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Analysis of the Stability of Retaining Walls Using FEM and LEM on the Dumai Duri Kandis Road

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ABSTRACT

This research aims to analyze and compare the stability of retaining walls using two analytical approaches, namely the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM), on the landslide-prone section of the Dumai Duri Kandis Road. The research was conducted using an exploratory method through field observations, collection of primary and secondary data, and numerical simulations. The research population consists of geotechnical structures in landslide areas, with samples taken from drilling points up to 24 meters deep as the location for soil analysis. The research instruments include a drilling machine, SPT (Standard Penetration Test), and Plaxis 2D and Slide 2 software for FEM and LEM simulations. Primary data were obtained from field soil stratification tests, while secondary data included earthquake maps, plan drawings, and bored pile specifications. Based on soil classification, the location falls within soft soil with an earthquake acceleration of 0.1088g. The analysis results show that the application of bored piles significantly increases the safety factor (SF) value. In conditions without bored piles, the average SF ranges from 1.02 to 1.27, whereas with bored piles, it increases to more than 2.1, depending on the water table conditions and loading. In conclusion, the FEM and LEM methods show that the use of bored piles can increase slope stability by more than 135% compared to without reinforcement. These findings recommend the use of bored piles as an effective reinforcement strategy for road sections with a high potential for landslides.

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1. INTRODUCTION

Earthquakes and landslides are types of geotechnical disasters that frequently occur in Indonesia and have serious impacts on the sustainability of road infrastructure (Dermawan et al., 2022; Naryanto et al., 2019), particularly in hilly areas with unstable slopes. One such case is the Dumai Duri Kandis Road, located in Riau Province, which serves as a strategic transportation route traversing several landslide-prone zones. The vulnerability of this area is attributed to factors such as extreme rainfall, weak geotechnical soil conditions, and heavy traffic loads from large vehicles (Wijaya et al., 2024). Historical records indicate that certain sections of the Dumai Duri Kandis Road have experienced significant landslides that disrupted transportation services, necessitating slope rehabilitation through the construction of retaining walls as an effective landslide mitigation measure (Nurhidayah et al., 2022).

Various types of retaining wall systems are commonly applied in practice, including cantilever retaining walls reinforced with bored piles, which require careful consideration of soil conditions and the surrounding environment for optimal design (Kaveh et al., 2020). The precision in designing such reinforcement systems largely depends on the chosen slope stability analysis method (Fareka et al., 2020). In geotechnical engineering practice, two widely used methods for analyzing slope stability and retaining wall systems are the Limit Equilibrium Method (LEM) (Shobari et al., 2019) and the Finite Element Method (FEM) (Bokko et al., 2019; Srivastava & Chakrabortty, 2025). LEM is based on the principle of force and moment equilibrium, typically assuming a predetermined slip surface. While computationally simpler, LEM often does not account for soil deformation and the interaction between soil and structural elements (Riza et al., 2018; Wang et al., 2023). Conversely, FEM offers a numerical approach capable of modeling the non-linear behavior of soil, as well as accurately simulating soil deformation and stress distribution (Carbonell et al., 2022). However, this method requires more complex soil parameter inputs and specialized software such as Plaxis 2D (Mina et al., 2022).

Challenges emerge when these two analytical methods yield significantly different results, both in terms of safety factor values and structural reinforcement recommendations. This disparity raises the need for comparative studies, particularly on real field cases such as the Dumai Duri Kandis Road, to evaluate the consistency and reliability of each method. Comparative analysis not only contributes to a better understanding of the characteristics and limitations of each method but also serves as an important basis for decision-making in selecting appropriate slope stability analysis methods, considering aspects of accuracy, efficiency, and field applicability.

Accordingly, this study aims to analyze and compare the stability of retaining walls using the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM), as well as to demonstrate that selecting an appropriate analysis method and implementing bored pile reinforcement are crucial factors in the design of slope stabilization systems for landslide-prone road infrastructure.

2. METHOD

The research was conducted in the border area of Bengkalis Regency, which is a landslide management area on the Dumai Duri Kandis road segment, using an exploratory method consisting of field surveys, data collection, and case study resolution. In the analysis, a 2D finite element method (FEM) simulation and limit equilibrium method (LEM) calculations were conducted to obtain soil stability analysis. The following are the steps in the research as shown in **Figure 1.**

