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(Research Article)

Analysis and Handling of STA 1+325 SD 1+475 Embankments in the Construction of the IKN Toll Road, Balang Island Bridge Segment – Sp. Riko

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Abstract: The construction of the IKN Toll Road on the Balang Island Bridge – Sp. Riko segment serves as a strategic infrastructure project aimed at enhancing connectivity and accelerating regional development in the Indonesian Capital City area. However, within the STA 1+325 to STA 1+475 section, complex geotechnical challenges were identified due to the subgrade's low bearing capacity and high consolidation potential. These conditions threaten the embankment's stability, which could affect construction quality and long-term performance. This study analyzes the subgrade characteristics, evaluates embankment stability, and proposes effective improvement methods based on geotechnical design standards. Field investigations, including *sondir* testing, soil laboratory analyses, and numerical simulations using PLAXIS finite element software, were conducted. The analysis involved assessing bearing capacity, consolidation settlement, and slope stability under both normal and seismic conditions. The selected improvement method—subgrade replacement with a 2.0-meter-thick material—successfully increased the safety factor to 1.715 under service conditions and 1.258 under earthquake conditions, while reducing potential settlement to acceptable limits. These results demonstrate that the replacement method effectively enhances embankment stability and ground performance. Hence, this technique is recommended as a reliable geotechnical solution for toll road and other infrastructure projects facing similar subgrade challenges.

Keywords: Embankment stability; Geotechnical analysis; PLAXIS modeling; Replacement; Soil bearing capacity.

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1. Introduction

Toll road infrastructure development is a top priority in supporting connectivity and national economic growth. One of the ongoing strategic projects is the construction of the Indonesian Capital City (IKN) Toll Road, the Pulau Balang Bridge – Sp. Riko segment. This segment plays a crucial role in connecting strategic areas in East Kalimantan, ensuring efficient accessibility between the IKN area and its surrounding areas. However, road infrastructure development in this region faces significant geotechnical challenges, particularly related to the subgrade conditions at STA 1+325 to 1+475. Based on the results of soil investigations, it was found that the subgrade at the location has a low bearing capacity and a high degree of consolidation, which can pose a risk to the stability of the road embankment. Therefore, this study aims to evaluate the soil characteristics, analyze the embankment stability, and determine the optimal handling method to ensure the safety and sustainability of the road infrastructure.

Studies on the stability of embankments on soft soils have been extensively conducted in recent decades. Research byBergado & Miura (2022)on soft ground improvement in a Singapore highway project showed that the preloading and vertical drain method was able to reduce consolidation time by up to 50%.[1]. Meanwhile, a study byLesov et al. (2021)highlights the effectiveness of soil improvement using geosynthetic techniques in increasing embankment stability.[2]. Other research bySujatmiko (2023)In Indonesia, the effectiveness of the replacement method with granular material was also studied in increasing the bearing capacity of the base soil.[3]However, there are not many studies that specifically examine soil improvement in East Kalimantan with its unique geotechnical conditions, so further research is needed to adapt treatment methods to local conditions.

This study presents a novel approach and implementation of embankment management methods in the geotechnical environment typical of East Kalimantan. Unlike previous studies that focused on preloading or vertical drain methods, this study emphasizes the use of a 2.0 m thick replacement embankment as the optimal solution based on local soil conditions. In addition, the numerical modeling approach using PLAXIS 2D to evaluate slope stability under service and seismic conditions also provides a new contribution to geotechnical analysis in Indonesia. This study also considers the availability of granular materials and the limited project implementation time, which are rarely focused on in previous studies. The construction of the IKN Toll Road, Pulau Balang Bridge – Sp. Riko segment, faces significant challenges in embankment stability due to unfavorable subgrade conditions. Based on geotechnical studies and supporting theories, an appropriate embankment management method is needed to ensure long-term embankment durability without excessive deformation. This study offers an innovative approach using the replacement method as a more effective and practical solution compared to other conventional techniques. By considering the results of the analysis and numerical modeling, this study is expected to provide applicable recommendations in the planning and construction of road infrastructure in areas with similar soil characteristics.

