Multiscenario Slope Stability Back-Analysis in Open-Pit Mining: A Case Study from Tanjung Enim, South Sumatra

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Abstract: *The landslide event on March 5, 2025, at 09:15 WIB was triggered by high-intensity rainfall lasting 5.95 hours, with a daily accumulation of 95.16 mm/day. The initial slope analysis showed a stable Factor of Safety (FoS) of 1.46 using the Morgenstern-Price method. However, since a landslide occurred in reality, a back analysis of slope stability was conducted to evaluate the failure mechanisms and contributing geotechnical parameters through engineering geological assessment, slope geometry modeling, and numerical simulations using Slide2 software. The Morgenstern-Price method was applied under various hydrological and dynamic loading scenarios to obtain the critical FoS value of the slope close to the actual landslide event. The 30-day cumulative rainfall infiltration scenario significantly reduced the FoS to 1.01 due to increased saturation in the middle and lower slope zones. The most critical condition occurred under the combined influence of haul load, seismic load, and rainfall infiltration, resulting in the lowest FoS of 0.99. These results indicate that the landslide was primarily triggered by extreme rainfall, which reduced the FoS below the slope stability threshold (FoS > 1.0) and did not meet the standards of SNI 8460:2017 and the Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 1827K/30/MEM/2018, which require FoS < 1.1 for overall slope stability.*

Keywords: Slope stability, back-analysis, open-pit mining, rainfall infiltration, dynamic loading

Introduction

Slope stability is one of the most crucial components in open-pit mining operations, as it directly affects worker safety, protects high-value mining equipment, and ensures the continuity of production. An unstable slope not only threatens operational efficiency but also poses serious risks to human safety and the environment. As emphasized by Hoek (1997), slope behavior is controlled by the complex interaction of several key factors, including geological structures, the strength and deformation characteristics of the rock mass, groundwater and hydrogeological conditions, as well as mining activities that may disrupt the natural equilibrium of slopes. The interrelation of these factors creates multidimensional challenges, requiring a holistic approach that integrates geotechnical and hydrogeological analysis. This approach aims to ensure a reliable slope design and to maintain safe slope configurations throughout the mine's lifespan.

In Indonesia, the importance of slope stability has been institutionalized through a regulatory framework. Minister of Energy and Mineral Resources Decree No. 1827K/ME/30/2018, for example, stipulates that the minimum acceptable Factor of Safety (FoS) under static conditions is 1.3, and under dynamic conditions is 1.1. This regulation underscores the need for rigorous slope design, appropriate engineering, and continuous monitoring to mitigate potential slope failures in mining operations. Compliance with these standards not only reflects the fulfillment of legal requirements but also demonstrates a commitment to operational safety, risk management, and sustainable mining practices.

Indonesia itself is endowed with abundant coal reserves, making it one of the world's largest coal producers and exporters. The energy sector relies heavily on this resource, both for domestic consumption and international trade. One of the state-owned mining companies that plays a vital role in this sector is PT X, which holds a central role in meeting national coal demand. The company's primary mining operations are located in Tanjung Enim, Muara Enim Regency, South Sumatra, a region well known for its extensive coal reserves. The company employs open-pit mining methods, a technique that involves large-scale stripping of overburden to expose economically valuable coal seams.

Nevertheless, the open-pit mining method inevitably creates high and steep slopes. Without adequate engineering control, these slopes are prone to instability, which can eventually trigger landslides or slope failures. The geological and geomorphological conditions in Muara Enim further increase this vulnerability. The latest data released by the Central Statistics Agency (BPS) in 2024 recorded 61 landslide incidents in Muara Enim between 2021 and 2024. This fact highlights the region's high susceptibility, caused not only by natural conditions but also by increasing anthropogenic activities related to intensive mining operations and land-use changes.

Considering these conditions, a comprehensive slope stability analysis is of paramount importance, particularly in strategic mining zones. Such analysis must integrate field investigations, laboratory testing, numerical modeling, and groundwater monitoring to accurately depict the geotechnical behavior of slopes under various conditions. By adopting a multidisciplinary and proactive approach, mining operations can be more effective in anticipating potential failure mechanisms, optimizing slope design, and implementing appropriate mitigation strategies. Ultimately, ensuring slope stability in open-pit mining is not merely a technical requirement, but a fundamental aspect of achieving safe, efficient, and sustainable mining practices in Indonesia's coal sector.