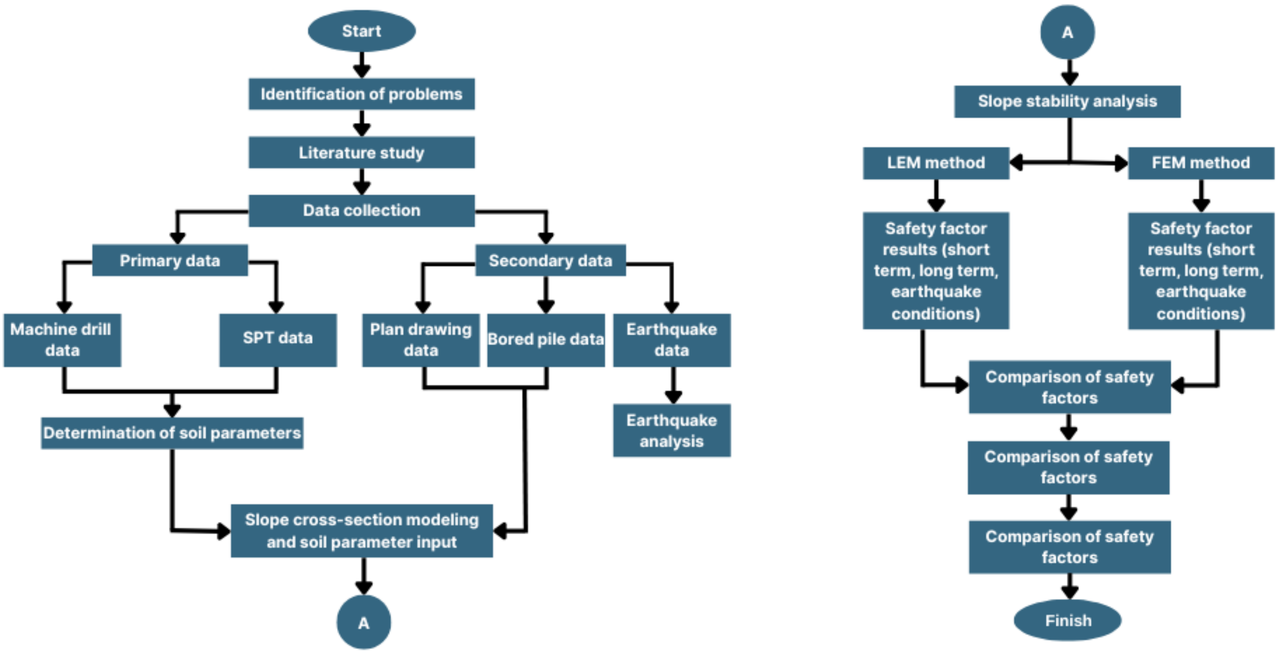

Figure 1. Research Scheme

This research begins with the problem identification stage, which involves recognizing technical issues related to slope stability. After the problems were identified, a literature review was conducted to examine relevant theories and previous research, in order to strengthen the theoretical foundation and research methodology. The next stage is data collection, which is divided into primary data and secondary data. Primary data are soil stratification parameters based on SPT results from a single borehole up to 24 meters deep at 2-meter intervals to the hard ground surface, while secondary data include plan drawings, earthquake maps, and credible bored pile validation data. Primary data are used to determine the soil parameters needed for analysis, while earthquake data are specifically analyzed to understand the seismic load characteristics relevant to the research location. The bored pile method for the SPT test is conducted based on SNI 4153:2008

After the data has been collected and analyzed, slope cross-section modeling is performed by incorporating the previously determined soil parameters. The next stage is the slope stability analysis conducted using two approaches, namely the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM).

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For the FEM analysis, the safety factor evaluation was carried out in stages using a staged construction method to simulate the real sequence of slope construction and stabilization processes. The simulation was divided into three main phases: the construction phase (short-term), the post-drainage phase (long-term), and the earthquake phase (pseudostatic).

In each phase, three variations of groundwater levels were considered based on field observations and geohydrological analysis: (1) actual groundwater level (at approximately 3 meters depth), (2) normal groundwater level (around 5 meters depth), and (3) extreme groundwater level during heavy rainfall (at 1–1.5 meters depth). Additionally, three surface loading conditions were applied in the simulation scenarios: 0 kN/m^2 (no traffic load), 10 kN/m^2, and 20 kN/m^2. This approach aimed to provide a comprehensive understanding of safety factor variations under different hydrological and loading scenarios.

For long-term conditions, it is assumed that the soil has undergone complete consolidation (fully drained), considering the low soil permeability value, which ranges from 10^-4 to 10^-5 m/day based on laboratory data. This value indicates that over a weathering period of more than 6 months, the pore water pressure has significantly decreased, allowing the drained condition to be assumed valid. Subsequently, a comparison of the safety factors between the two methods for each of these conditions was conducted to evaluate the differences in analysis results and determine the most representative approach. This stage concludes with the formulation of conclusions and recommendations based on the comparison results, marking the end of the research series.

3. RESULT AND DISCUSSION

3.1 Soil Stratification

Soil data were obtained from a single drilling point (BH-04) at a depth of 24 meters, chosen based on the critical landslide location. Although a single drilling point was used, secondary data from geological maps and field surveys indicate the uniformity of morphology and stratigraphy at the site. Therefore, the data is considered sufficiently representative for the purposes of initial analysis. However, for the final design purposes, it is recommended to conduct additional drilling at two other points to verify the homogeneity of the soil conditions.

Based on the data from the drilling and Standard Penetration Test (SPT), the soil layer composition at the research location can be identified as shown in **Figure 2**. This information outlines the properties and characteristics of each soil layer from the surface to a certain depth, and serves as the main reference in conducting slope stability analysis and designing an appropriate soil reinforcement system.