2. Literature Review

The theory underlying this research encompasses several key geotechnical concepts, namely soil bearing capacity, slope stability, consolidation settlement, and replacement methods for soil improvement. Soil bearing capacity theory is the primary basis for determining the stability of a structure built on the ground.Cascone et al. (2021)developed a theory that considers the shape, depth, and slope factors of the load in determining the bearing capacity of the soil[4]. According toEl Hariri et al. (2023), the ultimate bearing capacity of a soil can be calculated by taking into account the soil shear strength parameters, effective pressure, and external loads acting on it.[5]. In the context of this study, the soil bearing capacity theory is used to evaluate whether the subgrade at STA 1+325 to 1+475 is capable of supporting the embankment load to be applied or requires additional engineering intervention.

Slope stability theory plays a role in determining the potential for slope failure due to changes in geometry and additional loads from embankments.Mamat et al. (2021)explains that slope stability can be analyzed using the limit equilibrium method which takes into account parameters such as the internal friction angle, soil cohesion, and pore water pressure.[6]. The Mohr-Coulomb model is often used in this analysis to evaluate the stability conditions of a slope by taking into account the combination of shear and normal forces acting on the potential failure plane.[7], [8]In this study, PLAXIS 2D software was used to simulate various slope stability scenarios both in service conditions and during earthquakes, so that a complete picture of the safety of the embankment to be constructed can be obtained.

The theory of land consolidation, as developed byHu & Liu (2021), explains how soft soil undergoes compaction due to external loads applied over a period of time.[9]This process involves the release of pore water from the soil, causing significant subsidence. Consolidation parameters such as the compressibility index (Cc) and pre-consolidation pressure (Pc) are key in determining how much and how quickly the soil will subside.[10], [11], [12]In this study, consolidation theory is used to estimate the magnitude of land subsidence after embankment is applied, so that it can be assessed whether repair methods are needed to reduce the negative impact on the stability of the road structure.

The replacement method for soil improvement is an effective technique for increasing the bearing capacity of soft soil by replacing layers of soil with more stable granular material. This technique has been widely used in infrastructure projects to reduce deformation due to consolidation settlement and increase the soil's bearing capacity.Kang et al. (2022) and Liu et al. (2024)shows that this method can significantly reduce the risk of deformation on roads built on soft ground.[13], [14]In this study, the replacement method with a thickness of 2.0 m was applied as the main solution to ensure that the bearing capacity of the subgrade meets the established safety standards.

3. Method

This study uses a quantitative approach with geotechnical analysis methods to evaluate the stability and bearing capacity of embankments at STA 1+325 to 1+475 in the construction of the IKN Toll Road, Pulau Balang Bridge Segment – Sp. Riko. Data were obtained through literature studies of technical documents that include sondir data, soil characteristics, and geotechnical parameters used in embankment design. The data collection method involves interpreting soil test results, including analysis of shear strength, internal friction angle, soil unit weight, modulus of elasticity, and Poisson's ratio, which are correlated with geotechnical design standards such as SNI 8460:2017 and SNI 1726:2019. Data analysis was carried out by modeling using Plaxis 2D software to evaluate slope stability and embankment safety factors, both in conditions without treatment and with repair methods such as subgrade replacement. The analysis results were then compared with established design criteria to assess the effectiveness of treatment solutions and ensure the safety and sustainability of toll road construction at the study site.

4. Results and Discussion

The research location is on the IKN Toll Road segment that connects the Balang Island Bridge with the Riko Intersection, specifically at STA 1+325 to 1+475. Based on the results of the soil investigation, this area has poor surface soil characteristics, with variations in soft soil depth ranging from 1 to 5 meters. The sounding results show that the average cone resistance (qc) value at a depth of 2 meters is 4 – 8 kg/cm², which indicates soil with a very soft to soft consistency. Table 1 below shows a recapitulation of sounding data in the embankment area, which can be used for the analysis of the bearing capacity and stability of the embankment.

Table 1. Streetmap of Soil Sondir Data (qc) on Embankments STA 1+325 to 1+475.