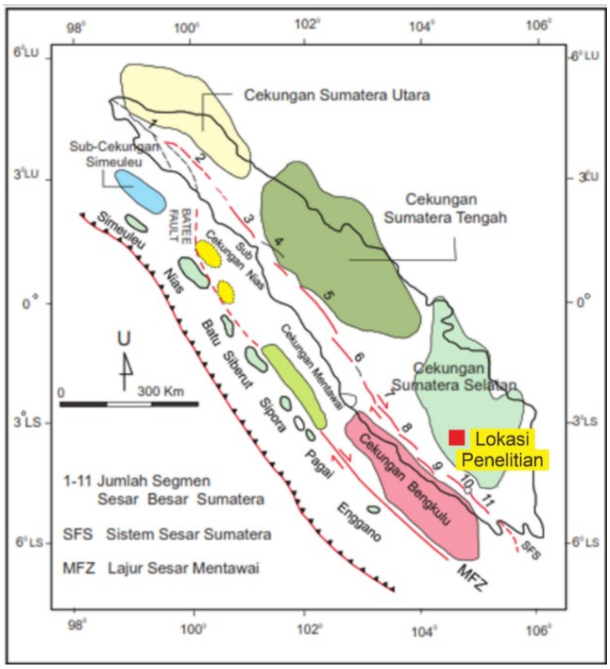
Literature Review

a. Geological Setting

Physiographically, the study area is situated on the eastern flank of the Barisan Mountains, representing the westernmost margin of the South Sumatra Basin. The South Sumatra Basin is a Tertiary-aged sedimentary basin with a predominant northwest–southeast orientation. This basin is structurally bounded by the Semangko Fault and the Barisan Mountains to the southwest, the Sunda Shelf to the northeast, the Lampung High to the southeast which separates it from the Sunda Basin, and the Dua Belas Mountains and Tiga Puluh Mountains to the northwest which define the boundary with the Central Sumatra Basin (Wisnu et al., 1997). The tectonic framework of the South Sumatra Basin is strongly influenced by the regional stress regime associated with the ongoing subduction of the Indo-Australian Plate beneath the Eurasian Plate along the Sunda Trench, offshore western Sumatra and southern Java. This subduction system has been active since the Late Oligocene and continues to shape the geodynamic evolution of the region. The resulting compressional forces have given rise to complex structural patterns within the basin, dominated by fault systems and graben structures that generally trend north–northwest to south–southeast. Depositional processes in the basin are controlled by major fault activities trending northwest–southeast and north–south. During the Miocene to Plio–Pleistocene, episodes of basin inversion caused reactivation of pre-existing fault systems, generating uplift and deformation that significantly influenced sedimentary facies distribution and basin architecture. The development of half-grabens and syn-depositional faulting provided accommodation space for thick successions of clastic and coal-bearing strata, which today form an important part of the basin's stratigraphy and economic resources.

Stratigraphically, the South Sumatra Basin comprises a succession of Paleogene to Neogene sedimentary formations deposited in fluvial, deltaic, and shallow marine environments. These deposits unconformably overlie pre-Tertiary basement rocks composed of metamorphic and igneous complexes associated with the Barisan Orogeny. The interplay between tectonics, subsidence, and sediment supply has produced a heterogeneous stratigraphic framework that records multiple phases of basin evolution.

In summary, the geological setting of the South Sumatra Basin is characterized by its position as a foreland basin adjacent to the Barisan Mountains, its tectonic complexity associated with subduction and inversion events, and its rich sedimentary record that reflects the dynamic interplay of structural and depositional processes throughout the Tertiary.



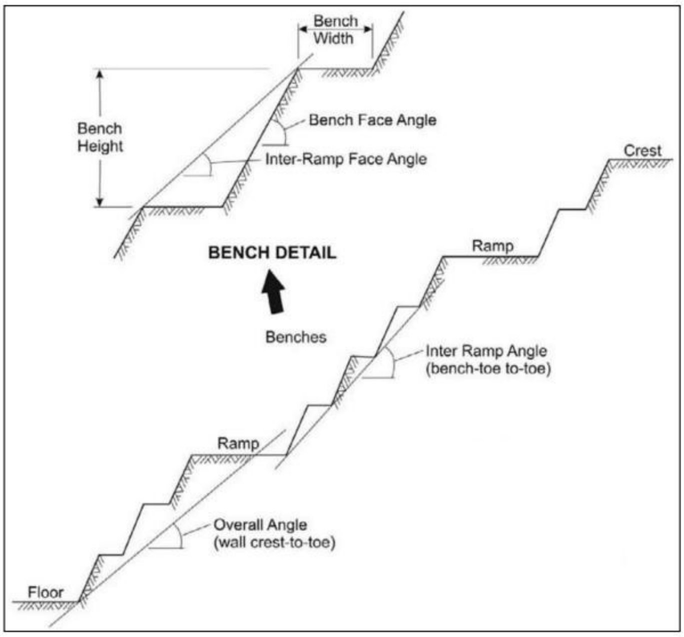
Source: Dedi, 2021, modified from Gafoer, 1985; Pulunggono, 1985

Figure 1: Physiographic map of the study area within the South Sumatra Basin

b. Slope Stability

Slope stability plays a fundamental role in open-pit mining operations, as it is closely tied to the safety of workers, the protection of valuable equipment, and the overall continuity of production activities. Hoek (1997) emphasizes that the stability of a slope is governed by a combination of geological structures, the mechanical properties of the rock mass, hydrogeological settings, and mining-induced disturbances that may disrupt the natural equilibrium of forces along the slope. Landslides, as defined by Cruden (1991), refer to the downslope movement of soil, debris, or rock material. Similarly, Skempton and Hutchinson (1969) describe mass movement as the downward displacement of slope-forming materials, triggered by the loss of their inherent stability.

Within the context of mining, designing stable open-pit slopes is a central element of mine planning and operations, since it not only ensures safe working conditions but also improves efficiency and reduces potential economic losses. While most mining companies adopt internal guidelines for slope design, modifications are often required to adapt to specific geotechnical, geological, and hydrogeological conditions at each mining location. To describe slope geometry, several standard technical terms are widely used, including bench height, bench width, bench face angle, inter-ramp angle, and overall slope angle, as outlined by Read and Stacey (2009).



