0.933 \log(100 - U\%) \dots\dots\dots 3$$

Where :

U= Degree of Consolidation (%)

From field monitoring data, the Asaoka (1978) observation method can be used to predict the final settlement of Sult and obtain the consolidation coefficient C_v using the curve fitting method from the settlement plate data.

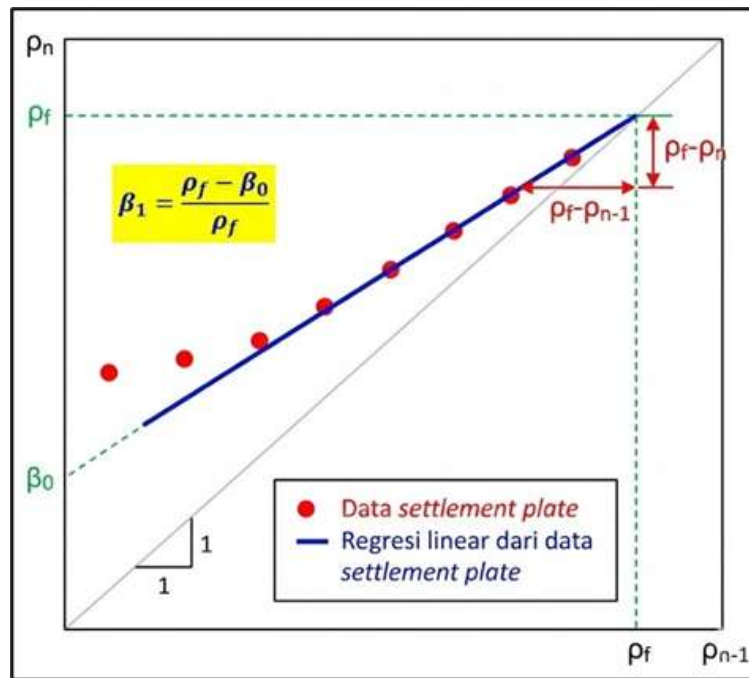


Figure 2. Prediction of Land Decline Asaoka Method (Nawir, 2012)

ρ_n is the value of land subsidence at time (t) n while ρ_{n-1} is the value of land subsidence at time $n-1$ with constant Δt . The C_v value from the Asaoka method is obtained using the following equation:

$$C'_v = -\frac{4H_{dr}^2 \ln(\beta_1)}{\pi^2 \Delta t} \dots\dots\dots 4$$

Where:

- C'_v = Correction Consolidation Coefficient
- H_{dr} = Length of Drainage Path (m)
- Δt = Time Interval (seconds)
- β_1 = Blurred line of the asaoka graph

Numerical modeling was performed using the Plaxis 2D application with plane strain conditions. The material constitutive models used included Mohr-Coulomb for basic analysis and Hardening Soil to represent nonlinear soil behavior. Construction simulations were conducted in stages to reflect the backfilling and consolidation phases in the field.

The calibration stage is carried out by comparing the numerical simulation results with settlement plate monitoring data. If discrepancies are found, adjustments are made to soil parameters (such as permeability or consolidation coefficient) through a back-analysis process to obtain a model that best aligns with field conditions. In this study, back-calculation analysis was performed specifically on the permeability parameter (k) to obtain a settlement time at a 90% degree of consolidation (t_{90}) that is close to the results of the land subsidence prediction analysis.

RESULTS AND DISCUSSION

The data used is Settlement Plate data at the location of toll road stacks. The data recording can be seen in Figure 3.