Original STA	STA 1+350		STA 1+400		STA 1+450		STA 1+475	
Embed Height (m)	5.6	5.6	5.2	5.2	4.6	4.6	4.7	4.7
MAT (m)	-	-	-	-	-	-	-	-
0.2D	6	3	4	2	6	2	8	2
0.4D	5	2	3	1	6	4	6	4
0.5D	8	3	4	2	4	4	4	3
0.6D	4	4	6	4	8	5	9	6
1.0D	8	6	5	2	10	3	7	5
1.2D	5	4	8	6	14	2	5	8
1.4D	3	8	6	10	4	4	10	7
1.5D	7	6	8	4	6	6	8	5
1.6D	11	12	10	8	10	7	12	7
2.0D	9	10	14	6	12	3	9	6
2.2D	6	13	12	10	7	7	10	3
2.4D	9	15	14	8	12	13	7	5
2.5D	15	12	11	12	14	10	12	8
2.6D	13	14	15	15	8	12	17	6
3.0D	10	19	17	20	16	16	21	4
3.2D	12	16	10	13	20	7	18	8
3.4D	16	15	13	17	18	12	23	6
3.5D	22	16	19	13	16	14	27	4
3.6D	15	18	18	21	24	22	19	7
4.0D	11	25	15	17	22	17	16	5

4.2D	25	19	21	22	41	25	39	3
4.4D	19	17	19	35	28	21	47	3
4.5D	27	46	43	32	24	39	72	9
4.6D	32	33	30	47	65	27	60	12
5.0D	41	48	45	65	65	38	80	10
5.2D	49	39	65	100	50	38	105	11
5.4D	45	50	59	200	68	30	90	8
5.5D	53	78	70	250	75	42	110	15
5.6D	65	99	105		95	75	250	11
6.0D	70	95	100		80	45		9
6.2D	90	110	125		110	45		7
6.4D	95	100	200		130	100		17
6.5D	100	120	250		200	80		15
6.6D	80	200			250	90		21
7.0D	105	250				120		35
7.2D	105					100		29
7.4D	110					125		40
7.5D	200					200		60
7.6D	250					250		37
8.0D								75
8.2D								80
8.4D								120
8.5D								110
8.6D								130
9.0D								200
9.2D								250

The bearing capacity of the subgrade is a crucial factor in embankment planning, especially to ensure the stability of the road structure.

Table 2. Bearing Capacity of Basic Soil STA 1+325 to 1+475.

No	STA	Embankment Height (m)	Soil Load (ton)	Vehicle Load (ton)	Total Load (ton)	Soil Data	N-SPT	Soil Type	Without Treatment Undrained Shear Strength (kPa)	Subgrade Bearing Capacity (ton/m²)	SF Actual	Bearing Capacity Evaluation	With Replacement Undrained Shear Strength (kPa)	Subgrade Bearing Capacity (ton/m²)	SF Actual	Bearing Capacity Evaluation	Further Treatment
1	1+350	5.6	9.52	1.5	110.2	S-8A, S-8B	CPT Data	Clay	18	92.52	0.84	NOT OK	53	272.42	2.47	OK	-
2	1+400	5.2	8.84	1.5	103.4	S-9A, S-9B	CPT Data	Clay	11	56.54	0.55	NOT OK	65	334.1	3.23	OK	-

3	1+450	4.6	7.82	1.5	93.2	S-10A, S-10B	CPT Data	Clay	18	92.52	0.99	NOT OK	57	292.98	3.14	OK	-
4	1+475	4.7	7.99	1.5	94.9	S-11A, S-11B	CPT Data	Clay	20	102.8	1.08	NOT OK	28.5	146.49	1.54	OK	-

Based on Table 2, most of the embankment areas of STA 1+325 to 1+475 have a safety factor (SF) of less than 1.5, meaning the subgrade is not strong enough to support the embankment load without improvement. Therefore, the recommended solution is to replace the subgrade with a thickness of 1–2 meters to increase its bearing capacity.

Table 3. STA 1+450 Consolidation Calculation (Without Handling).