Source: Read and Stacey (2009)

Figure 2: Terms used in open-pit mine slopes

According to the Regulation of the Ministry of Energy and Mineral Resources (ESDM) No. 1827-K/30/MEM/2018, the required safety factor for slope stability analysis is presented in Table II.1. In this research, several design trials were conducted to determine the most effective slope geometry. The procedure involved adjusting the slope angle and bench width through both incremental increases and decreases of these parameters. From the simulations, a suitable configuration was identified where the combination of slope angle and bench width fulfilled the safety factor criteria set by the regulation. The analysis was performed under the assumption of a disturbance factor of 1.0, ensuring the obtained slope design adhered to applicable engineering and safety standards.

Table 1: Safety Factor Values and Probability of Slope Failure in Open-Pit Mines

		Acceptable criteria		
Slope type	**Failure severity**	**Static Safety Factor (min)**	**Dynamic Safety Factor (min)**	**Probability of Failure (max) (PoF ≤ 1)**
Single slope	Low - High	1,1	None	25-50%
Inter-ramps	Low	1,15-1,2	1,0	25%
	Medium	1,2-1,3	1,0	20%
	High	1,2-1,3	1,1	10%
Overall slope	Low	1,2-1,3	1,0	15-20%
	Medium	1,3	1,05	10%
	High	1,3-1,5	1,1	5%

Source: Regulation of the Ministry of Energy and Mineral Resources (ESDM) Number 1827-K/30/MEM/2018

c. Landslide

A landslide refers to the downslope movement or displacement of rock, debris, and soil masses, as defined by Cruden (1991). Skempton and Hutchinson (1969) further describe it as the movement of soil or rock that composes a slope, triggered by the disturbance of the stability of slope-forming materials. Meanwhile, Varnes (1978) provides a classification system for landslides, distinguishing them based on the type of material involved, whether dominated by rock or soil. These definitions highlight that landslides represent both a process of mass movement and a hazard influenced by geological and geotechnical conditions.

Table 2: Types of Landslide Movements and Materials

Type of movement		Type of material		
		Rock	Soil	
			Coarse-grained (Debris)	Fine-grained (Earth)
Topples		Rock Topple	Debris topple	Earth topple
Falls		Rock fall	Debris fall	Earth fall
Flows		Rock flow	Debris flow	Earth flow
Lateral spreads		Rock spread	Debris spread	Earth spread
Slide	Rotasional	Rock slide	Debris slide	Earth slide
	Translasional			
Complex		Combination of movements		

Source: the classification of (Varnes, 1978)

Methodology

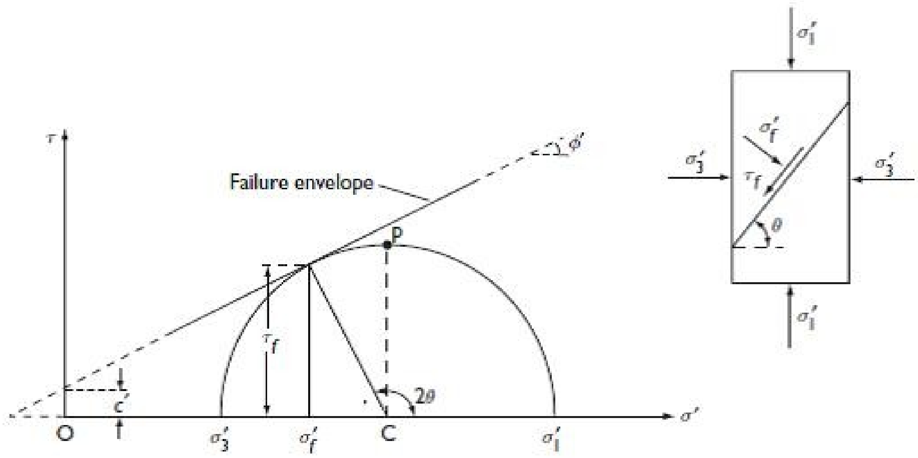
The research methodology comprises field observations and laboratory testing, preceded by a literature review to establish the theoretical basis of slope stability and back analysis methods for landslides (Hoek, 2006; Wyllie & Mah, 2005). Primary data collected include lithological descriptions from direct field observations, documentation of the current visual condition of slopes, and the physical characteristics of rocks from the Muaraenim Formation. Meanwhile, secondary data consist of laboratory test results of rock mechanics parameters, geological drilling data, topographic information, mining equipment specifications, seismic zonation maps, and relevant historical rainfall data (Bock, 2006). All of these data serve as input for slope stability modeling using the back analysis approach to evaluate the limiting conditions of existing slopes with respect to potential failure.

Sensitivity analysis was employed to assess the influence of variations in geotechnical parameters on the slope safety factor (SF) in order to identify the most critical parameters controlling slope stability (Hoek, 2006). The evaluation was conducted using the geotechnical software Slide2, based on the Limit Equilibrium Method (LEM), which applies the principles of force and moment equilibrium (Duncan et al., 2014). The results provide insights into the sensitivity of the SF to each parameter and form the basis for more effective landslide risk mitigation planning (Wyllie & Mah, 2005).