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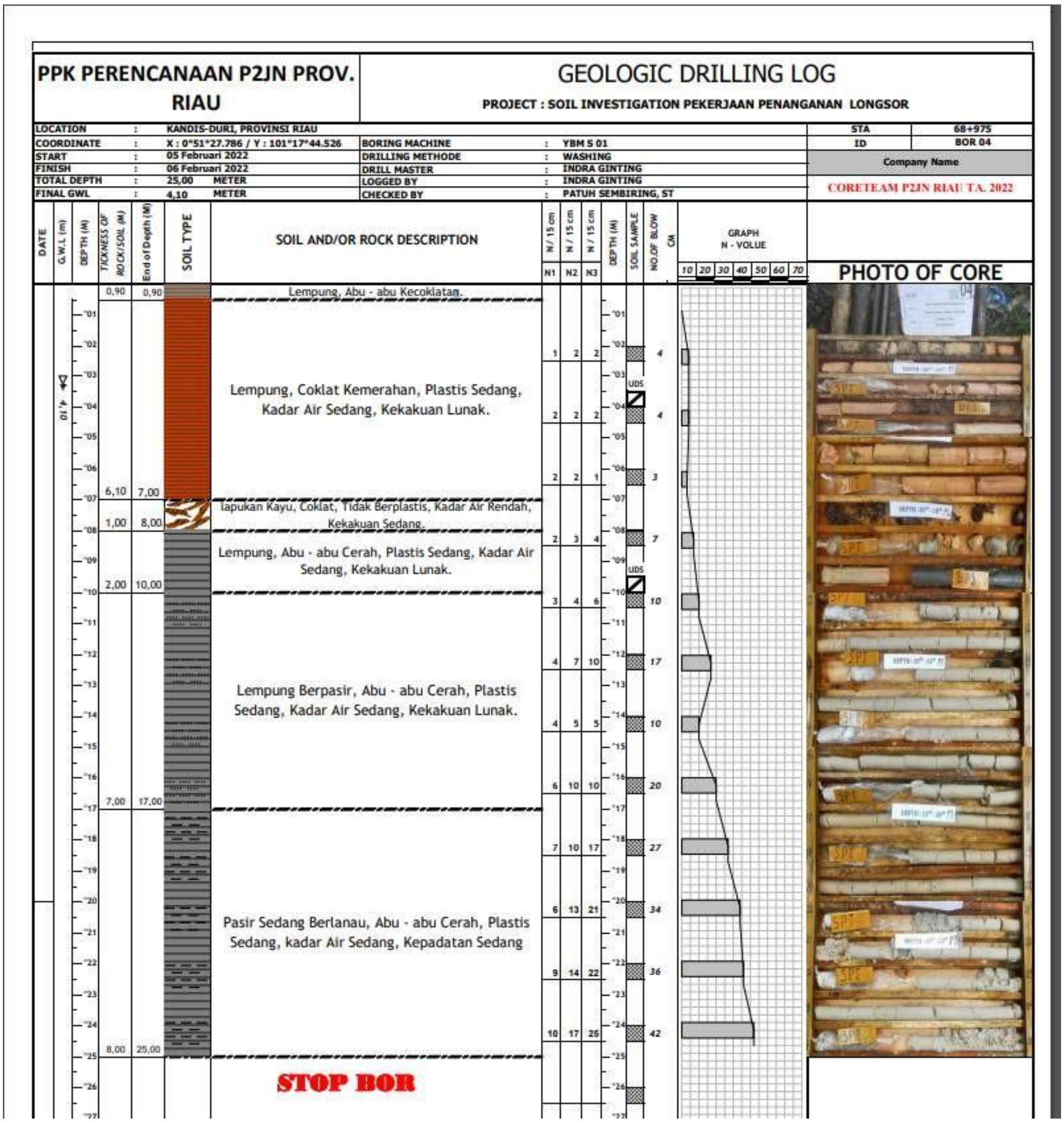


Figure 2. BH-04 Soil Stratigraphy

The soil layer structure at the research site was obtained through the interpretation of drilling data and the Standard Penetration Test (N-SPT). The analysis results show that the soil is divided into several layers from the surface to a depth of approximately 25 meters. The top layer consists of dense non-cohesive sand, while the layers beneath it are dominated by high plasticity clay with low bearing capacity, requiring special attention in slope stability calculations. On at a depth of 0 to 7 meters, a layer of reddish-brown clay was found with soft characteristics and moderate plasticity, which tends to become water-saturated during heavy rainfall and is at risk of landslides. Next, at a depth of 7 to 10 meters, there is gray clay with almost similar properties, although its bearing capacity is slightly better. Between 10 and 17 meters, a layer of gray sandy clay with a soft consistency is found, where the sand content contributes to the improvement of soil stability. Meanwhile, at a depth of 17 to 25 meters, a layer of gray silty sand with a medium density is composed.

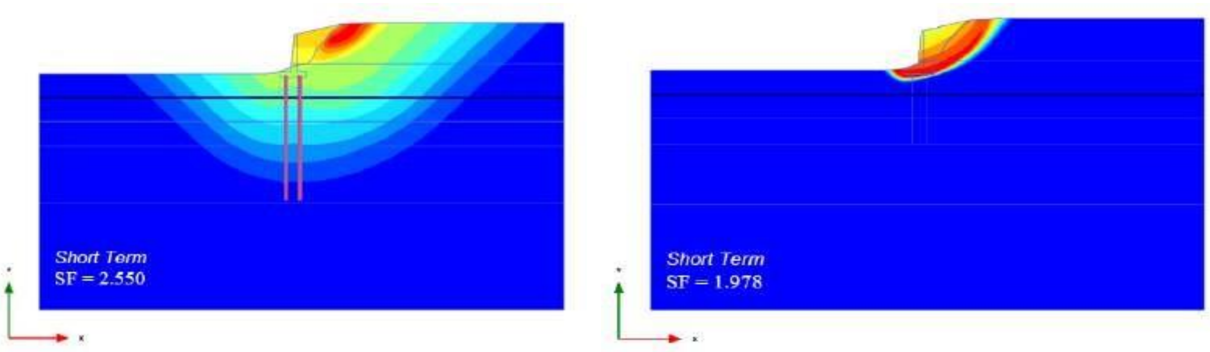
This layer has relatively stable non-cohesive characteristics and is suitable as a foundation for construction or reinforcement systems. Generally, the soil composition at the site is dominated by clay material from the surface to intermediate depths, which tends to be less stable due to its plastic nature and low stiffness. At a depth of more than 17 meters, the presence of silty sand offers a higher soil bearing capacity, making it suitable for use as a support point for structural elements such as bored piles. Therefore, effective mitigation strategies are needed to strengthen slope stability, especially in clay soil zones prone to land movement.

3.2 Determination of Soil Parameters

The identification of the type and arrangement of soil layers is carried out through the determination of various geotechnical parameters. These parameters are analyzed based on the Mohr-Coulomb Model, which is used to evaluate slope stability in three conditions: short-term, long-term, and earthquake conditions (Wahab et al., 2023). According to the findings of (Pramulandani & Hamdhan, 2020), stability analysis in the short-term phase or immediately after construction usually refers to total stress analysis (TSA), also known as undrained conditions, because the loading process occurs faster than the dissipation of pore water pressure. In this condition, the parameters used include cohesion (c) and the internal friction angle (ϕ) to determine the factor of safety (SF). For long-term or drained conditions, the calculation is based on Effective Stress Analysis (ESA) using effective parameters. Therefore, two sets of soil parameters are used in this study, namely effective and non-effective parameters.