											Total (mm)	88.9
Consolidation Settlement of BC Fill (Without Treatment)												
Depth	Soil Type	Consolidated	Hi (m)	Δσ' (kN/m²)	γsat (kN/m³)	σ0 (kN/m²)	Cc	Cs	e0	Pc	Condition	Consolidation Settlement (mm)
0–1	Clay	Consolidation	1	90.19	13.4	3	0.3	0.0375	1.1	165	OC	30.9
1–2	Clay	Consolidation	1	90.19	13.4	5.1	0.3	0.0375	1.1	165	OC	22.7
2–3	Clay	Consolidation	1	88.29	13.4	8.5	0.3	0.0375	1.1	165	OC	18.9
3–4	Clay	Consolidation	1	86.47	13.4	11.9	0.3	0.0375	1.1	165	OC	16.4
4–5	Clay	-	1	84.73	13.4	15.3	-	-	-	-	-	-
5–6	Clay	-	1	83.05	13.4	18.7	-	-	-	-	-	-
6–7	Clay	-	1	81.44	13.4	22.1	-	-	-	-	-	-
7–8	Clay	-	1	79.89	13.4	25.5	-	-	-	-	-	-
8–9	Clay	-	1	78.39	13.4	28.9	-	-	-	-	-	-
9–10	Clay	-	1	76.95	13.4	32.3	-	-	-	-	-	-
10–11	Clay	-	1	75.57	13.4	35.7	-	-	-	-	-	-

Consolidation settlement is a critical parameter that must be considered in embankment design. Based on calculations using laboratory data, the untreated consolidation settlement reached 88.9 mm at STA 1+450 (Table 3). This value is still below the maximum limit of 100 mm set in the design criteria, thus indicating that the settlement is within safe limits. However, to improve long-term safety, a replacement method is still recommended to reduce the thickness of the soft soil layer that is likely to experience further settlement.

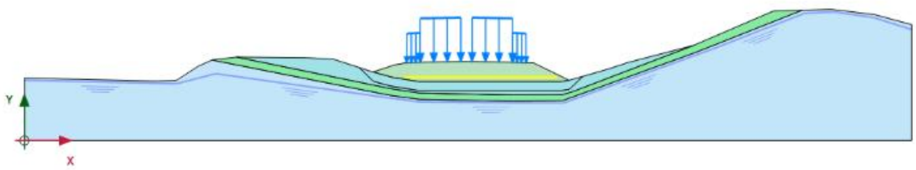


Figure 1.BC STA 1+450 Embankment Modeling.

Table 4. STA 1+450 Embankment Modeling Results (Without Handling).

Depth (m)	De-scrip-tion	Drainage	qc (kg/cm²)	fs (kg/cm²)	FR	γun-sat (kN/m³)	γsat (kN/m³)	σvo (kPa)	cu (kPa)	c' (kPa)	φ' (°)	Eu (kPa)	E' (kPa)	ν
0 – 2.5	Clay	Un-drained B	2	0.2	10	14.84	15.84	19.8	10.01	1	-	3003.4	2012.28	0.3
2.5 – 4	Clay	Un-drained B	12	0.3	2.5	15.99	16.99	32.54	64.85	6.49	-	19457.68	13035.65	0.3
4 – 15	Clay	Un-drained B	150	2	1.33	19.14	20.14	143.32	300	30	-	90000	60300	0.3
Fill	Clay	Un-drained B	-	-	-	17	18	-	45	4.5	-	13500	9045	0.3

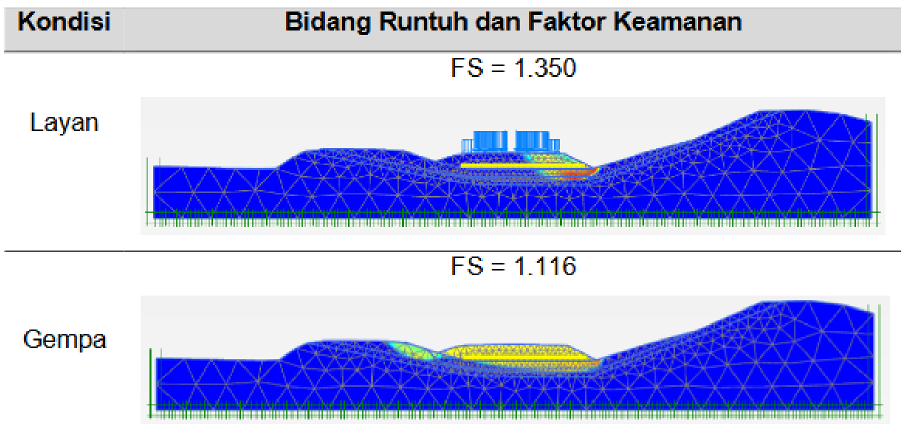
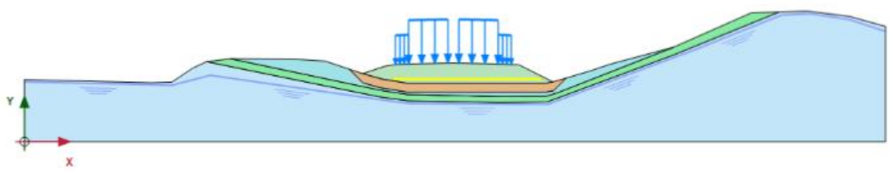