Back analysis is a retrospective approach used to evaluate the shear strength parameters of rock or soil at the time of slope failure, particularly cohesion (c) and internal friction angle (ϕ), to obtain realistic parameter estimates (Duncan et al., 2014; Nassirzadeh et al., 2024). The commonly applied material failure model in this analysis is the Mohr-Coulomb criterion, which relates normal stress and shear stress to the shear strength limit of the material, based on laboratory or empirical parameters (Hoek, 2006; Hudson & Harrison, 2005; Jaeger et al., 1979). This criterion states that failure occurs when the combination of shear stress and normal stress reaches or exceeds the shear strength limit of the material, expressed in the equation:

$$\tau = c + \sigma n \tan\phi$$

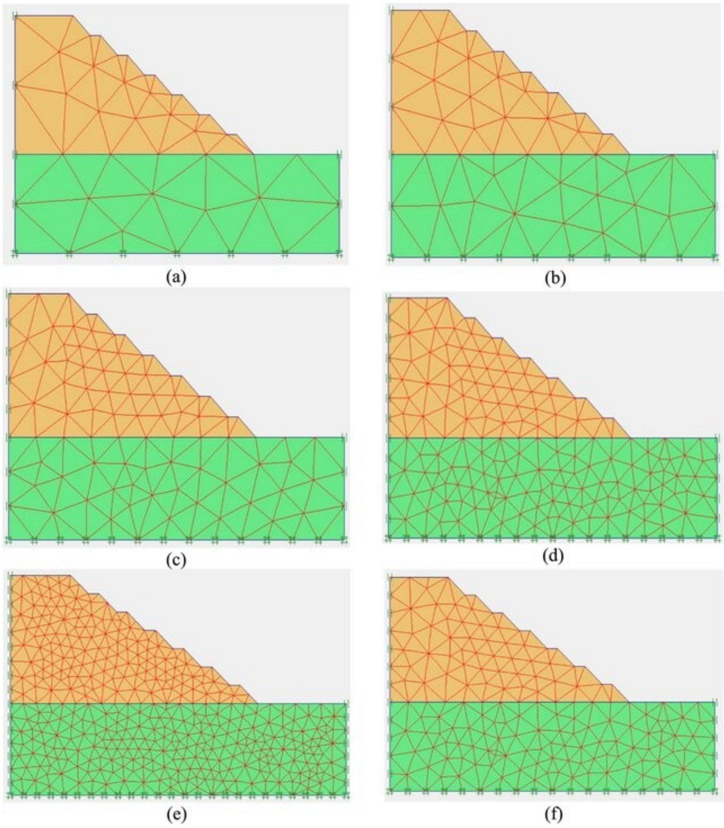
The Mohr-Coulomb criterion graph is illustrated as a straight line in the Mohr diagram, representing the failure envelope of a material (Figure 3).



Source: Jaeger et al., 1979

Figure 3: Mohr-Coulomb failure diagram

The Finite Element Method (FEM) is a numerical approach widely applied in geotechnical analysis to evaluate soil deformation, slope stability, and soil–structure interaction (Zienkiewicz et al., 2010). The fundamental principle of this method is the discretization of a continuous domain into small elements (mesh), which are interconnected by nodes where the equilibrium equations are formulated (Zienkiewicz et al., 2010). Each element is assigned material properties and specific boundary conditions, thereby enabling a realistic simulation of the mechanical response of soil under various loading conditions.

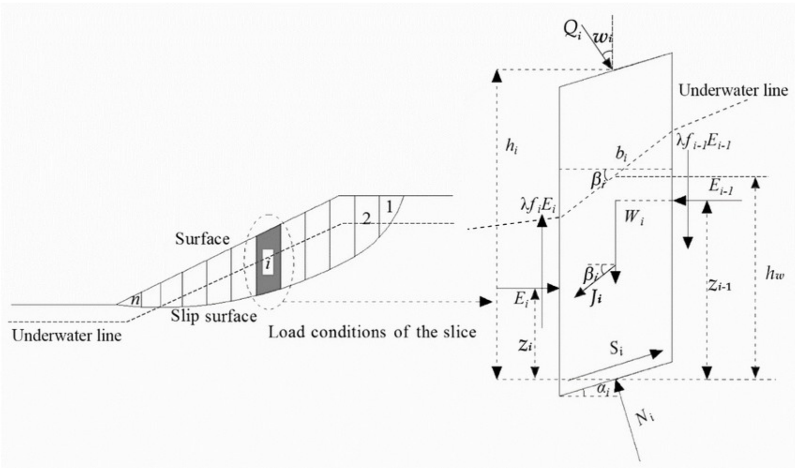


Source: Hosseini and Fereidooni, 2025

Figure 4: Illustration of finite element mesh

The Morgenstern–Price method represents one of the most advanced and widely accepted techniques within the framework of the Limit Equilibrium Method (LEM) for slope stability analysis. Unlike simpler approaches, this method simultaneously satisfies both force equilibrium and moment equilibrium along the assumed slip surface, making it more rigorous and reliable (Morgenstern and Price, 1965). The analysis begins by dividing the potential sliding mass into several slices. Each slice is then examined in terms of acting forces, including normal and shear stresses, pore water pressures, external loads, as well as interslice forces that influence the overall stability (Zhang et al., 2021). This slice-based approach allows for a detailed representation of slope conditions, accommodating variations in geometry, material properties, and groundwater levels.