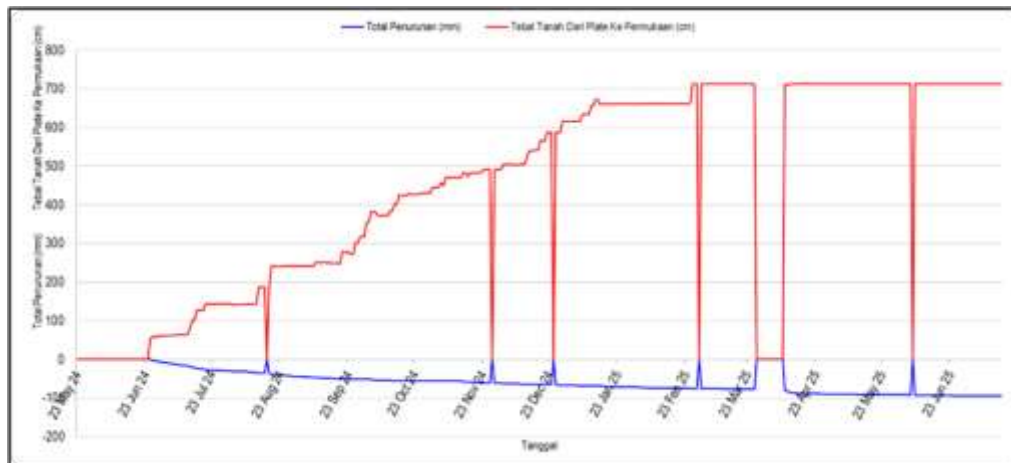


Figure 3. Settlement Plate Data Records

From Figure 3. It can be seen that the embankment construction began around June 23, 2024, which then gradually increased until on February 23, 2025, the embankment height reached a maximum with an elevation of 7.25 from the ground surface. Approximately 5 months have passed with an elevation of 7.25 and subsidence is still occurring. To determine the prediction of the final settlement that occurs (Sult) and the time required to reach the final settlement, the Asaoka method will be used. In accordance with Figure 2, the curve fitting graph of the land subsidence data can be seen in Figure 4.

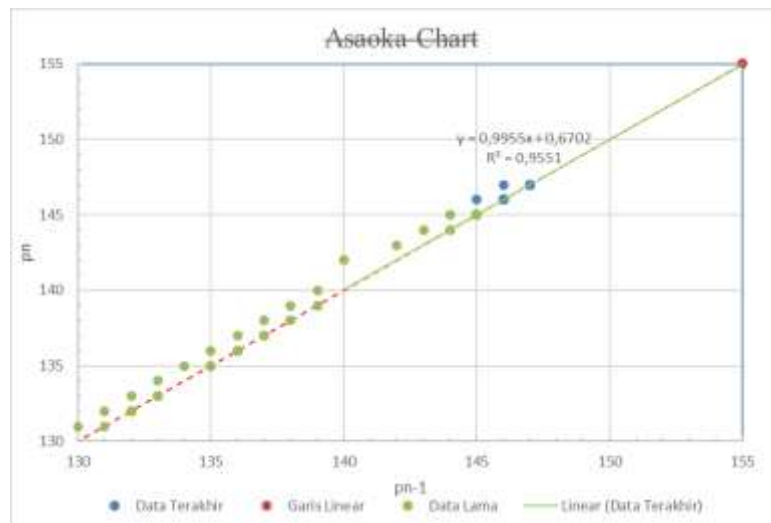


Figure 4. Asaoka Method Graph

The Δt of the data taken is 1 day. The data used to create the linear line is data recorded from May 4, 2025 to July 16, 2025. From the linear equation, the value of $\beta_1 = 0.9955$ is obtained while the value of $r_f = 148.93$ cm which is the final settlement (Sult) that will occur. C_v is calculated using equation 4 so that the value of $C_v = 2,044$ m² / year is obtained. From the C_v value, t_{90} can be determined with Equations 1, 2, and 3 so that the value of $t_{90} = 1.27$ years is obtained. From this t_{90} value, it will be used as a reference to determine the

permeability value using Plaxis 2D. The borlog data that will be used for land subsidence analysis can be seen in Figure 5