3.3 Safety Factor Analysis in Short Term Conditions

This analysis excludes traffic loads and involves three phases, including the short-term construction phase. It also evaluates slope performance differences between reinforced and unreinforced conditions using bored piles. **Figure 3** shows the SF FEM values of the actual short-term water table with a) bored pile, and b) without bored pile at a load of 0 kN/m².



a b

Figure 3. SF FEM – Short-Term Water Table (0 kN/m²): **a)** With vs. **b)** Without Bored Pile

The first stage of the analysis involves evaluating slope stability under short-term conditions by considering variations in groundwater levels. The SF values for actual, normal, and extreme groundwater conditions are summarized in **Table 1**.

Table 1. Recapitulation of SF Values in Short Term Conditions

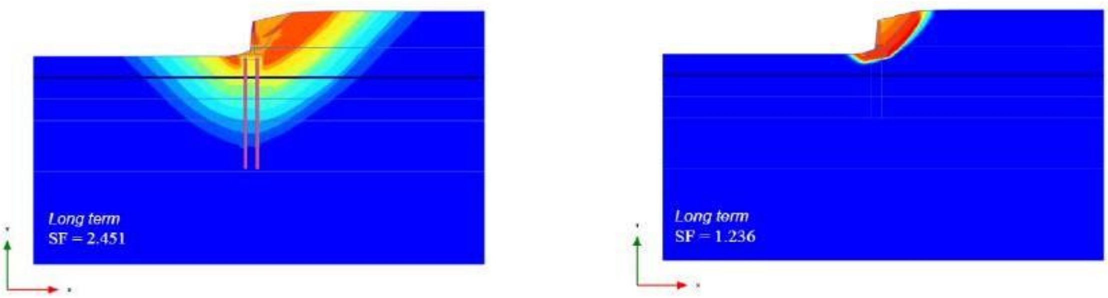
Condition	Groundwater Level	With Bored Pile	Without Bored Pile
Short Term	Actual	2,550	1,978
	Normal	2,453	1,906
	Extreme	2,258	1,714

Based on **Table 1**, it is observed that the slope safety factor (SF) decreases with the rise in groundwater level. Without reinforcement, the highest SF is achieved at the actual groundwater level of 1.978, decreasing to 1.906 at the normal groundwater level, and reaching the lowest value of 1.714 under extreme conditions. This decrease is caused by the increase in pore water pressure due to the higher groundwater level, which weakens the effective shear strength of the soil, as explained by (Feng et al., 2020) that slope stability is greatly influenced by changes in hydrological conditions.

The installation of bored piles has proven effective in increasing slope stability under all groundwater conditions. Under actual conditions, the SF increased from 1.978 to 2.550, or by approximately 28.9%. A similar increase occurred under normal conditions (from 1.906 to 2.453) and extreme conditions (from 1.714 to 2.258). This indicates that bored piles function optimally in cutting potential slip surfaces and transferring loads to more stable soil layers at depth. These findings are in line with the research results of (Zhang et al., 2021; Zhou et al., 2020) which state that bored piles are effective in improving slope stability, particularly in soft soil conditions with high pore water pressure. Therefore, bored piles are recommended to reinforce road slopes with fluctuating groundwater, ensuring the SF value remains above the SNI 8460:2017 minimum standard of 1.5.

3.4 Safety Factor Analysis in Long Term Conditions

In this Long term condition, as illustrated in Figure 4. **Figure 4** shows the actual long-term water surface SF FEM values with a) bored pile, and b) without bored pile at a load of 0 kN/m².



a b

Figure 4. SF FEM – Long-Term Water Table (0 kN/m²): a) With vs. b) Without Bored Pile

In order to evaluate the effect of groundwater level variations on slope stability under long-term conditions, a recapitulation of the factor of safety (FS) values for different water levels is required. This comparison allows for a clearer understanding of how changes in groundwater levels impact the overall slope stability, both with and without reinforcement. Next, the actual, normal, and extreme water levels in long-term conditions will be presented in tabular form as shown in **Table 2**.

Table 2. Recapitulation of SF Values in Long Term Conditions

Condition	Groundwater Level	With Bored Pile	Without Bored Pile
Long Term	Actual	2,451	1,236
	Normal	1,733	0,739
	Extreme	1,489	0,312

Based on **Table 2** and **Figure 4,** it is evident that the factor of safety (FS) value under long-term conditions generally experiences a significant decrease compared to short-term conditions across all variations of groundwater levels. This is reasonable, as under long-term conditions, the soil is assumed to have undergone full consolidation (fully drained), so the effective strength of the soil is entirely dependent on the effective shear strength parameters (ϕ' and c′), without the contribution of short-term pore water pressure. Without reinforcement, the highest SF value is only 1.236 under actual groundwater conditions, then it drastically decreases to 0.739 under normal conditions, and reaches a very low value of 0.312 under extreme conditions. This value is even far below the minimum standard of SNI 8460:2017, which is 1.5, meaning that unreinforced slopes in the long term are very susceptible to landslides, especially when the groundwater level is high.

The installation of bored piles significantly increases the SF value under all conditions. At the actual water table, the SF value with bored piles reached 2.451, an increase of approximately 98.3% compared to without reinforcement. Similarly, under normal and extreme conditions, the SF values become 1.733 and 1.489, all of which approach or meet the safety standards. The performance of the bored pile remains effective even at extreme water levels, although the SF value drops to 1.489, it is still much better than the unreinforced condition.

This finding is in line with the research results of (Liu et al.,2020), which state that under long-term conditions, bored piles are still able to maintain slope stability through the mechanism of transferring lateral loads to deeper soil layers. In addition, as stated by (Staubach et al., 2022), bored piles are capable of limiting lateral movement and maintaining soil mass integrity even under saturated hydrological conditions. The implication is that the installation of bored piles becomes an essential strategy in road infrastructure projects in areas with fluctuating groundwater levels and soft soil with high plasticity, particularly to ensure long-term stability.