Figure 2. Results of Calculation of Collapse Surface and Safety Factor Based on Conditions (Without Handling).

Geotechnical modeling using Plaxis 2D software was performed to evaluate the embankment stability under two conditions: without treatment and with subgrade replacement. The modeling results for the untreated condition (Figure 1) show a safety factor (SF) of 1,350 under service conditions, while under seismic conditions it is 1,116 (Table 4). These values are still below the design standard, which requires an SF greater than 1.5 for static conditions and greater than 1.1 for seismic conditions.



Picture 3. BC STA 1+450 Embankment Modeling.

Table 4. STA 1+450 Embankment Modeling Results (Replacement 2.0 m).

Depth (m)	Description	Drainage	qc (kg/cm²)	fs (kg/cm²)	FR	γunsat (kN/m³)	γsat (kN/m³)	σvo (kPa)	cu (kPa)	c' (kPa)	φ' (°)	Eu (kPa)	E' (kPa)	ν
0 – 2.5	Clay	Undrained B	2	0.2	10	14.84	15.84	19.8	10.01	1	-	3003.4	2012.28	0.3
2.5 – 4	Clay	Undrained B	12	0.3	2.5	15.99	16.99	32.54	64.85	6.49	-	19457.68	13035.65	0.3
4 – 15	Clay	Undrained B	150	2	1.33	19.14	20.14	143.32	300	30	-	90000	60300	0.3
Fill	Clay	Undrained B	-	-	-	17	18	-	45	4.5	-	13500	9045	0.3

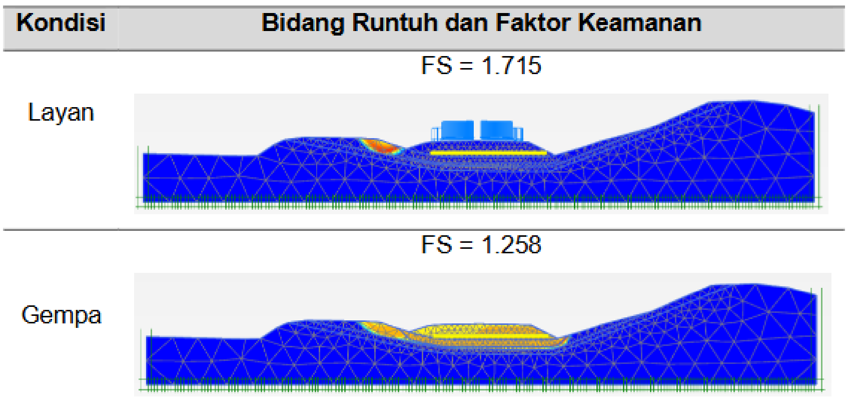


Figure 4. Results of Calculation of Collapse Surface and Safety Factor Based on Conditions (Replacement 2.0 m).

5. Comparison

Many studies have been conducted on the stability of embankments on soft soils to determine the most effective treatment methods for increasing bearing capacity and reducing the potential for deformation and consolidation settlement. One relevant study was conducted byAini et al. (2023), which discusses the use of prefabricated vertical drain (PVD) techniques in accelerating soft soil consolidation in large infrastructure projects.[15]The study shows that the use of PVD combined with preloading can accelerate the compaction process and reduce the risk of excessive deformation. These results are in line with the findings in the IKN Toll Road project, STA 1+325 to 1+475 segments, where the use of replacement is recommended as the primary method, but PVD can be an alternative in conditions of limited granular material as a substitute for subgrade.