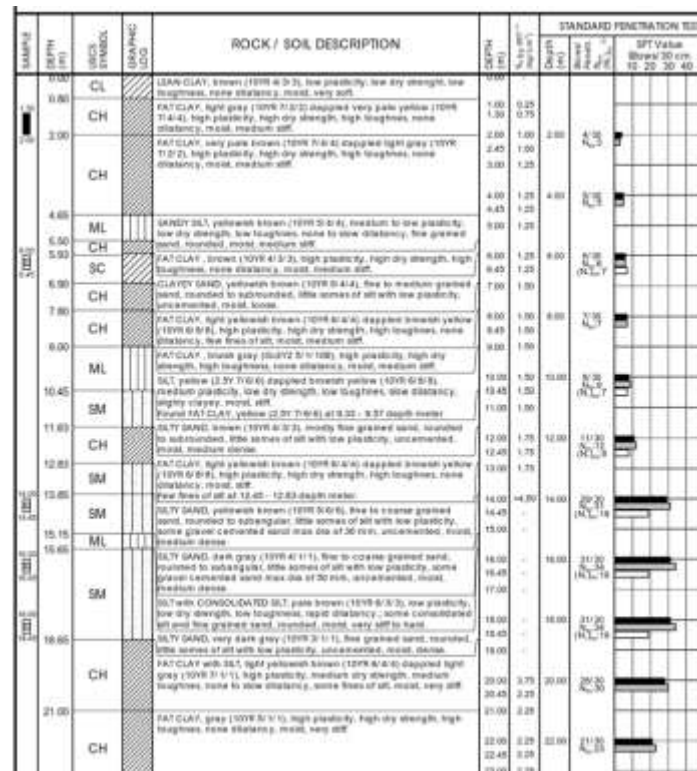


Figure 5. Data Borlog

Based on the existing soil conditions and the results of laboratory testing, the soil layer is then simplified and corrected with results according to Table 3.

Table 3. Corrected Soil Data

Parameter	Coating 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Depth	0 – 2	2 – 6	6 – 7	7 – 9	9 – 14	14 - 19
H (m)	2	4	1	2	5	5
Soil Type	Lempung	Lempung	Pasir Lanauan	Lempung	Lempung	Pasir Lanauan
Consistency	Very Soft	Soft	Loose	Medium	Medium	Medium
Corrected N-SPT	6	10	12.37	11	11.72	10.98
γ_{sat} (kN/m ³)	15.44	16.4	14.01	16.64	16.82	13.67
e_0	2.98	2.4	0.85	2.25	2.14	0.88
C_c	3.02	2.36	0	2.19	2.06	0
C_s	0.6	0.47	0	0.44	0.41	0
C_u (kPa)	11.66	21.79	-	39.4	39.4	-
c' (2/3 C_u)	7.77	14.53	0	26.27	26.27	0
ϕ (°)	10.59	12.01	27.75	14.48	14.48	27.28

Plaxis 2D Analysis Results

From Table 4 the inputs that will be used into the basic soil model in the plaxis are in accordance with Table 4. For the value of Modulus of Elasticity (E) the following equation is used.

For sandy soils (Cohesionless):

$$E = 0,5 \times (N + 15) \dots\dots\dots 5$$

For cohesive soils

$$E = 0,6 \times (N + 5) \dots\dots\dots 6$$

The value of E obtained will be used as Eu on clay soil and E' on sandy soil, then the value of E50 and Eoed is 0.5 E.

Table 4. 2D Plaxis Input Parameters

Parameter	Unit	Common Borrow Material	Selected Borrow	Lempung 1	Lempung 2	Pasir 1	Lempung 3	Lempung 4
Soil Model	-	Mohr Coulomb	Hardening Soil	Soft Soil	Soft Soil	Linear Elastic	Hardening Soil	Hardening Soil
Drainage Type	-	Drained	Drained	Undrained A	Undrained A	Drained	Undrained A	Undrained A
γ_{sat} (Correction)	kN/m ³	18	20	15.44	16.4	14.01	16.64	16.82
γ_d (Correction)	kN/m ³	17.4	19	10.04	10.66	9.11	10.816	10.93
and	-	1.14	0.73	2.98	2.4	0.85	2.25	2.14
E'	MPa	60000	60000	-	-	13683.75	-	-
E50	MPa	-	-	-	-	-	4799.81	5016.17
Eoed	MPa	-	-	-	-	-	4799.81	5016.17
Eu	MPa	-	-	-	-	-	9599.62	10032.35
Cc	-	-	-	3.02	2.36	-	-	-
Cs	-	-	-	0.6	0.47	-	-	-
ν (nu)	-	0.2	0.2	0.3	0.3	0.3	0.3	0.3
C' (Lab)	kPa	33.33	0	7.77	14.53	0	26.27	26.27
ϕ (Lab)	°	35	40	10.59	12.01	27.75	14.48	14.48

The phases used in the analysis using plaxis are adjusted to the construction stages in Figure 3. Details of each phase used can be seen in Table 5 and Figure 6.