An important advantage of the Morgenstern–Price method is its flexibility in incorporating different interslice force functions, which provides a more realistic approximation of slope behavior compared to methods that assume simplified force distributions. This capability enhances the accuracy of the calculated Factor of Safety (FoS), particularly in complex geological settings or slopes influenced by groundwater conditions. Moreover, the method is highly adaptable and has been integrated into modern numerical software, enabling engineers to perform advanced stability analyses efficiently.



Source : Morgenstern and Price, 1965

Figure 5: Principle of Calculation and Model of the Morgenstern–Price Method

Results and Discussion

The study area is dominated by hills and lowlands with slopes ranging from gentle to steep, according to Van Zuidam (1985). In addition, open-pit mining activities in the region have caused changes in landforms, including the formation of artificial slopes and mining voids. In general, the geomorphology of the study area is influenced by several processes, including both endogenic and exogenic forces. The hilly morphology is predominantly composed of rocks with high to moderate resistance, located in the northeastern part of the study area, while the lowland areas are mainly underlain by rocks with moderate to low resistance, covering almost the entire region. At the landslide location, the slopes formed because of excavation and mining activities are dominated by gentle to steep slopes (Figure 6).

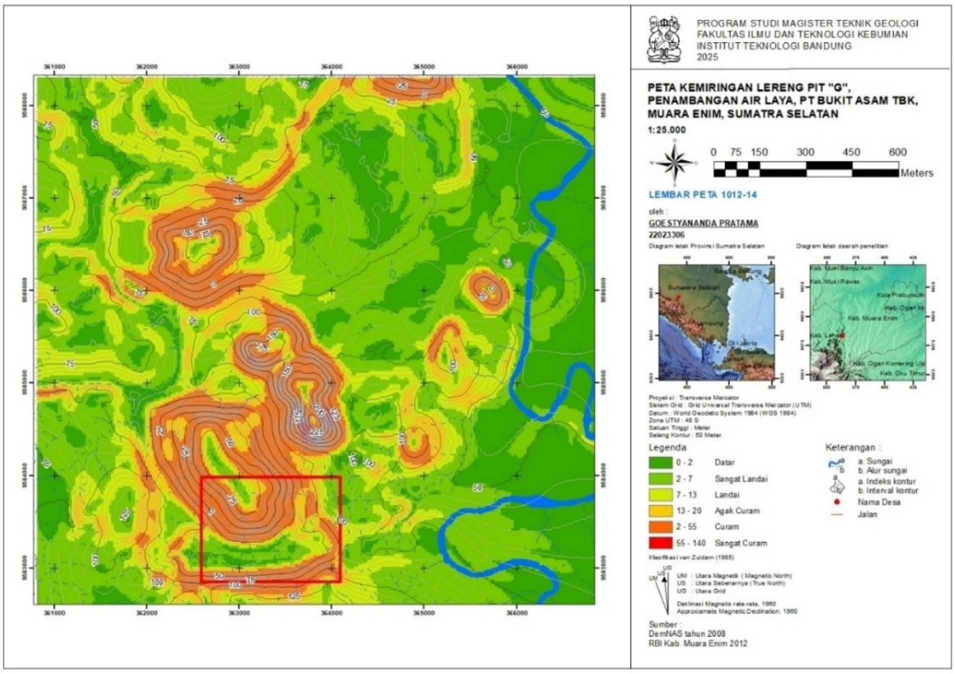


Figure 6: Slope map of the study area

The landslide event was recorded on March 5, 2025, at 09:15 WIB, with high-intensity rainfall occurring from 06:30 WIB to 12:27 WIB, with a total duration of about 5.95 hours and a daily rainfall accumulation of 95.16 mm/day. In slope stability analysis, groundwater conditions are one of the most influential geotechnical parameters affecting the FoS value. Therefore, it is important to include saturation variation scenarios as part of the back-analysis approach, including partially drained conditions (Duncan et al., 2014). Slope stability analysis was carried out to show the initial condition of the slope before the landslide occurred (Figure 7), using rock engineering parameters, and the results obtained showed that the FoS was 1.46 under stable conditions using the Morgenstern-Price method, but in reality the slope experienced a landslide. Therefore, back-analysis needs to be carried out to determine the geotechnical parameters until an FoS ≈ 1.1 is obtained to identify the actual critical condition of the slope at the time of the landslide.