In addition to the PVD method, several studies have also shown that the use of geosynthetics as soil reinforcement materials can improve embankment stability. For example, research conducted byJia et al. (2021)to study the effectiveness of geogrids in reinforcing soft soil, especially in highway and high embankment projects[16]This study revealed that the installation of geogrids between layers of embankment can increase the bearing capacity by up to 40% and significantly reduce lateral deformation. In the context of the IKN Toll Road project, geosynthetics can be applied to increase stability if replacement is not possible due to limited granular materials or high costs. Therefore, the application of geosynthetics as a substitute for granular soil in embankment repair is an option that needs further study to improve construction efficiency without sacrificing structural stability.

Furthermore, research bySkinner et al. (2023)on the bearing capacity of soft soil against highway embankments emphasizes the importance of evaluating slope safety factors and the effects of traffic loads on embankment stability.[17]. In his study, Skinner proposed that the combination of replacement and soil reinforcement methods with preloading can increase the safety factor by more than 1.5, in accordance with modern geotechnical design standards. This supports the results of Plaxis 2D modeling in this project, where a 2-meter-thick replacement is able to increase the safety factor from 1,350 to 1,715, which means this method is very effective in increasing the stability of the embankment base soil at STA 1 + 325 to 1 + 475. Thus, the results of this previous study further strengthen that the replacement method is the right solution for this project, especially in soil conditions that have soft characteristics with high potential for settlement.

In line with previous research, the geotechnical standards applied in this project, such as SNI 8460:2017 and SNI 1726:2019, were designed based on the results of studies and experiences from various similar infrastructure projects. The study conducted byAlmeida et al. (2023)indicates that geotechnical design standards should consider minimum safety factors for embankments on soft ground, especially under high seismic conditions.[18]This is in accordance with the approach used in the IKN Toll Road project, where stability analysis was conducted in two scenarios, namely static conditions and earthquake conditions, using the phi-c reduction method in Plaxis 2D software. By considering all these aspects, this project can be a model for the development of embankment stabilization techniques in areas with similar soil characteristics, while ensuring safe and sustainable construction.

6. Conclusion

Based on the research results, it can be concluded that the subgrade conditions at STA 1+325 to 1+475 have low bearing capacity and significant potential for consolidation settlement, thus requiring engineering intervention to ensure embankment stability. Bearing capacity analysis and stability modeling using PLAXIS software indicate that without treatment, several areas do not meet the minimum safety factor, both under service and seismic conditions. The application of the replacement method with a thickness of 2.0 meters has proven effective in improving embankment stability, with the safety factor increasing from 1.350 to 1.715 under service conditions and from 1.116 to 1.258 under seismic conditions, as well as reducing the risk of excessive deformation. Therefore, the replacement method is recommended as the primary solution in this project, especially in locations with soft soils that have high settlement potential. However, given the limitations of granular materials as subgrade replacement materials, it is recommended that similar projects consider additional alternatives such as the use of geosynthetics or other soil reinforcement technologies. In addition, careful logistical planning is needed to ensure material availability and efficient implementation time. With the implementation of appropriate techniques and in accordance with geotechnical standards, the construction of the IKN Toll Road in this segment can proceed safely, efficiently, and sustainably, while also becoming a model for the application of embankment stabilization techniques for infrastructure projects in areas with similar geotechnical conditions.

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Reference

[1] D. T. Bergado and N. Miura, "Improvement Techniques for Soft and Subsiding Ground," in *Lowlands*, Routledge, 2022, pp. 103–133.

[2] K. Lesov, M. Kenjaliyev, A. Mavlanov, and S. Tadjibaev, "Stability of the embankment of fine sand reinforced with geosynthetic materials," in *E3S Web of Conferences*, EDP Sciences, 2021, p. 2011.