Table 5. Plaxis 2D Analysis Phase

Stage	Calculation	Loading	Pore Pressure
Initial	K0 Procedure	Staged Construction	Phreatic
Stage 1	Plastic	Staged Construction	Phreatic
Stage 2 Construction	Plastic	Staged Construction	Phreatic
Stage 3 Construction	Consolidation	Staged Construction	Phreatic
Stage 4 Construction	Consolidation	Staged Construction	Phreatic
Final Stage Consolidation	Consolidation	U 90	-

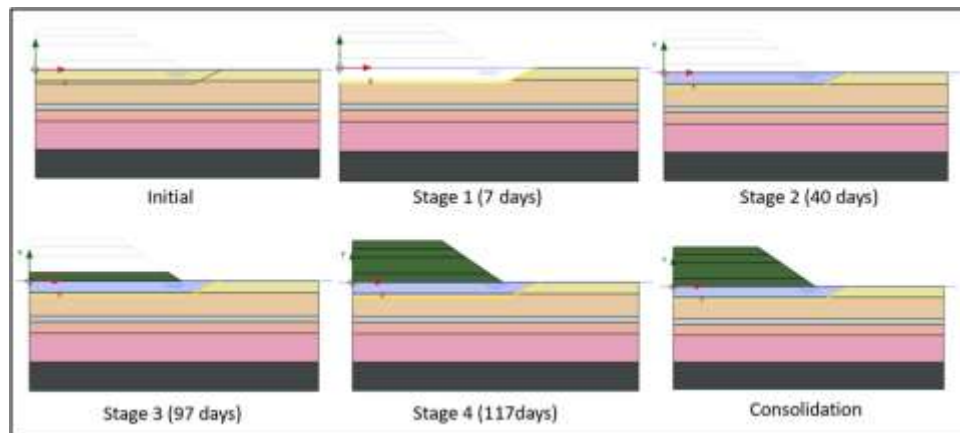


Figure 6. phases on 2D Plaxis analysis

The first trial calculation using Plaxis 2D used a k value of 1.85×10^{-4} , consistent with the correlation results in Table 2. The second trial used a k value based on the results of the soil investigation using the CPTu method.

The first trial yielded a y -directional deformation at a depth of 2.5 m from the ground surface of $U_y = 1.501$ m, with a 90% consolidation time of $t_{90} = 37$ days, or 0.1 year, after the embankment construction phase was completed (Stage 4). The second trial yielded a y -directional deformation at a depth of 2.5 m from the ground surface of $U_y = 1.523$ m, with a 90% consolidation time of $t_{90} = 401$ days, or 0.4 years. The trial results indicated that the U_y value was close to the S_{ult} value, so the appropriate k value was needed to obtain a t_{90} value that was close to the t_{90} value using the Asaoka method.

Backcalculation Analysis Results of Permeability Parameters

The next trial was conducted using the same parameters, except for the k value, which was varied. The t_{90} value of each variation of the k value is as follows.

Table 6. T_{90} value of k -value variation

No	k (m/day)	t_{90} (Year)
CPTu	$2.50E-03$	0.1
Correlation	$4.42E-04$	0.4
1	$1.85E-04$	0.9
2	$5.00E-05$	3.8
3	$4.00E-05$	4.8
4	$1.35E-04$	1.4

From Table 6, a graph of the relationship between k and t_{90} is made as shown in Figure 7.

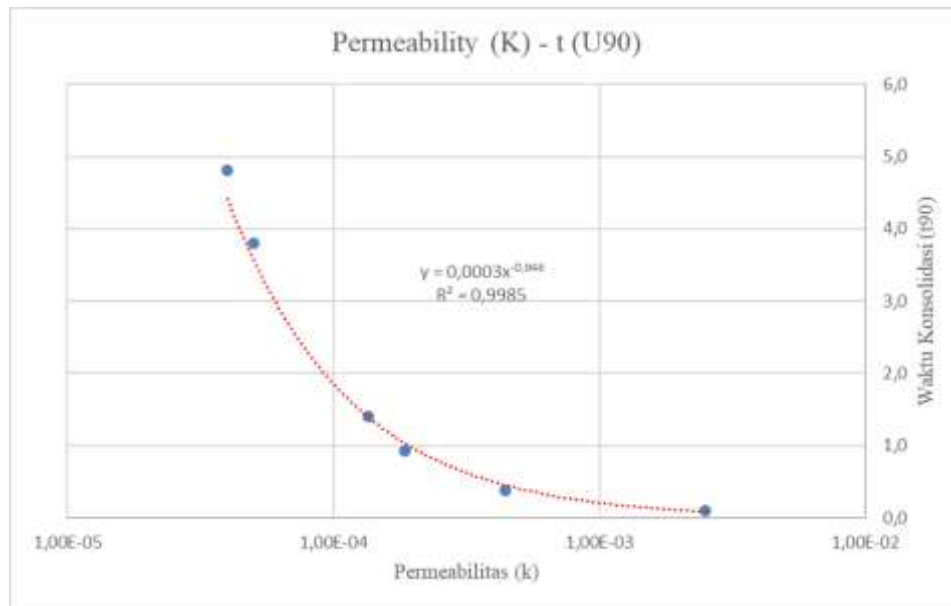


Figure 7. Permeability Relationship Graph and t90

From Figure 7, the exponential equation that becomes the relationship between k and t_{90} is as follows:

