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FACTOR OF SAFETY AND PROBABILITY OF FAILURE ASSESSMENT OF ROCK SLOPES IN ARTISANAL KAOLIN MINE USING LIMIT EQUILIBRIUM METHOD AND MONTE CARLO SIMULATION

PENILAIAN FAKTOR KEAMANAN DAN PROBABILITAS KEGAGALAN LERENG BATU DI TAMBANG KAOLIN TRADISIONAL MENGGUNAKAN METODE KESEIMBANGAN BATAS DAN SIMULASI MONTE CARLO

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Abstract

This study aims to evaluate the stability of three rock slopes in an artisanal kaolin mine in Semin, Gunungkidul, Yogyakarta, Indonesia, using deterministic and probabilistic approaches, and to identify the geotechnical parameters most influencing slope stability. The evaluation is conducted in compliance with Indonesian Mining Regulation (Kepmen ESDM No. 1827 K/30/MEM/2018) to provide quantitative geotechnical evidence for a mine that has been operated without prior formal geotechnical assessment. Field data were collected using the scanline method to characterize rock mass discontinuities. Laboratory tests comprising direct shear and physical properties tests were conducted to determine cohesion (c), friction angle (ϕ), and unit weight (γ) for each slope. Seismic coefficient (ks = 0,0913) was incorporated as a dynamic loading parameter. Slope stability was analyzed using the General Limit Equilibrium (GLE) method to obtain the deterministic Factor of Safety (FoS). Monte Carlo simulation (N = 10.000 iterations) was applied to determine the Probability of Failure (PoF), coefficient of variation of FoS (CoV), and reliability index (β). Sensitivity analysis was performed to quantify the contribution of each geotechnical parameter to FoS reduction. Results show that FoS values ranged from 2,019 (Slope III) to 10,55 (Slope II), all exceeding the regulatory minimum of 1,1. The PoF was 0,00% for all three slopes, well below the maximum allowable limit of 25%, with reliability indices ranging from 5,70 to 31,38. The CoV of FoS ranged from 3% to 9%, indicating low dispersion in stability outcomes despite parameter variability. Sensitivity analysis identified cohesion as the most dominant parameter in Slopes I and II, contributing 28% and 31% to FoS reduction respectively, while Slope III exhibited near-equal contributions from cohesion (20%) and friction angle (21%), reflecting its lower shear strength conditions. All three slopes satisfy the acceptance criteria of Kepmen ESDM No. 1827 K/30/MEM/2018 under current geotechnical and geometric conditions. The combined deterministic-probabilistic approach provides a more

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comprehensive slope safety assessment than deterministic analysis alone and is recommended for application in artisanal kaolin mining operations. Cohesion is identified as the critical parameter to be monitored and preserved to maintain slope stability.

Keywords : Factor of Safety, Probability of Failure, Limit Equilibrium Method, Kaolin.