3.5 Safety Factor Analysis in Earthquake (Pseudostatic) Conditions

Following the analysis under long-term conditions, the next step is to assess slope stability during earthquake (pseudostatic) conditions. This stage is crucial, as seismic forces can

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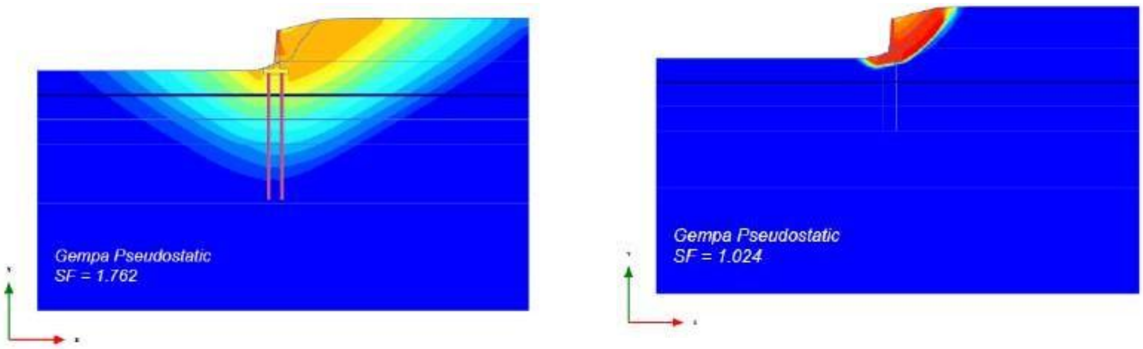
considerably reduce the safety factor (SF), especially in areas with fluctuating groundwater levels. The results of the FEM analysis for these conditions are illustrated in **Figure 5.**



b

a

Figure 5. The SF FEM value of the actual groundwater level during an earthquake with **a)** bored pile, and **b)** without bored pile at a load of 0 kN/m^2

Following the analysis under long-term conditions, the evaluation of slope stability under pseudostatic (earthquake) conditions is also conducted. The recapitulation of SF values for actual, normal, and extreme groundwater levels under these conditions is shown in **Table 3**.

Table 3. Recapitulation of SF Values in Pseudostatic Conditions

Condition	Groundwater Level	With Bored Pile	Without Bored Pile
Pseudostatic	Actual	1,762	1,024
	Normal	1,257	0,480
	Extreme	1,042	0,203

From **Table 3** and **Figure 5**, it can be seen that the safety factor (SF) generally experiences the most significant decrease during earthquake conditions compared to short-term or long-term conditions. Without reinforcement, the SF value only reaches 1.024 at the actual water level, then drops to 0.480 at the normal water level, and 0.203 under extreme conditions. These values are entirely below the minimum standard of SNI 8460:2017, which is 1.5, indicating a high susceptibility of the slope to potential landslides during an earthquake.

The installation of bored piles has proven capable of increasing the SF value under all seismic conditions. At the actual water table, the SF value with bored piles reached 1.762, an increase of 72% compared to without reinforcement. Similarly, under normal and extreme conditions, the SF values become 1.257 and 1.042, respectively. Although the SF values at normal and extreme water levels are still below the minimum standard, the presence of bored piles can significantly slow down the potential for slope failure when lateral seismic forces occur.

The performance of the bored pile remains effective in seismic conditions due to its ability to distribute lateral earthquake loads to more stable soil layers below the potential slip surface, as well as to control the lateral movement of the soil mass. This is in accordance with the research findings of (Zheng et al., 2024), which state that the reinforcement of bored piles effectively increases the SF value in pseudostatic simulations, although it still requires a combination of additional mitigation measures such as vertical drainage or geotextile reinforcement for extreme groundwater conditions.

The implication is that in the planning of road infrastructure in earthquake-prone areas with soft soil, the installation of bored piles becomes a mandatory reinforcement element. However, under extreme groundwater conditions, it is necessary to consider additional groundwater control systems to maintain the SF value above the safe limit during an earthquake.

3.6 Safety Factor Analysis using the FEM Method

Next, **Table 4** explains the findings of the Safety Factor using the FEM method. It can be seen that the safety factor (SF) under actual groundwater conditions with a load of 0 kN/m² decreases from the short-term construction phase to the long-term phase (earthquake phase). The ΣM*sf* curve displayed should show stability at its end, as this stability reflects the accuracy level of the analysis conducted using Plaxis software. **Figure 6** is an example of the M*sf* Curve for Actual Water Table Condition with a Load of 0 kN/m².