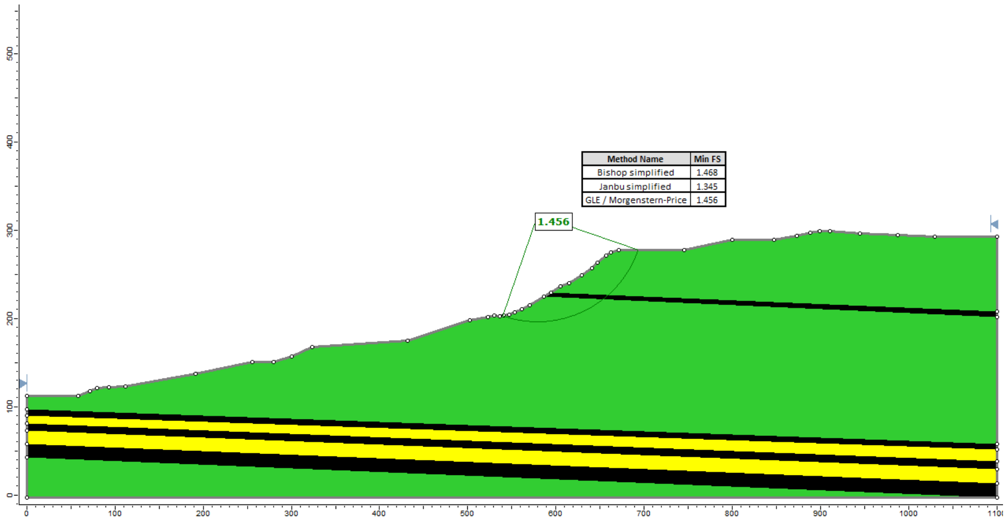


Figure 7: The cross-sectional model under normal slope conditions has a factor of safety (FoS) of 1.46, calculated using the Morgenstern-Price method.

Dynamic condition analysis involving seismic loads is applied to account for the influence of earthquakes as an external factor that may trigger slope failures. Seismic forces generated during an earthquake alter the balance between driving shear forces and resisting forces along the slip surface, potentially reducing slope stability (Kramer, 1996). In slope stability studies, these seismic loads are incorporated into the Limit Equilibrium Method (LEM) to evaluate the reduction of the Factor of Safety (FoS) under earthquake scenarios. This approach provides a more realistic assessment of slope performance in seismically active regions.

Based on the site classification regulated in SNI 1726:2019, the soil conditions at the study location fall into site class SD (stiff soil). This category is determined by the Vs30 value ranging from 175–350 m/s, characterized by fine-grained soils, stiff clays, or dense sands, which generally exhibit higher deformation compared to hard rock. The interpretation results from the average shear wave velocity (Vs30) map published by the Geological Agency, Ministry of Energy and Mineral Resources (2022), indicate that the Muara Enim region, where the study was conducted, is predominantly within this Vs30 range, thus corresponding to the SD category. Therefore, earthquake load calculations in the slope stability analysis at this location must consider the seismic amplification factor, which is greater than that of hard rock conditions.

Tabel 3: The site class coefficient FPGA

Site Class	PGA ≤ 0,1	PGA = 0,2	PGA = 0,3	PGA = 0,4	PGA = 0,5	PGA ≥ 0,6
SA	0,8	0,8	0,8	0,8	0,8	0,8
SB	0,9	0,9	0,9	0,9	0,9	0,9
SC	1,3	1,2	1,2	1,2	1,2	1,2
SD	1,6	1,4	1,3	1,2	1,1	1,1
SE	2,4	1,9	1,6	1,4	1,2	1,1
SF	SS (a)					

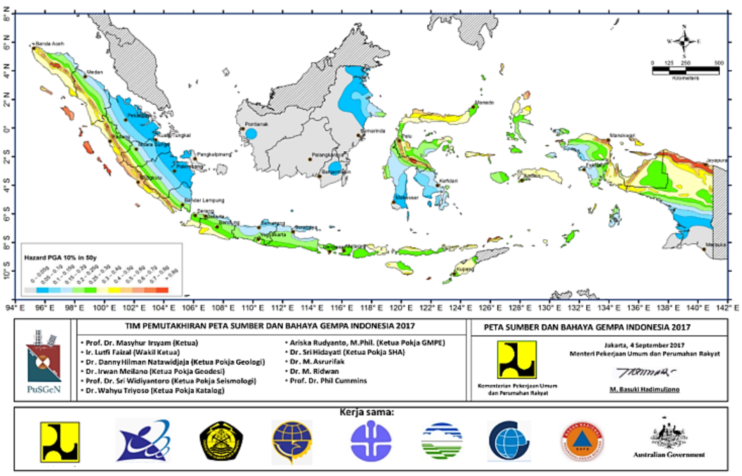
Source : SNI 1726:2019

$$PGAm = FPGA \times PGA$$

PGAm = MCE*G* peak ground acceleration adjusted for the influence of site classification
PGA = mapped peak ground acceleration as shown Figure 8
FPGA = site coefficient from Table 3

$$PGAm = FPGA \times PGA$$
$$PGAm = 0{,}15 \times 1{,}6$$
$$PGAm = 0{,}24$$

$$Kh = PGAm \times 0{,}5$$
$$Kh = 0{,}24 \times 0{,}5$$
$$\mathbf{Kh = 0{,}12}$$



Source : Ministry of Public Works and Housing, 2017

Figure 8: Map of peak horizontal rock acceleration with a 10% probability of exceedance in 50 years of 0.15 – 0.2 g

The influence of other dynamic loads may also result from the operation of heavy equipment on the slope, specifically the HDD 785-5 haul trucks, as stated in the *Komatsu Specifications Handbook: Off-Highway Dump Trucks*, which are used in mining operations at PT X. The distribution load exerted by the haul truck is determined in units of kPa or kN/m², based on the technical specifications of the HDD 785-5 dump truck.