Abstrak

Penelitian ini bertujuan untuk mengevaluasi stabilitas tiga lereng batuan di tambang kaolin artisanal di Semin, Gunungkidul, Yogyakarta, Indonesia, menggunakan pendekatan deterministik dan probabilistik, serta untuk mengidentifikasi parameter geoteknik yang paling berpengaruh terhadap stabilitas lereng. Evaluasi dilakukan sesuai dengan Peraturan Pertambangan Indonesia (Kepmen ESDM No. 1827 K/30/MEM/2018) untuk memberikan bukti geoteknik kuantitatif untuk tambang yang telah beroperasi tanpa penilaian geoteknik formal sebelumnya. Data lapangan dikumpulkan menggunakan metode scanline untuk mengkarakterisasi diskontinuitas massa batuan. Uji laboratorium yang terdiri dari uji geser langsung dan sifat fisik dilakukan untuk menentukan kohesi (c), sudut gesekan (ϕ), dan berat jenis (γ) untuk setiap lereng. Koefisien seismik (ks = 0,0913) dimasukkan sebagai parameter pembebanan dinamis. Stabilitas lereng dianalisis menggunakan metode General Limit Equilibrium (GLE) untuk mendapatkan Faktor Keamanan (FoS) deterministik. Simulasi Monte Carlo (N = 10.000 iterasi) diterapkan untuk menentukan Probabilitas Kegagalan (PoF), koefisien variasi Faktor Keamanan (FoS) (CoV), dan indeks keandalan (β). Analisis sensitivitas dilakukan untuk mengukur kontribusi setiap parameter geoteknik terhadap pengurangan FoS. Hasil menunjukkan bahwa nilai FoS berkisar dari 2,019 (Lereng III) hingga 10,55 (Lereng II), semuanya melebihi minimum peraturan sebesar 1,1. PoF adalah 0,00% untuk ketiga lereng, jauh di bawah batas maksimum yang diizinkan sebesar 25%, dengan indeks keandalan berkisar dari 5,70 hingga 31,38. CoV FoS berkisar dari 3% hingga 9%, menunjukkan dispersi yang rendah dalam hasil stabilitas meskipun terdapat variabilitas parameter. Analisis sensitivitas mengidentifikasi kohesi sebagai parameter paling dominan pada Lereng I dan II, yang masing-masing berkontribusi 28% dan 31% terhadap pengurangan Faktor Keamanan (FoS), sedangkan Lereng III menunjukkan kontribusi yang hampir sama dari kohesi (20%) dan sudut gesekan (21%), yang mencerminkan kondisi kekuatan gesernya yang lebih rendah. Ketiga lereng tersebut memenuhi kriteria penerimaan Kepmen ESDM No. 1827 K/30/MEM/2018 dalam kondisi geoteknik dan geometris saat ini. Pendekatan deterministik-probabilistik gabungan memberikan penilaian keamanan lereng yang lebih komprehensif daripada analisis deterministik saja dan direkomendasikan untuk diterapkan dalam operasi penambangan kaolin skala kecil. Kohesi diidentifikasi sebagai parameter kritis yang harus dipantau dan dijaga untuk mempertahankan stabilitas lereng.

Kata Kunci : Faktor Keamanan, Probabilitas Kegagalan, Metode Keseimbangan Batas, Kaolin.

1. INTRODUCTION

Slope stability is a fundamental aspect of mining safety that directly determines the operational continuity and human safety of mining activities. Slope failures in mining environments can result in severe economic losses, environmental damage, and fatalities (Le Roux et al., 2025; Sdvyzhkova et al., 2022) in artisanal and small-scale mining (ASM) operations, this risk is considerably amplified by the absence of formal geotechnical assessment prior to slope construction, as evidenced by documented slope instability cases in Indonesian mining areas where factor of safety values as low as 0.38–0.64 have been recorded due to inadequate slope geometry design (Alfat et al., 2019; Mgiba and Rupprecht, 2023; Saputra et al., 2024). The conventional deterministic approach using Factor of Safety

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(FoS) through the Limit Equilibrium Method has been widely applied and proven effective in identifying slope conditions and informing slope geometry optimization in various Indonesian and global mining contexts (Alfat et al., 2019; Anarta et al., 2025; Bezie et al., 2024), suggesting that slope stability can be evaluated through fixed representative values of geotechnical parameters. However, deterministic methods inherently neglect the variability and uncertainty of geotechnical parameters such as cohesion, friction angle, and unit weight, potentially misrepresenting actual slope safety conditions; furthermore, the application of probabilistic slope stability analysis incorporating Probability of Failure (PoF) remains limited in artisanal kaolin mining operations, particularly within Indonesia's tropical geological setting where geotechnical data scarcity further compounds the uncertainty of slope behavior (Abdulai and Sharifzadeh, 2021; Torres et al., 2022). The General Limit Equilibrium (GLE) method combined with Monte Carlo simulation provides a rigorous and well-established framework for integrated deterministic-probabilistic slope stability assessment (Alok et al., 2024; Vecci and Sayão, 2026), applicable to the three rock slopes at an artisanal kaolin mine in Semin, Gunungkidul, Yogyakarta, Indonesia. Slopes that have been excavated conventionally without prior geotechnical study and where FoS and PoF evaluations against Indonesian Mining Regulation (Kepmen ESDM No. 1827, 2018) are critically needed to ensure miner safety and regulatory compliance. This study therefore contributes a quantitative, regulation-compliant probabilistic slope stability assessment for artisanal kaolin mining by bridging the gap between formal geotechnical engineering practice and artisanal mining operations, while providing a replicable framework that can serve as a practical reference for slope safety evaluation in similar small-scale mining environments across Indonesia and the broader tropical region.