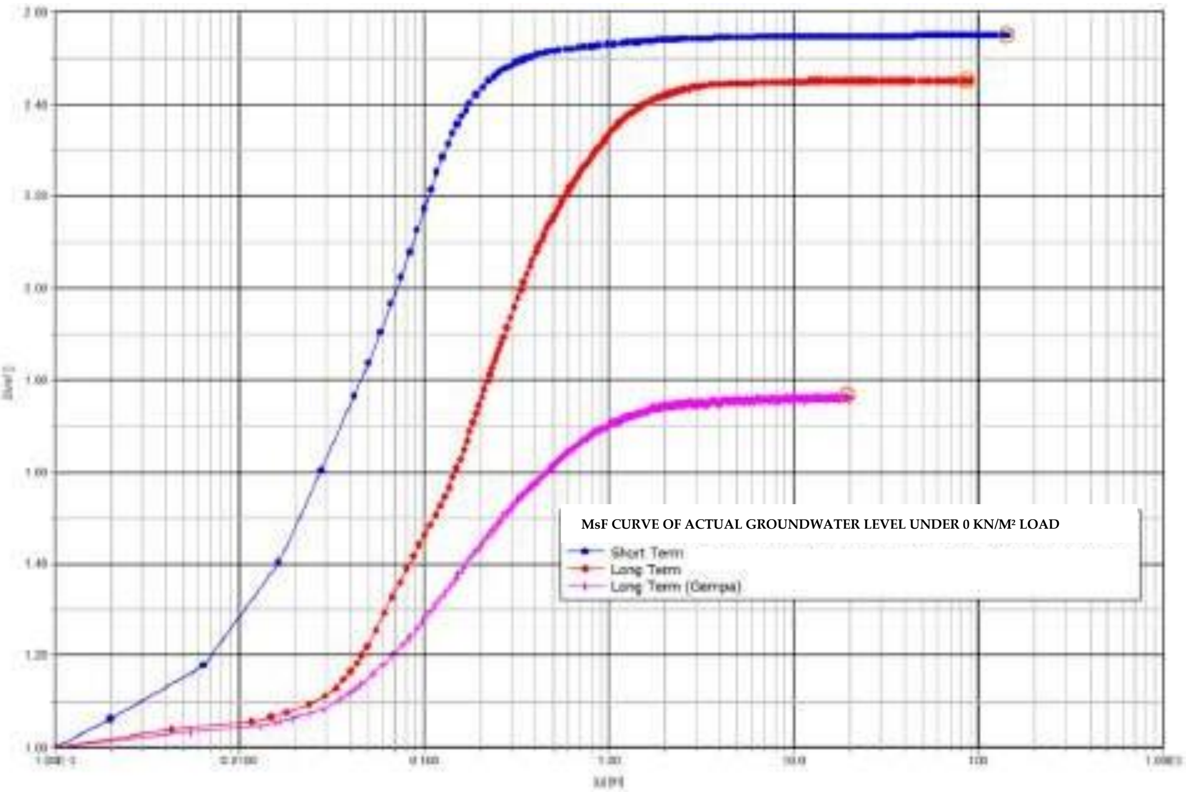


Figure 6. M*sf* Curve Actual Water Surface Condition with Load 0 kN/m2

Subsequently, a comprehensive summary of the safety factor results obtained from the Finite Element Method (FEM) under various conditions is presented in **Table 4**.

Table 4. Recap of Safety Factor Method FEM

No.	Groundwater Condition	Surface Load (kN/m²)	Short Term	Long Term	Earthquake (Pseudostatic)
	Existing Slope			**1.237**	
1	Actual	0	1.978	1.236	1.024
2		10	1.858	1.209	1.002
3		20	1.742	1.177	0.741
4	Half Height of Retaining Wall	0	1.906	0.739	0.480
5		10	1.795	0.722	0.433
6		20	1.686	0.626	0.406
7	Equal to Retaining Wall Height	0	1.714	0.312	0.203
8		10	1.622	0.310	0.203
9		20	1.529	0.307	0.203

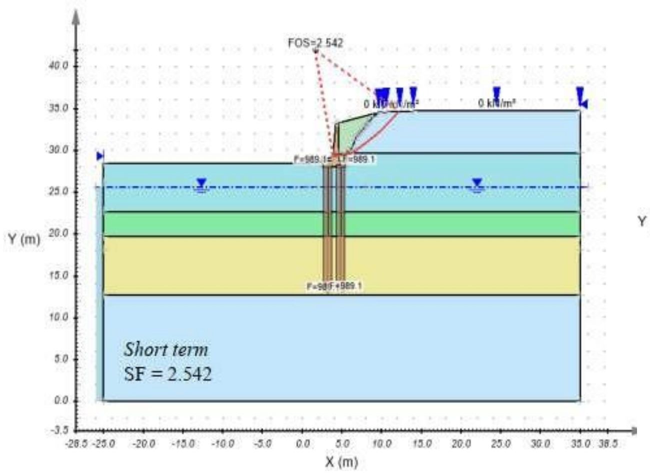
The analysis of the Safety Factor (SF) on the slope using the Finite Element Method (FEM) as presented in Table 2 shows that the stability of the slope is highly dependent on the position of the groundwater table and the presence of surface loads. The results show that the higher the groundwater level, the lower the SF value, which is consistent with previous findings that increased pore water pressure reduces the soil's shear strength, thereby decreasing slope stability. Several studies, such as (Latief & Zainal, 2019), even show an improvement in stability performance when the water table is lowered due to the matric suction effect that enhances soil cohesion.

In addition to the groundwater factor, road load also has a significant impact on SF. As seen in the analysis in Table 2, the increase in load from 0 to 20 kN/m² tends to decrease the SF value, especially under long-term conditions and during an earthquake. This is consistent with the basic principle that additional load increases shear stress, thereby increasing the likelihood of failure. A low SF value (approaching or below 1.1) under dynamic conditions (earthquake) indicates a high potential for failure and the need for mitigation measures.

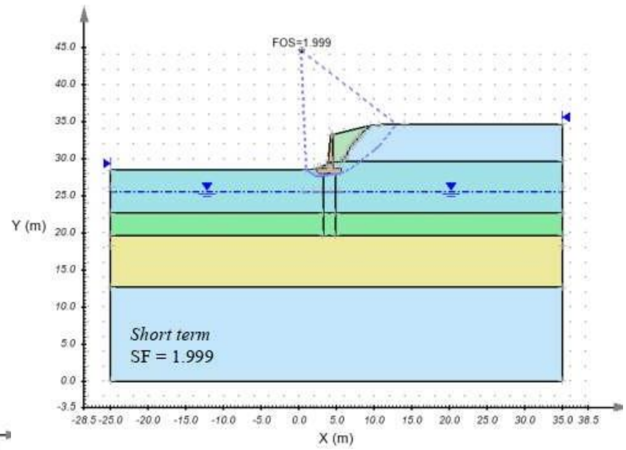
Interestingly, there are conditions where the SF is relatively high even when the maximum road load is applied—namely when the water level is at a depth of DPT ("at the level of DPT"). In that scenario, the SF value under earthquake conditions reaches 1.350. This phenomenon can be explained through the counter-pressure theory that forms beneath the water surface, providing additional stability, something also described in the FEM literature regarding pore water pressure in various configurations.