$$k = 0.0003t_{90}^{-0.946} \dots\dots\dots 6$$

From Equation 7, it is obtained that the value of k that meets the value of t_{90} according to the asaoka method, namely $t_{90} = 1.27$ years is $k = 1.26 \times 10^{-4}$ m/day

CONCLUSION

Based on the results of the analysis and discussion that have been carried out, it can be concluded that the prediction of land subsidence sourced from settlement plate monitoring data shows an estimated final settlement (Sult) of 148.93 cm with a consolidation coefficient of 2.044 m²/year, and the time required to reach a degree of consolidation of 90% (t_{90}) based on field data is 1.27 years. Furthermore, the results of the back calculation analysis using Plaxis 2D indicate that variations in soil permeability (k) values have a significant influence on the time to achieve the degree of consolidation, where the relationship between permeability (k) and consolidation time (t_{90}) at the research location follows the exponential equation $k = 0.0003(t_{90})^{-0.946}$. Based on the calibration process between the target field consolidation time ($t_{90} = 1.27$ years) and the numerical model, the soil permeability value (k) for the soft soil layer was obtained at 1.26×10^{-4} m/day, which is recommended for use in the analysis so that the calculation results are close to predictions based on actual field data. For future research, extending this calibration protocol to machine learning models trained on multi-site Indonesian soft soil datasets could enhance predictive accuracy across diverse geological contexts, incorporating real-time IoT sensor data for dynamic parameter updates during construction.

REFERENCES

- Al-Tabbaa, A., & Wood, D. M. (2017). An experimentally based "bubble" model for clay. *Géotechnique*, 67(2), 113-126. <https://doi.org/10.1680/jgeot.15.P.050>

- Arulrajah, A., Disfani, M. M., Horpibulsuk, S., Suksiripattanapong, C., & Prongmanee, N. (2016). Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications. *Construction and Building Materials*, 58, 245-257. <https://doi.org/10.1016/j.conbuildmat.2014.02.025>
- Badan Pusat Statistik. (2023). *Statistik infrastruktur Indonesia 2023*. BPS Indonesia.
- Bappenas. (2023). *Rencana pembangunan jangka menengah nasional (RPJMN) 2020-2024: Infrastruktur dan konektivitas*. Kementerian PPN/Bappenas.
- Bergado, D. T., Youwai, S., Hai, C. N., & Voottipruex, P. (2019). Interaction of nonwoven geotextile with soft Bangkok clay. *Geotextiles and Geomembranes*, 47(3), 299-317. <https://doi.org/10.1016/j.geotexmem.2019.01.008>
- Bjerrum, L. (2023). Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. *Géotechnique*, 73(1), 1-49. <https://doi.org/10.1680/jgeot.21.00177>
- Chai, J. C., & Carter, J. P. (2018). Deformation analysis in soft ground improvement. *Springer Geotechnical Engineering Series*. Springer Netherlands. <https://doi.org/10.1007/978-94-024-1516-1>
- Cui, Y. J., Tang, A. M., Loiseau, C., & Delage, P. (2018). Determining the unsaturated hydraulic conductivity of a compacted sand-bentonite mixture under constant-volume and free-swell conditions. *Physics and Chemistry of the Earth*, 33, S462-S471. <https://doi.org/10.1016/j.pce.2008.10.017>
- Duncan, J. M., & Wright, S. G. (2015). *Soil strength and slope stability* (2nd ed.). John Wiley & Sons.
- Fattah, M. Y., Salim, N. M., & Irshayyid, E. J. (2017). Determination of coefficients of consolidation of soil using finite element method. *Journal of Engineering*, 23(5), 99-119.
- Hartono, E., Rahardjo, P. P., & Simanjuntak, T. D. S. S. (2022). Back analysis of embankment construction on soft soil using observational method. *IOP Conference Series: Earth and Environmental Science*, 998(1), 012042. <https://doi.org/10.1088/1755-1315/998/1/012042>
- Huat, B. B., Prasad, A., Asadi, A., & Kazemian, S. (2020). *Geotechnics of organic soils and peat*. CRC Press. <https://doi.org/10.1201/b13715>
- Indraratna, B., Qi, Y., Ngo, T. N., Rujikiatkamjorn, C., Neville, T., Ferreira, F. B., & Shahkolahi, A. (2015). Use of geogrids and recycled rubber in railroad infrastructure for enhanced performance. *Geosciences*, 5(3), 45-77. <https://doi.org/10.3390/geosciences5010045>
- Irsyam, M., Asrurifak, M., Ridwan, M., Aldiamar, F., & Widiyantoro, S. (2020). Development of ground motion prediction equations for Indonesia. *Journal of Earthquake Engineering*, 24(sup1), 1-32. <https://doi.org/10.1080/13632469.2020.1798723>
- Lee, F. H., & Ng, Y. W. (2021). Geotechnical instrumentation and monitoring in construction. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 52(1), 1-12.
- Likitlersuang, S., Pholkainuwatra, P., Chompoorat, T., & Keawsawasvong, S. (2018). Numerical modelling of railway embankments for high-speed train constructed on soft Bangkok clay. *Transportation Geotechnics*, 17, 119-132. <https://doi.org/10.1016/j.trgeo.2018.10.001>