Kaolin mining in Karangsari Village, Semin District, Gunungkidul Regency, represents an artisanal operation where slope design is conducted empirically without formal geotechnical analysis, creating uncertainty regarding actual slope stability conditions. The primary problem addressed in this study is the absence of quantitative slope stability data (both deterministic and probabilistic) for the three existing rock slopes at this mine. This study therefore addresses the following questions: (1) What are the FoS and PoF values of each slope under current geotechnical and geometric conditions based on the GLE method and Monte Carlo simulation? (2) Which geotechnical parameters most significantly influence slope stability at this site? The study aims to determine the FoS and PoF of each slope, evaluate compliance with Kepmen ESDM No. 1827 K/30/MEM/2018, and identify the most sensitive parameters through sensitivity analysis. Theoretically, this study contributes to the growing body of knowledge on probabilistic slope stability analysis in ASM operations in tropical geological settings. Practically, the results provide mine operators and regulators with quantitative geotechnical data to support evidence-based slope design and monitoring decisions in artisanal kaolin mining environments.

Several previous studies have investigated slope stability and rock mass characterization in kaolin and small-scale mining contexts in Indonesia. At the same study location, Rianse et al. (2025) characterized the weathering degree of the rock mass at the Semin, Gunungkidul artisanal kaolin mine using petrographic analysis and Uniaxial Compressive Strength (UCS) testing. Their study identified three weathering classes in the Altered Mudrock lithology: fresh (Class I) with 15% secondary minerals and UCS of 40.66 MPa; slightly weathered (Class II) with 30% secondary minerals and UCS of 35.18 MPa; and completely weathered (Class V) dominated by clay and oxide minerals with a UCS of only 0.02 MPa. A strong negative correlation ($R^2 = 0.9707$) was established between secondary mineral content and UCS, demonstrating that progressive weathering substantially reduces the geomechanical properties of the rock mass at this site. These findings establish the geotechnical context within which slope stability assessment is critically needed. The present study extends this characterization by evaluating the stability of the actual mine slopes using deterministic and probabilistic approaches based on the geotechnical parameters of each weathering class. At a broader kaolin mining scale, Chusna et al. (2021) conducted a geotechnical analysis of a kaolin quarry in Semin District using the Limit Equilibrium Method under static and pseudo-static conditions,

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demonstrating that slope angle variations significantly affect FoS and reserve estimation. Similarly, Alfat et al. (2019) documented slope instability in Indonesian mining with FoS values as low as 0.38–0.64, highlighting the consequences of slope construction without geotechnical assessment. Haeriska et al. (2025) applied the Morgenstern-Price method — mathematically equivalent to the GLE method — to evaluate slope stability in an Indonesian open-pit nickel mine, demonstrating the relevance of LEM in tropical mining environments. In the probabilistic domain, Obregon and Mitri (2019) demonstrated the advantage of probabilistic approaches over deterministic methods in capturing the variability of discontinuity parameters at an open-pit mine bench slope, while Abdulai and Sharifzadeh (2021) provided a comprehensive review of Monte Carlo simulation and other probabilistic methods for rock slope design in open-pit mining. More recently, Rusydy et al. (2024) developed a probabilistic design flowchart for rock slope stability assessment in Indonesia, integrating LEM and Monte Carlo simulation within a systematic probabilistic framework. Despite these advances, a gap remains in the application of integrated deterministic- probabilistic analysis to artisanal kaolin mining operations where weathering has been documented to significantly alter rock mass properties, as demonstrated by Rianse et al. (2025) at Semin, Gunungkidul.

The conceptual framework of this study follows a sequential analytical approach. Field data collection using the scanline method provides discontinuity parameters for rock mass characterization. Laboratory tests (comprising direct shear and physical properties tests) yield geotechnical input parameters: cohesion (c), friction angle (ϕ), and unit weight (γ). These parameters, together with the seismic coefficient (ks) derived from the Indonesian Design Spectra Application, constitute the input for slope stability analysis. The GLE method is applied as the primary analytical tool to compute the deterministic FoS for each of the three actual slopes, following the Mohr-Coulomb failure criterion (Alok et al., 2024; Azarafza et al., 2021). Monte Carlo simulation is then applied to the same GLE framework to obtain the probabilistic outputs: PoF, coefficient of variation of FoS (CoV), and reliability index (β). Sensitivity analysis is performed as the final step to rank the relative influence of each input parameter on FoS reduction. The resulting FoS and PoF values are evaluated against the regulatory acceptance criteria of Kepmen ESDM No. 1827 K/30/MEM/2018 to determine slope safety compliance.