[3] H. Sujatmiko, "The Effect Of Holcim Cement Substitution On Fine-Grained Soils Its Influence On The Stability Of Soil Bearing Capacity Using The Terzaghi Method And Meyerhoff Method," *Int. J. Eng. Sci. Inf. Technol.*, vol. 3, no. 4, pp. 19–24, 2023.

[4] E. Cascone, G. Biondi, and O. Casablanca, "Groundwater effect on bearing capacity of shallow strip footings," *Comput. Geotech.*, vol. 139, p. 104417, 2021.

[5] A. El Hariri, A. E. E. Ahmed, and P. Kiss, "Review on soil shear strength with loam sand soil results using direct shear test," *J. Terramechanics*, vol. 107, pp. 47–59, 2023.

[6] R. C. Mamat, A. Ramli, A. Kasa, S. F. M. Razali, and M. B. H. C. Omar, "Artificial neural networks in slope of road embankment stability applications: a review and future perspectives," *Int. J. Adv. Technol. Eng. Explor.*, vol. 8, no. 75, p. 304, 2021.

[7] S. Kumar, S. S. Choudhary, and A. Burman, "Recent advances in 3D slope stability analysis: a detailed review," *Model. Earth Syst. Environ.*, vol. 9, no. 2, pp. 1445–1462, 2023.

[8] T. K. Mebrahtu, T. Heinze, S. Wohnlich, and M. Alber, "Slope stability analysis of deep-seated landslides using limit equilibrium and finite element methods in Debre Sina area, Ethiopia," *Bull. Eng. Geol. Environ.*, vol. 81, no. 10, p. 403, 2022.

[9] L. Hu and Z. Liu, "Analysis of deformation mechanism of soft soil reinforcement by vacuum preloading," *Rock Soil Mech.*, vol. 42, no. 3, p. 7, 2021.

[10] H. Guo *et al.*, "Land subsidence and its affecting factors in Cangzhou, North China Plain," *Front. Environ. Sci.*, vol. 10, p. 1053362, 2022.

[11] M. Awad, A. Aldaood, and I. Alkiki, "Development of a compressibility prediction model based on soil index properties and area under/bounded by consolidation and rebound curves," *Geotech. Geol. Eng.*, vol. 40, no. 9, pp. 4787–4807, 2022.

[12] B. S. Olek, "State-of-the-Art Review on determining one-dimensional consolidation parameters based on compression and distribution of pore water pressure: coefficient of consolidation (cv), end of primary (eop) consolidation," *Arch. Comput. Methods Eng.*, vol. 32, no. 1, pp. 605–644, 2025.

[13] Y. Kang, Z. Geng, Q. Liu, B. Liu, and Y. Zhu, "Research progress on support technology and methods for soft rock with large deformation hazards in China," *Rock Soil Mech.*, vol. 43, no. 8, p. 1, 2022.

[14] J. Liu, K. Zhu, J. Zuo, K. Sun, Y. Sheng, and B. Jia, "Soft rock deformation and failure modes under principal stress rotation from roadway excavation," *Bull. Eng. Geol. Environ.*, vol. 83, no. 8, p. 335, 2024.

[15] I. A. Aini, E. I. Maulana, and H. T. Santoso, "Evaluasi Metode Perbaikan Tanah Lunak dengan Preloading Kombinasi PVD-PHD pada Proyek Pembangunan Jalan Tol Semarang-Demak Paket II," *Bentang J. Teor. Dan Terap. Bid. Rekayasa Sipil*, vol. 11, no. 1, pp. 21–36, 2023.

[16] M. Jia, W. Zhu, and C. Xu, "Performance of a 33m high geogrid reinforced soil embankment without concrete panel," *Geotext. Geomembranes*, vol. 49, no. 1, pp. 122–129, 2021.

[17] H. Skinner, D. G. Toll, K. Higgins, M. Brown, and J. Burland, *ICE Manual of Geotechnical Engineering Volume 1: Geotechnical engineering principles, problematic soils and site investigation*, vol. 1. Emerald Group Publishing, 2023.

[18] M. de S. S. de Almeida *et al.*, "Ground improvement techniques applied to very soft clays: state of knowledge and recent advances," *Soils and Rocks*, vol. 46, no. 1, p. e2023008222, 2023.