3.7 Safety Factor Analysis using the LEM Method

The analysis was conducted under a traffic load condition of 0 kN/m² through three main stages, namely the construction stage (short term), the drying stage (long term), and the earthquake phase. This simulation also aims to compare the effectiveness of reinforcement using bored piles with the condition without such reinforcement. **Figure 7** is an example of a simulation showing the SF Value of the LEM Method with actual short-term groundwater level (a) with Bored (b) without Bored Pile (Load 0 kN/m²).



a



b

Figure 7. SF (LEM) for Short-Term Groundwater: a) With vs. b) Without Bored Pile

In addition to the FEM analysis, a comparative evaluation was also conducted using the Limit Equilibrium Method (LEM) to assess slope stability under various groundwater conditions and surface loads. This approach aims to verify the consistency of the safety factor (SF) trends obtained from different analysis methods. The results of these simulations are presented in **Table 5**, which shows the influence of bored piles on slope stability under normal and extreme groundwater conditions.

Table 5. Recap of Safety Factor Method LEM

No.	Groundwater Condition	Surface Load (kN/m²)	Short Term	Long Term	Earthquake (Pseudostatic)
	Existing Slope		**1.237**		
1	Actual	0	1,999	1,252	1,061
2		10	1,879	1,232	1,023
3		20	1,752	1,196	0,823
4	Half Height of Retaining Wall	0	1,936	0,786	0,514
5		10	1,834	0,761	0,452
6		20	1,715	0,654	0,412
7	Equal to Retaining Wall Height	0	1,732	0,325	0,296
8		0	1,628	0,323	0,270
9		10	1,537	0,313	0,262

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Based on **Table 5**, the slope safety factor (SF) values analyzed using the Limit Equilibrium Method (LEM) show a consistent decreasing pattern with the increase in surface load and groundwater level in all analysis conditions, whether short term, long term, or pseudostatic (earthquake). In short-term conditions, the SF value is still considered high. The highest value recorded at the actual water surface without load was 1.999, and it gradually decreased to 1.537 when the surface load reached 20 kN/m² at the water surface height of DPT. Although it decreased, the SF values in this short-term condition mostly remained above the minimum standard of SNI 8460:2017, which is 1.5. This indicates that the unreinforced slope remains sufficiently stable in the short term as long as the load and groundwater level are controlled. These findings are consistent with the limit equilibrium theory, which states that in undrained conditions, the soil's shear strength is still influenced by the initial pore water pressure and the undrained cohesion parameter (cu), as explained by (Yan et al., 2023).

In long-term conditions, there is a significant decrease in SF value. The highest value is only 1.252 at the actual water table without load, while the lowest value recorded is 0.313 at the water table height of DPT with a load of 20 kN/m². All SF values in the long-term condition are mostly below the minimum standard of 1.5. This is due to the long-term influence where the soil has undergone full consolidation (fully drained) and its strength relies solely on the effective shear strength parameters (c' and φ'), without any contribution from pore water pressure. These findings are consistent with the study by (Cai et al., 2019), which states that the stability of water-saturated clay slopes tends to decrease drastically over the long term due to the weakness of the effective shear strength parameters.

The most critical condition occurs in the earthquake analysis (pseudostatic). In this condition, the SF value decreases drastically. The highest value is only 1.061 at the actual water surface without load, while the lowest value of 0.262 occurs at the water surface at DPT height with a load of 20 kN/m². This condition indicates that without reinforcement, the slope is highly vulnerable to landslides during an earthquake, especially under conditions of high water table and large surface loads. The implication is that, based on the trend of these results, the installation of reinforcements such as bored piles and efforts to control groundwater levels have become mandatory in the slope stability design in the Dumai Duri Kandis area. This is important to ensure that the safety factor remains above the minimum standard, especially under long-term conditions and during an earthquake (Bokko et al., 2019).

4. CONCLUSION

The analysis results at the Dumai Duri Kandis Road section location indicate that this area has a high vulnerability to earthquakes and landslides, with a peak ground acceleration (PGA) value of 0.25g and classified as site class SE (soft soil). Based on the slope stability calculations without reinforcement, a safety factor value of 1.232 was obtained using the Finite Element Method (FEM) and 1.273 using the Limit Equilibrium Method (LEM). After applying reinforcement in the form of a Retaining Wall (RW) with bored piles, the safety factor value significantly increased to 2.170 under existing groundwater conditions. The comparison between FEM and LEM shows relatively comparable results, where both provide a consistent

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picture of the positive impact of bored piles on slope stability improvement. Without the use of bored piles, the safety factor value drastically decreases under extreme groundwater conditions, even reaching only 0.473 based on Plaxis LE analysis results. This strengthens the evidence that the use of bored piles is very effective in stabilizing slopes, especially in areas prone to geotechnical disasters. Thus, this research has successfully achieved its objectives, namely analyzing and comparing the stability of retaining walls using the FEM and LEM methods, and demonstrating that the selection of the appropriate method and the application of bored piles are crucial in the design of slope reinforcement systems for landslide-prone road infrastructure.

REFERENCES

Bokko, J., Johan, Rusan, P., & Bunga, E. (2019). Analisis kelongsoran jalan poros sangalla-batualu dengan program plaxis. *Journal Dynamic Saint*, *4*(1), 764–772.

Cai, X., Zhou, Z., Liu, K., Du, X., & Zang, H. (2019). Water-weakening effects on the mechanical behavior of different rock types: phenomena and mechanisms. *Applied Sciences*, *9*(20), 4450.

Carbonell, J. M., Monforte, L., Ciantia, M. O., Arroyo, M., & Gens, A. (2022). Geotechnical particle finite element method for modeling of soil-structure interaction under large deformation conditions. *Journal of Rock Mechanics and Geotechnical Engineering, 14*(3), 967–983.