The stability of a slope is quantified through the Factor of Safety (FoS), defined as the ratio of resisting to driving forces along a potential failure surface (Azarafza et al., 2021). The Mohr-Coulomb failure criterion, expressed as $\tau = c + \sigma \tan \phi$, provides the theoretical basis for evaluating shear strength along the critical slip surface (Alidaryan et al., 2023). Among the various Limit Equilibrium Methods, the GLE method (equivalent to the Morgenstern-Price method) is considered the most rigorous because it satisfies both moment and force equilibrium simultaneously, unlike simplified methods that satisfy only one condition (Alok et al., 2024; Koca and Koca, 2020). This characteristic makes the GLE method particularly appropriate for complex slope geometries and heterogeneous geotechnical conditions encountered in mining environments (Haeriska et al., 2025; Assis and Nogueira, 2023).

The deterministic FoS, while widely used, is a single-value estimate that fails to capture the inherent variability of geotechnical parameters (Abdulai and Sharifzadeh, 2021). Probabilistic analysis addresses this limitation by treating input parameters as random variables characterized by probability distributions and computing the PoF (the likelihood that FoS falls below unity) and the reliability index (β) (Kar and Roy, 2022; Vecci and Sayão, 2026). Among available probabilistic methods, Monte Carlo simulation is the most robust and widely adopted due to its flexibility in handling various distribution types and parameter correlations without requiring simplifying assumptions (Abdulai and Sharifzadeh, 2021; Obregon and Mitri, 2019). Sensitivity analysis further enhances the probabilistic framework by identifying the parameters that most significantly contribute to FoS variability, providing critical information for slope management and monitoring prioritization (Zeng et al., 2024; Yang et al., 2023).

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2. RESEARCH METHOD

1. Study Area

The study was conducted at an artisanal kaolin mine in Karangsari Village, Semin District, Gunungkidul Regency, Yogyakarta Special Region, Indonesia. Three rock slopes with varying geotechnical conditions were selected as research objects with the following dimensions: Slope I (height 15,9 m, inclination 65°), Slope II (height 12,5 m, inclination 74°), and Slope III (height 17,4 m, inclination 65°). Geologically, the slope-forming rocks are classified as mudstone, rich in plagioclase minerals, and exhibit varying degrees of weathering.

2. Field Data Collection

Field data were collected using the scanline method, a systematic and well-established technique for measuring discontinuity parameters on exposed rock faces (Zulfahmi et al., 2023); (Zangerl et al., 2022). A measuring tape was positioned horizontally along each slope face, with a minimum length of 1 meter. All discontinuities intersecting the tape were recorded, including orientation (dip and dip direction), spacing, persistence, roughness, aperture, infilling material, and groundwater condition, following ISRM (1981) standards.

Discontinuity data were subsequently processed to determine the Rock Quality Designation (RQD) value using the equation proposed by Priest and Hudson (1976), and further used for Rock Mass Rating (RMR) and Geological Strength Index (GSI) classification. Additionally, kinematic analysis was performed using stereographic projection to identify potential failure modes at each slope (Albar and Mohd-Nordin, 2022).

3. Laboratory Testing

Rock samples were collected from each slope and subjected to laboratory tests in accordance with ISRM and ASTM standards. The laboratory tests consisted of:

Direct Shear Test

The direct shear test was conducted to determine shear strength parameters, namely cohesion (c) and internal friction angle (ϕ), which are the primary input parameters governing slope stability under the Mohr-Coulomb failure criterion (Wang et al., 2025; (Alidaryan et al., 2023). Tests were performed under three different normal stress conditions for each slope sample (15 samples total, 5 per slope), yielding both peak and residual values of cohesion and friction angle. The Mohr-Coulomb failure criterion is defined as:

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

where τ is shear strength, c is cohesion, σ is normal stress, and ϕ is internal friction angle.

Physical Properties Test

Physical properties tests were carried out to determine the unit weight (γ) of rock samples from each slope. Unit weight is a critical parameter governing the driving forces acting on a slope (Lin et al., 2024); (Karthik et al., 2022a), with larger values contributing to greater gravitational loading on the potential failure surface.

4. Seismic Coefficient

The study area lies near the Indo-Australian and Eurasian plate subduction zone and is influenced by several active faults, including the Opak, Oyo, and Dengkeng faults. The seismic coefficient (ks) was estimated following the NCHRP Report 611 framework using Peak Ground Acceleration (PGA) data from the Indonesian Design Spectra Application (Anderson, 2008). The mean seismic coefficient was calculated as 0,0913 with a Coefficient of Variation (CoV) of 1%.