Tabel 4: Specifications and weight distribution of the haul truck HDD 785-5 at the study area,

Item/Description	HDD 785-5
Max. Gross vehicle weight	166.000 kg
Weight Distribution (front : rear)	33% : 67%
Contact Area of Supporting Tire	0.444 m^2
sW (67% x *vehicle weight*)	111,233 kg
F (W × 9.81)	1.091,13 kN
Distribution Load	614.5 kPa

Source: Handbook Komatsu Specifications: Off-Highway Dump Trucks

The slope stability analysis was conducted to evaluate the impact of 30-day cumulative rainfall under conditions where the upper one-third of the slope experienced drying and a 25% drainage system was applied. Rainfall infiltration was simulated using the Steady State Finite Element Method combined with Transient Groundwater Modeling, with rainfall data covering the period from February 4 to March 5, 2025 (Tabel 5).

Tabel 5: Thirty-Day Rainfall Record at the Research Site

Date	Rainfall (mm)	Rainfall Duration (hours)	Frequency	Cumulative Rainfall
4 February 2025	2,5	0,71667	1	2,5
5 February 2025	0,23	0,2	1	2,73
6 February 2025	22,29	7,96667	2	25,02
7 February 2025	22,39	5,28333	3	47,41
8 February 2025	7,56	7,05	2	54,97
9 February 2025	0	0	0	54,97
10 February 2025	0,9	0,71667	2	55,87
11 February 2025	0	0	0	55,87
12 February 2025	0	0	0	55,87
13 February 2025	49,09	3,38333	1	104,96
14 February 2025	41,92	1,51667	1	146,88
15 February 2025	0,54	0,75	1	147,42
16 February 2025	9,96	1,43333	3	157,38
17 February 2025	0,12	2	1	157,50
18 February 2025	13,56	5	1	171,06
19 February 2025	3,1	6,78333	4	174,16
20 February 2025	41,25	3,1	2	215,41
21 February 2025	13,67	3,85	2	229,08
22 February 2025	11,37	4,33333	2	240,45

23 February 2025	27,26	5,46667	4	267,71
24 February 2025	24,11	4,85	1	291,82
25 February 2025	2,41	2,58333	2	294,23
26 February 2025	4,9	3,63333	2	299,13
27 February 2025	13,95	4,93333	2	313,08
28 February 2025	0	0	0	313,08
1 March 2025	4,43	2,3	2	317,51
2 March 2025	22,44	3,8	2	339,95
3 March 2025	77,71	8,33333	2	417,66
4 March 2025	7,74	3,3	2	425,40
5 March 2025	95,16	5,95	1	520,56
Total	520,56	99,2333	49	5899,64

Source: Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2025

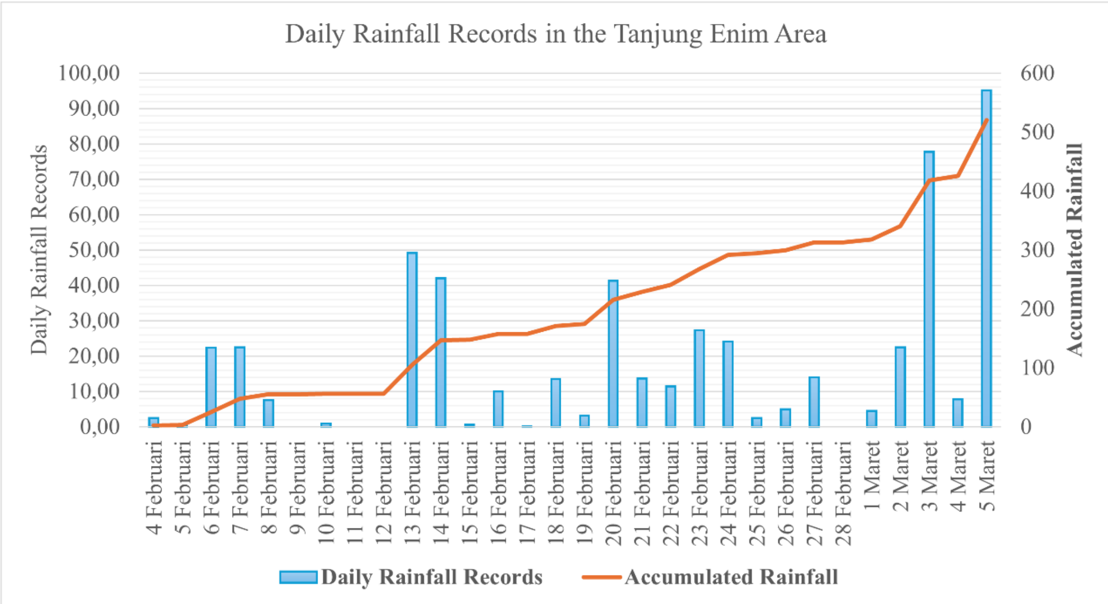


Figure 9: Cumulative Rainfall in the Study Area from February 4 to March 5, 2025

a. Normal scenario with partially drain conditions

The partially drain scenario represents a slope condition with a higher degree of saturation compared to the previous scenario, where only the half of the slope is assumed to be unsaturated, while the remaining two-thirds are saturated due to a possible rise in the groundwater table from high rainfall or an ineffective drainage system **(Wyllie & Mah, 2005)**. The numerical simulation in this condition was carried out without considering external loads such as heavy equipment activity, seismic load, or rainfall, and the factor of safety (FoS) of 1.2 was obtained using the Morgenstern-Price method (Figure 10a). This value indicates that the slope is still relatively stable under the initial condition and serves as a reference for comparing the influence of additional loads in subsequent scenarios.