Dermawan, M. R., Budi Kudwadi, & Parmono. (2022). Tingkat pengetahuan dan sikap siswa smk dpib mengenai risiko gempa bumi terhadap kerusakan bangunan. *JPTB: Jurnal Pendidikan Teknik Bangunan, 2*(1), 31–40.

Fareka, M. A., Sutarto, N. R., & Pamungkas, T. D. (2020). Analisis stabilitas lereng pada pelapukan batuan vulkanik di Cikalongwetan Kabupaten Bandung Barat Jawa Barat. *Jurnal Geografi Gea, 20*(1), 26–38.

Feng, S., Liu, H. W., & Ng, C. W. W. (2020). Analytical analysis of the mechanical and hydrological effects of vegetation on shallow slope stability. *Computers and Geotechnics*, 118, 103335.

Kaveh, A., Hamedani, K. B., & Bakhshpoori, T. (2020). Optimal design of reinforced concrete cantilever retaining walls utilizing eleven meta-heuristic algorithms: A comparative study. Periodica Polytechnica Civil Engineering, 64(1), 156–168.

Latief, R. H., & Zainal, A. K. E. (2019). Effects of water table level on slope stability and construction cost of highway embankment. *Engineering Journal*, *23*(5), 1-12.

Liu, D., Hu, X., Zhou, C., Xu, C., He, C., Zhang, H., & Wang, Q. (2020). Deformation mechanisms and evolution of a pile-reinforced landslide under long-term reservoir operation. Engineering Geology, 275, 105747.

Mina, E., Fathonah, W., Kusuma, R. I., & Ramadhani, A. F. (2022). Analisis Stabilitas Lereng dengan Alternatif Perkuatan Menggunakan Software Plaxis 2D dan Slope/w (Studi Kasus : Proyek Pembangunan Kampus Baru UNTIRTA Sindangsari). *Fondasi : Jurnal Teknik Sipil, 11*(2), 161–171.

Naryanto, H. S., Soewandita, H., Ganesha, D., Prawiradisastra, F., & Kristijono, A. (2019). Analisis penyebab kejadian dan evaluasi bencana tanah longsor di Desa Banaran, Kecamatan Pulung, Kabupaten Ponorogo, Provinsi Jawa Timur Tanggal 1 April 2017. Jurnal Ilmu Lingkungan, 17(2), 272–282.

Nurhidayah, E., Putra, P. P., & Nurtjahjaningtyas, I. (2022). Analisis perkuatan lereng akibat longsor di Desa Dompyong. *Rekayasa Sipil, 16*(1), 9–14.

Pramulandani, A., & Hamdhan, I. N. (2020). analisis stabilitas lereng dengan perkuatan geocell menggunakan metode elemen hingga (plaxis 2d). *RekaRacana: Jurnal Teknil Sipil, 6*(2), 86.

Riza, M., Herdiyan, C., & Surjo, A. (2018). reliabilitas metode finite elemen dan limit equilibrium pada analisis stabilitas bendungan. Proceeding 9th Indonesian Geotechnical Conference and 15th Annual Scientific Meeting, June.

Shobari, A. F., Mufti, I. J., Khoirullah, N., Zakaria, Z., Sophian, R. I., & Mulyo, A. (2019). Hubungan nilai koefisien gempa horizontal (kh) dengan nilai safety factor (fs) Daerah Cilengkrang, Jawa Barat. Padjadjaran *Geoscience Journal, 3*(4), 243–253.

Srivastava, L. S., & Chakrabortty, P. (2025). Probabilistic Seismic Slope Stability Analysis Using Limit Equilibrium and Finite Element Methods. Geotechnical and Geological Engineering, 43(5), 153. https://doi.org/10.1007/s10706-025-03113-2

Staubach, P., Machaček, J., Bienen, B., & Wichtmann, T. (2022). Long-term response of piles to cyclic lateral loading following vibratory and impact driving in water-saturated sand. Journal of Geotechnical and Geoenvironmental Engineering, 148(11), 04022097.

Wahab, D. A., Tohari, A., & Hamdhan, I. N. (2023). Pemodelan Numerikal Kestabilan Lereng Batulempung (Studi Kasus Ruas Jalan Sumedang-Cirebon Km 68 + 750). Jurnal Ilmu Dan Terapan Bidang Teknik Sipil, 29(2), 173–182. https://doi.org/10.14710/mkts.v29i2.53704

Wang, Y., Li, Y., & Chen, J. (2023). Comprehensive Analysis Method of Slope Stability Based on the Limit Equilibrium and Finite Element Methods and Its Application. *Open Journal of Civil Engineering, 13(*04), 555–571.

Wijaya, E. P., Wibowo, D. E., & Malik, A. (2024). Pengembangan Video Pembelajaran Pengujian Sondir Tanah untuk Mahasiswa Program Studi Pendidikan Teknik Sipil dan Perencanaan. *Jurnal Pendidikan Teknik Bangunan, 4*(1), 1–14.

Yan, R., Yu, H., Yang, D., Tang, H., & Zhang, Q. (2023). Shear strength and pore pressure characteristics of methane hydrate-bearing soil under undrained condition. International Journal of Hydrogen Energy, 48(33), 12240-12256.

Zeng, B., Zhang, D. W., Yang, S. S., Hou, J., Zhang, A. J., Cheng, C. H., & He, L. (2024, February). Performance enhancement of large diameter bored pile reinforced by cement-soil in clay under static and cyclic loadings. In Structures (Vol. 60, p. 105923). Elsevier.

Zhang, C., Lijun, S. U., Weizhi, C. H. E. N., & Jiang, G. (2021). Full-scale performance testing of bored piles with retaining walls in high cutting slope. Transportation Geotechnics, 29, 100563.

Zhou, J. J., Yu, J. L., Gong, X. N., & Yan, T. L. (2020). Field tests on behavior of pre-bored grouted planted pile and bored pile embedded in deep soft clay. Soils and Foundations, 60(2), 551-561.