5. Slope Stability Analysis Using GLE Method

Slope stability analysis was performed using the General Limit Equilibrium (GLE) method, which is mathematically equivalent to the Morgenstern-Price method and satisfies both moment and force equilibrium simultaneously (Alok et al., 2024; (Azarafza et al., 2021). This makes the GLE method one of the most rigorous among available limit equilibrium approaches (Haeriska et al., 2025b). The analysis was performed using Rocscience Slide2 software with the seismic coefficient incorporated as a dynamic loading parameter.

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$$FoS = \frac{cA + W \cos \alpha p \tan \phi}{W \sin \alpha p}$$

where A is the slip surface area, W is the weight of the sliding mass, and αp is the slope angle. The Mohr-Coulomb failure criterion was adopted as the shear strength model for all slopes.

6. Probabilistic Analysis Using Monte Carlo Simulation

Probabilistic analysis was performed using Monte Carlo simulation to quantify the uncertainty in geotechnical input parameters and determine the Probability of Failure (PoF) (Abdulai and Sharifzadeh, 2021b); (Kar and Roy, 2022). The random input variables considered were cohesion (c), friction angle (ϕ), and unit weight (γ), each characterized by mean value, standard deviation, and probability distribution type determined through statistical fitting using the Kolmogorov-Smirnov test. The PoF is defined as:

$$PoF = \frac{(N - M)}{N}$$

where N is the total number of simulations (N = 10.000) and M is the number of simulations where FoS ≥ 1,0 (Wyllie and Mah, 2004).

The statistical distribution types applied were as follows: unit weight followed a Gamma distribution for all slopes; cohesion followed a Normal distribution for Slope I and Gamma distribution for Slopes II and III; friction angle followed a Gamma distribution for Slope I and Lognormal distribution for Slopes II and III (Wang et al., 2023); (Chuaiwate et al., 2022).

7. Sensitivity Analysis

Sensitivity analysis was conducted to identify the most influential geotechnical parameters on slope stability (Lin et al., 2024); (Espinosa Fuentes and El Naggar, 2025). The contribution of each random variable (cohesion, friction angle, and unit weight) to FoS reduction was evaluated by varying each parameter across its statistical range while computing resulting changes in FoS. Results are expressed as percentage contributions to FoS reduction for each slope, presented in the form of tornado plots and bar charts (Hu et al., 2022; Karthik et al., 2022).

8. Acceptance Criteria

All stability analysis results were evaluated against the acceptance criteria of Indonesian Mining Regulation (Kepmen ESDM No. 1827, 2018), which requires minimum static FoS ≥ 1,1 and maximum PoF ≤ 25% (for single slopes). These criteria serve as the primary benchmarks for evaluating slope safety throughout this study.

3. RESULT AND DISCCUSSION

1. Geotechnical Input Parameters

Direct shear tests and physical properties tests were conducted on rock samples from each slope to obtain geotechnical input parameters. Statistical characterization of each parameter was performed using Kolmogorov-Smirnov distribution fitting. Results are summarized in Table 1.

Table 1. Geotechnical Input Parameters

Slope	Statistical Parameter	Physical & Mechanical Properties		
		Unit Weight (kN/m^3)	Cohesion, c (kPa)	Friction Angle, ϕ (°)
I	Distribution	Lognormal	Normal	Gamma
	Mean	23,112	529	54,033
	Standard Deviation	0,37	116,155	0,478
	Rel. Min.	0,263	134	0,353
	Rel. Max	0,424	72	0,677
II	Distribution	Gamma	Gamma	Lognormal
	Mean	21,313	450	53,77

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Slope	Statistical Parameter	Physical & Mechanical Properties		
		Unit Weight (kN/m^3)	Cohesion, c (kPa)	Friction Angle, ϕ (º)
	Standard Deviation	1,796	96,267	0,992
	Rel. Min.	2,484	72	0,95
	Rel. Max	1,34	142	1,03
III	Distribution	Gamma	Gamma	Lognormal
	Mean	9,386	35,304	32,949
	Standard Deviation	0,352	4,156	5,141
	Rel. Min.	0,57	6,296	4,799
	Rel. Max	0,519	6,198	10,971

Source: Primary Data, 2026

The CoV of cohesion was 22% for Slope I, 21% for Slope II, and 12% for Slope III, reflecting moderate variability consistent with typical geotechnical parameters in rock slope studies (Velarde and Macciotta, 2024; Phoon et al., 2022). The highest CoV of friction angle was observed in Slope III (15,6%), indicating greater uncertainty in the shear strength parameters of this slope compared to Slopes I and II (0,88% and 1,85%, respectively).