b. Mining haul truck load scenario with partially drain conditions

In this scenario, the slope condition was simulated with an additional dynamic load of 614.50 kN/m² from mining haul truck activity on the slope surface. Slope stability analysis using the Morgenstern-Price method showed that the slope's factor of safety (FoS) decreased to 1.06 (Figure 10b), indicating a critical condition and potential failure if the additional load continues without any control measures.

c. Seismic load scenario with partially drain conditions

In the next scenario, slope stability analysis was carried out under the influence of seismic load with one-third of the upper slope unsaturated and a 25% drainage condition. The earthquake acceleration used was 0.12 g, referring to the Peak Ground Acceleration (PGA) Map for bedrock with a 10% probability of exceedance in 50 years, according to the 2017 Indonesian Earthquake Map issued by the Ministry of Public Works and Housing (PUPR, 2017). The analysis results using the Morgenstern-Price method showed a slope factor of safety (FoS) of 1.16, indicating that the slope remains stable against the seismic load influence (Figure 10c).

d. 30-day rainfall scenario with partially drain conditions

In this scenario, slope stability analysis was conducted under the influence of accumulated rainfall over 30 days (from February 4 to March 5, 2025), with one-third of the upper slope unsaturated and a 25% drainage condition. Rainfall infiltration simulation was modeled using the Steady-State Finite Element Method and Transient Groundwater Modeling in Slide2 software. The simulation results showed increased saturation in the middle and lower zones of the slope, which significantly reduced stability, with an FoS of 1,01 based on the Morgenstern-Price method (Figure 10d). This value indicates that long-term rainfall has a major role in decreasing slope stability to an unstable condition.

e. Combined overall scenario with partially drain conditions

This scenario represents the most critical condition, where all loads affecting slope stability were modeled simultaneously, namely the mining haul truck load, seismic load, and 30-day rainfall infiltration prior to the landslide event on February 4 – March 5, 2025. The analysis results showed that the combination of all factors caused a significant reduction in the FoS to 0,99, placing the slope in an unstable condition (Figure 10e).

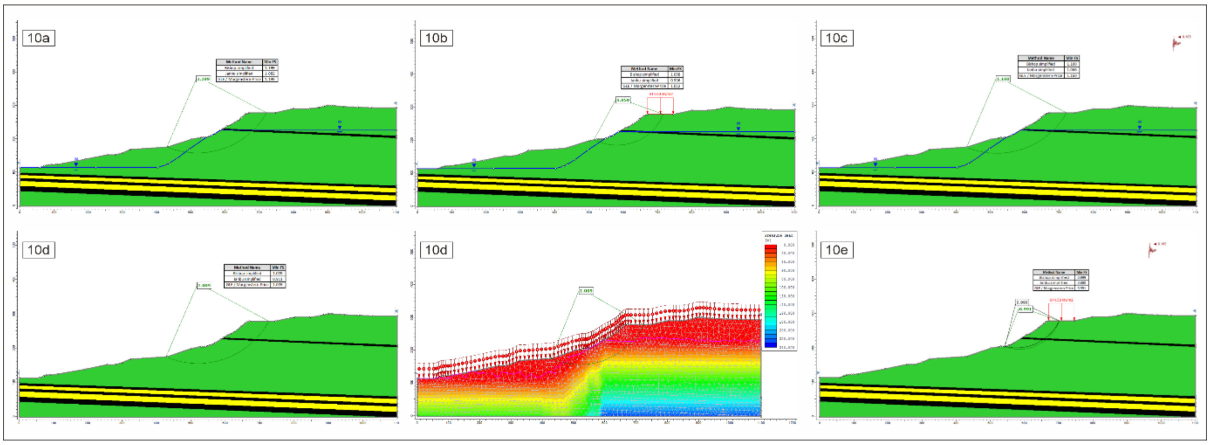


Figure 10: Results of slope stability analysis under: a) normal condition, b) mining haul truck load, c) seismic load, d) 30-day rainfall, and e) combined overall scenarios.

Conclusion

Based on the analysis results, the back-analysis of slope stability at the study site demonstrates that extreme rainfall over a 30-day period (February 4 – March 5, 2025) was the primary factor contributing to slope instability and the subsequent landslide event on March 5, 2025. Cumulative rainfall infiltration significantly reduced the factor of safety (FoS) to 1.01, and when combined with other loading scenarios, the FoS further decreased to 0,99, indicating an unstable condition. Compared to the influence of dynamic loads from haul truck operations and seismic forces, long-term and high-intensity rainfall exerted the most critical impact on slope stability. These findings emphasize that rainfall-induced saturation is the dominant triggering mechanism of slope failure in the study area.

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