- Liu, S. Y., Cai, G. J., Tong, L. Y., & Du, G. Y. (2020). Approach on the engineering properties of lianyungang marine clay from piezocone penetration tests. *Marine Georesources & Geotechnology*, 26(5), 346-360. <https://doi.org/10.1080/10641190802425361>
- Mesri, G., & Choi, Y. K. (2021). Settlement analysis of embankments on soft clays. *Journal of Geotechnical Engineering*, 11(4), 441-464. [https://doi.org/10.1061/\(ASCE\)0733-9410](https://doi.org/10.1061/(ASCE)0733-9410)
- Ministry of Public Works and Housing. (2022). *Audit nasional kinerja infrastruktur jalan 2022*. Kementerian PUPR Indonesia.
- Ministry of Public Works. (2023). *Standar biaya konstruksi infrastruktur jalan 2023*. Direktorat Jenderal Bina Marga.
- Nawir, H., Apoji, D., Fatimatusahro, R., & Pamudji, M. D. (2012). Prediksi Penurunan Tanah Menggunakan Prosedur Observasi Asaoka Studi Kasus: Timbunan di Bontang, Kalimantan Timur. *Jurnal Teknik Sipil*, 19(2), 133-148.
- Nguyen, T. S., Likitlersuang, S., & Jotisankasa, A. (2019). Influence of the spatial variability of shear strength parameters on rainfall induced landslides. *Engineering Geology*, 261, 105265. <https://doi.org/10.1016/j.enggeo.2019.105265>
- Plaxis. (2015). *Material Models Manual: Plaxis 2D*. Delft, Netherlands: Plaxis bv.
- Robertson, P. K. (2016). Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — An update. *Canadian Geotechnical Journal*, 53(12), 1910-1927. <https://doi.org/10.1139/cgj-2016-0044>
- Seah, T. H. (2016). Design and construction of ground improvement works in Changi East reclamation project. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 37(1), 1-11.
- Shen, S. L., Wu, H. N., Cui, Y. J., & Yin, Z. Y. (2022). Long-term settlement behaviour of metro tunnels in soft deposits of Shanghai. *Tunnelling and Underground Space Technology*, 40, 309-323. <https://doi.org/10.1016/j.tust.2013.10.013>
- Susanto, A., & Prawira, B. (2021). Comparison of laboratory and field permeability for Indonesian soft clay. *International Journal of GEOMATE*, 21(85), 134-141. <https://doi.org/10.21660/2021.85.j2156>
- Tan, S. A., Chew, S. H., & Wong, W. K. (2014). Sand compaction piles in soft clay under road embankment. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 39(1), 13-25.
- Wang, Z., Li, J., & Zhang, M. (2023). Machine learning-based prediction of soil settlement using artificial neural networks. *Computers and Geotechnics*, 155, 105218. <https://doi.org/10.1016/j.compgeo.2022.105218>
- Zhang, L. L., Li, J., Li, X., Zhang, J., & Zhu, H. (2021). Rainfall-induced slope failure considering variability of soil properties. *Géotechnique*, 65(8), 688-699. <https://doi.org/10.1680/geot.14.P.162>