In addition to the rock mass shear strength and physical properties, the seismic coefficient was estimated as a dynamic loading parameter for slope stability analysis under pseudo-static conditions. The seismic coefficient was derived from Peak Ground Acceleration (PGA) data obtained from the Indonesian Design Spectra Application, following the NCHRP Report 611 framework. Statistical characteristics of the seismic coefficient are presented in Table 2.

Table 2. Seismic Coefficient Statistical Characteristics

Parameter	Value
Mean (ks)	0,091310
Standard Deviation	0,000511737
Coefficient of Variation (CoV)	1%
Relative Minimum	0,000810
Relative Maximum	0,001190

Source: Primary Data, 2026

The seismic coefficient exhibited a very low CoV of 1%, indicating minimal variability and high consistency of seismic loading conditions across the study area. This low variability reflects the relatively stable seismic hazard characteristics of the region as derived from the national seismic hazard database and confirms the reliability of using a single representative seismic coefficient value (ks = 0,0913) for pseudo-static slope stability analysis in this study, consistent with the approach recommended by Anarta et al. (2025) and Le Roux et al. (2025) for incorporating seismic loading in mining slope design.

2. Factor of Safety (FoS) Results

Slope stability analysis using the GLE method incorporating seismic coefficient (ks = 0,0913) as a dynamic loading parameter was performed for the three actual slopes. Results are presented in Figure 1 and Table 3.

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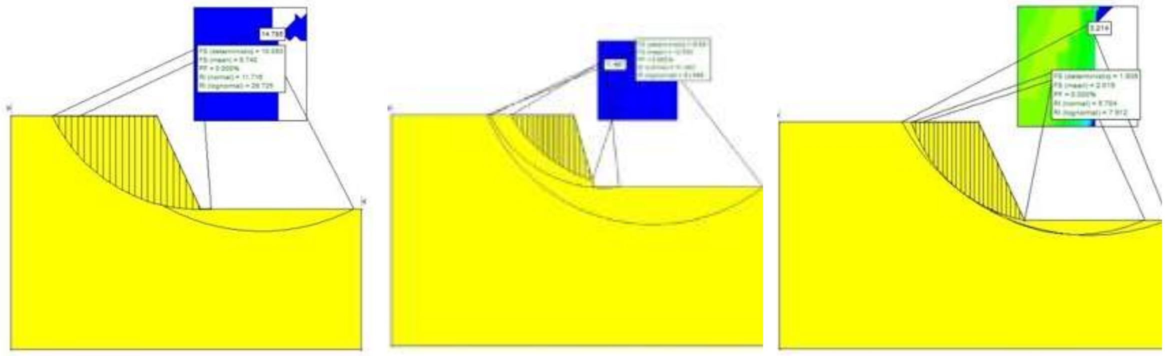

(a) (b) (c)

Figure 1. (a) Slope I, (b) Slope II, (c) Slope III

Table 3. FoS Results (GLE Method)

Slope	Height (m)	Angle (°)	FoS	SD	CoV (FoS)
I	15,9	65	9,74	0,746	8%
II	12,5	74	10,55	0,304	3%
III	17,4	65	2,019	0,179	9%

Source: Primary Data, 2026

All three slopes recorded FoS values exceeding the minimum static threshold of 1.1 stipulated by Indonesian Mining Regulation (Kepmen ESDM No. 1827 K/30/MEM/2018), indicating stable conditions under current geometric and loading configurations.

Slope III recorded the lowest FoS of 2,019, reflecting the substantially reduced shear strength parameters of this slope compared to Slopes I and II. Slope II recorded the highest FoS of 10,55, despite having a steeper inclination (74°) than Slope I (65°), which is attributable to its greater shear strength relative to its lower height (12,5 m).

The CoV of FoS ranged from 3% to 9% across the three slopes. Slope II exhibited the lowest CoV (3%), consistent with the more uniform geotechnical conditions of its rock mass, while Slope III exhibited the highest CoV (9%), reflecting greater variability in its input parameters. These CoV levels of FoS are within the range associated with reliable slope designs as reported by Velarde and Macciotta (2024) and (Abdulai and Sharifzadeh, 2021), who noted that low CoV values of FoS are indicative of stable and well-constrained slope conditions.

3. Probability of Failure (PoF) and Reliability Index

Probabilistic analysis using Monte Carlo simulation was conducted to determine the PoF and reliability index (β) for each slope. Results are presented in Table 4.

Table 4. Probabilistic Analysis Results

Slope	FoS	PoF (%)	CoV (FoS)	β
I	9,74	0,00	8%	11,72
II	10,55	0,00	3%	31,38
III	2,019	0,00	9%	5,70

Source: Primary Data, 2026

All three slopes yielded a PoF of 0,00%, well within the maximum allowable limit of 25% for single slopes as required by Kepmen ESDM No. 1827 K/30/MEM/2018. This confirms that all slopes are stable under current geotechnical and geometric conditions. The reliability index (β) ranged from 5,70 to 31,38. Slope II recorded the highest β (31,38), while Slope III recorded the lowest β (5,70). The high β values across all three slopes are consistent with the near-zero PoF results and confirm the stability findings of the deterministic analysis. Vecci and Sayão (2026) and Kar and Roy (2022)

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similarly demonstrated that when mean FoS values are substantially above unity, the reliability index tends to be high and PoF near zero, reflecting conservative slope conditions.

The combined use of FoS, PoF, and β provides a more complete picture of slope safety than deterministic analysis alone (Abdulai and Sharifzadeh, 2021; Vecci and Sayão, 2026). Notably, the low standard deviation of FoS for Slope III (SD = 0,179) despite its lower mean FoS (2,019) reflects the narrow and concentrated distribution of its strength parameters, which explains the consistently zero PoF despite its lower safety margin relative to Slopes I and II.

4. Sensitivity Analysis

Sensitivity analysis was performed to quantify the relative contribution of each geotechnical parameter — cohesion (c), friction angle (ϕ), and unit weight (γ) — to FoS reduction. Results are presented in Table 5.

Table 5. Parameter Contribution to FoS Reduction (%)

Parameter	Slope I	Slope II	Slope III
c (%)	28	31	20
ϕ (%)	1	1	21
γ (%)	2	17	7

Source: Primary Data, 2026

Slope I

Cohesion contributed the most to FoS reduction at 28%, followed by unit weight (2%) and friction angle (1%). The dominant influence of cohesion is consistent with findings by and Yang et al. (2023), who reported that cohesion is the parameter that most significantly affects slope stability. The minimal contribution of friction angle in Slope I reflects its high value (54,033°) combined with very low variability (CoV = 0,88%).

Slope II

Cohesion remained the most dominant parameter at 31%, while unit weight showed an increased contribution of 17% compared to Slope I. This increase is attributable to the higher CoV of unit weight in Slope II (8,43%), which amplifies its influence on the driving forces acting on the slope. Zeng et al. (2024) and Zhou et al. (2023) similarly found that unit weight becomes increasingly significant in slope stability when its variability is relatively high compared to other parameters.

Slope III

Slope III exhibited a near-equal contribution of cohesion (20%) and friction angle (21%), a pattern notably different from Slopes I and II where friction angle contributed only 1%. This shift is attributable to the substantially lower friction angle of Slope III (32,949°) combined with its highest CoV (15,6%), making it as influential as cohesion in governing stability. Yue and Kang (2021) demonstrated that the relative contributions of cohesion and friction angle to FoS depend on slip depth and parameter magnitudes, with friction angle becoming more significant as its value decreases.

Discussion

Adequacy of Deterministic and Probabilistic Approaches

The GLE method produced consistent results across both deterministic (FoS) and probabilistic (PoF, β) indicators, with all three slopes demonstrating stable conditions under current configurations. The combined use of both approaches is strongly recommended over exclusive reliance on deterministic analysis (Vecci and Sayão, 2026; Abdulai and Sharifzadeh, 2021), as it captures both the magnitude and variability of slope safety. This is particularly important in artisanal mining contexts where geotechnical data are limited and parameter uncertainty is inherently high.

The low CoV values of FoS (3%–9%) and high reliability indices (5.70–31.38) indicate that parameter variability has a limited effect on the overall stability classification of all three slopes. This finding is consistent with Ricchio-Hitchcock and Chatterjee (2025), who noted that when mean FoS values are substantially above unity, the impact of geomechanical uncertainty on the probabilistic outcome is limited.

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Critical Parameters for Slope Management

Sensitivity analysis consistently identified cohesion as the most dominant parameter across all slopes, in agreement with Yang et al. (2023), Poso and Onia (2024), and Fang et al. (2024). This has direct practical implications: any mechanism reducing cohesion (including prolonged rainfall infiltration, progressive weathering, or surface disturbance) may significantly reduce slope stability. Artisanal mine operators should therefore implement slope surface protection measures to preserve cohesion values.

The increasing importance of friction angle in Slope III (21%) compared to Slopes I and II (1%) suggests a transition in parameter dominance as shear strength diminishes. This is consistent with Yue and Kang (2021), who showed that in slopes with lower shear strength parameters, friction angle gains importance alongside cohesion in controlling stability.

Regulatory Compliance

All three slopes satisfy the acceptance criteria of Kepmen ESDM No. 1827 K/30/MEM/ 2018, with FoS > 1,1 and PoF = 0,00%. However, Slope III recorded the lowest FoS (2,019) and β (5,70), and the most balanced parameter sensitivity profile, indicating a reduced safety margin. Regular geotechnical monitoring is strongly recommended, particularly for Slope III, to ensure continued stability as conditions evolve over time.

4. CONCLUSION

This study evaluated the stability of three rock slopes at an artisanal kaolin mine in Semin, Gunungkidul, Yogyakarta, Indonesia, using the General Limit Equilibrium (GLE) method combined with Monte Carlo simulation under pseudo-static loading conditions (ks = 0.0913). The following conclusions are drawn based on the analysis results:

1. All three slopes satisfied the minimum acceptance criteria of Indonesian Mining Regulation (Kepmen ESDM No. 1827 K/30/MEM/2018). The FoS values obtained from the GLE method were 9.74 (Slope I), 10.55 (Slope II), and 2.019 (Slope III), all exceeding the minimum static threshold of 1.1. The PoF was 0.00% for all three slopes, well below the maximum allowable limit of 25% for single slopes.
2. The reliability index (β) ranged from 5.70 (Slope III) to 31.38 (Slope II), confirming high reliability across all three slopes. The CoV of FoS ranged from 3% (Slope II) to 9% (Slope III), indicating low dispersion in stability outcomes despite parameter variability in the input data.
3. Sensitivity analysis identified cohesion as the most dominant parameter in Slopes I and II, contributing 28% and 31% to FoS reduction respectively, while unit weight contributed 2% and 17%, and friction angle contributed 1% for both slopes. In Slope III, cohesion (20%) and friction angle (21%) exhibited near-equal dominance, with unit weight contributing 7%, indicating a shift in parameter influence as shear strength diminishes.
4. The results of this study provide quantitative geotechnical evidence for an artisanal kaolin mine that has been operated without prior formal geotechnical assessment. The combined deterministic (FoS) and probabilistic (PoF, β) approach adopted in this study offers a more comprehensive basis for slope safety evaluation than deterministic analysis alone and is recommended for application in similar artisanal mining operations across Indonesia. The findings demonstrate that regulatory compliance can be achieved even in informally managed mines, provided that slope geometries are appropriate for the prevailing geotechnical conditions.
5. This study has several limitations that should be acknowledged. First, the analysis was conducted on three slopes under static and pseudo-static loading conditions only; dynamic transient loading scenarios and groundwater fluctuation effects were not explicitly modeled. Second, the rock mass characterization of Slope III was conducted using the intact rock approach due to the highly weathered nature of its material, which may introduce uncertainty in the representativeness of the derived geotechnical parameters. Third, the study was limited to current actual slope geometries; long-term changes in slope configuration due to continued mining activities were not considered.

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6. Based on the findings and limitations of this study, the following recommendations are proposed:
a. Regular geotechnical monitoring should be implemented, particularly for Slope III, which recorded the lowest FoS (2.019) and reliability index ($\beta = 5.70$) among the three slopes, indicating the smallest safety margin under current conditions.
b. Special attention should be given to preserving cohesion values through slope surface protection measures, given its dominant contribution to FoS reduction across all slopes (20%–31%). Activities that may reduce cohesion (including prolonged rainfall exposure, surface disturbance, and progressive weathering) should be minimized.
c. Future studies should incorporate groundwater conditions, dynamic transient loading, and additional weathering classes to provide a more comprehensive assessment of long-term slope stability in artisanal kaolin mining operations
d. The probabilistic framework applied in this study is recommended as a replicable reference for geotechnical assessment of similar artisanal mining sites in Indonesia, particularly those operating without prior geotechnical studies.

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