



Geotechnical Analysis and Recommendations for Safe Slope Geometry in Nickel Laterite Open Mines in Tanggetada District

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ABSTRACT

Slope stability is a fundamental requirement in lateritic nickel open-pit mining, particularly in tropical regions where limonite and saprolite materials exhibit heterogeneous geotechnical properties and are sensitive to changes in moisture content and operational loading. This study aims to evaluate the physical and mechanical characteristics of lateritic materials and to formulate safe slope geometry recommendations for a lateritic nickel mining area in Tanggetada District, Southeast Sulawesi, Indonesia. The research integrates field investigation, geotechnical sampling, laboratory testing, diggability assessment, and slope stability analysis using the Limit Equilibrium Method under static and dynamic conditions. The analysis was conducted for single mine slopes, overall mine slopes, and overburden and ore dump slopes. The results indicate that limonite has higher cohesion, whereas saprolite shows higher water content and saturated unit weight, suggesting different slope responses for each material zone. Single mine slopes exhibit higher safety factors than overall slopes, while the overall ore dump represents the most critical configuration under dynamic loading. The recommended safe geometry consists of a 5 m single mine slope height at 55°, a 30 m overall mine slope height at 33°, a 5 m single dump slope height at 45°, and a 15 m overall dump slope height at 31°. These findings demonstrate that safe slope design in lateritic nickel open-pit mining requires the integration of material characterization, static and dynamic stability evaluation, geometry control, and continuous geotechnical monitoring to support safe and sustainable mining operations.

INTRODUCTION

Open-pit nickel laterite mining is a mining activity that is highly dependent on slope stability because the excavation process creates mining levels that must remain safe throughout the operation. Nickel laterite deposits are generally formed from the weathering of ultramafic rocks in tropical environments, resulting in a layered material profile consisting of overburden, limonite, saprolite, and bedrock zones (Atika, Werner, & Matsubae, 2026). Each of these zones has different physical and mechanical characteristics, so their response to excavation, heavy equipment loading, changes in water content, and changes in slope geometry also vary. These conditions make geotechnical studies a crucial basis in the planning of nickel laterite open-pit mines, particularly in determining slope geometry that is safe and remains operationally efficient (Everhart, 2012).

Slope stability is a key aspect of open-pit mining operations because slope instability can lead to production disruptions, equipment damage, loss of reserves, and safety risks for workers (Kolapo et al., 2022). In laterite nickel mines, the potential for slope instability is further complicated by the fact that limonite and saprolite materials generally have properties similar to weathered soil, are relatively heterogeneous, and are sensitive to changes in water content. Research in nickel mines indicates that





changes in slope geometry due to mining activities can affect the safety factor, requiring periodic analysis and evaluation of slope conditions based on actual geotechnical data (Elias, 2002).

Slope geometry, such as slope height, slope angle, step width, and berm width, are important factors that determine the level of stability of mining slopes (Kolapo et al., 2022). Slopes that are too steep can increase driving forces and reduce the safety factor, while slopes that are too gentle can reduce mining efficiency and decrease reserve recovery (Timchenko, 2021). Therefore, slope geometry recommendations must be formulated through an analysis that considers the balance between safety, productivity, and the characteristics of the slope's constituent materials. Geotechnical studies for the design of slope geometry for nickel mining pits in Southeast Sulawesi indicate that recommendations for safe slopes need to be determined based on the physical and mechanical properties of the slope's constituent soil and stability simulations using appropriate slope analysis methods (Chowdhury, Bhattacharya, & Metya, 2023).

The physical and mechanical parameters of laterite material are the main basis for slope stability analysis. Parameters such as bulk density, water content, cohesion, angle of internal friction, and compressive strength describe the material's ability to withstand shear forces acting on potential slip surfaces (Sujeeth, 2015). In laterite zones, differences in properties between limonite and saprolite can cause variations in the safety factor value for the same slope geometry (Haryanto et al., 2027). Research related to nickel mine slope design emphasizes the need to integrate field investigation data, laboratory testing, and slope stability analysis to produce safe slope designs in tropical mining environments (Le Roux et al., 2025).

The Limit Equilibrium Method (LEM) is one of the most widely used approaches in mining slope stability analysis. This method calculates the safety factor based on the ratio between the resisting force and the driving force on the potential slip plane (Deng et al., 2027). In geotechnical practice, this method is widely used because it has a relatively simple formulation, is easy to apply, and produces results that can be used as a basis for slope design recommendations. Liu et al., 2025 compared the results of the safety factor and critical slip plane from LEM with two finite element methods, thus demonstrating that LEM remains relevant as a primary and comparative approach in slope stability analysis.

In the context of the nickel mining area in Tanggetada District, geotechnical studies are important because this area is located in a tropical environment with laterite material characteristics and varied topography. The geotechnical study report in the area shows that the scope of the study includes slope geometry data, geological structures, physical and mechanical properties of materials, laboratory testing, slope stability analysis, and recommendations for geotechnical monitoring. Therefore, research on geotechnical analysis and recommendations for safe slope geometry is relevant to support the implementation of good mining engineering principles in the laterite nickel open-pit mine in Tanggetada District.

In addition to stability analysis, geotechnical monitoring is also a crucial component of mine slope risk management. Slope conditions can gradually change due to excavation, material degradation, water impacts, and heavy equipment activity. A systematic review of open-pit slope monitoring methods demonstrates the importance of geotechnical monitoring to detect changes in slope conditions and support faster safety decision-making. Therefore, recommendations for safe slope geometry need to be complemented by a monitoring plan to ensure that the established design remains consistent with actual conditions during mining operations.





Based on the description, the research entitled "Geotechnical Analysis and Recommendations for Safe Slope Geometry in Nickel Laterite Open Pit Mines" is important to be conducted to provide a scientific basis in planning safe, stable, and applicable mining slopes. This research is directed at examining the geotechnical characteristics of laterite materials, evaluating slope stability based on safety factors, and compiling recommendations for appropriate slope geometry to support the safety and sustainability of nickel laterite mining operations in Tanggetada District.

RESEARCH METHODS

This research uses a quantitative-descriptive approach based on geotechnical analysis to determine slope stability and develop recommendations for safe slope geometry in a laterite nickel mining area in Tanggetada District. The analysis was conducted by integrating field data, laboratory test results, and slope stability modeling using the Limit Equilibrium Method (LEM). This method was used because it can generate slope safety factors based on slope geometry, material shear strength parameters, unit weight, and groundwater level conditions.

Research Location and Objects

The research was conducted in a laterite nickel mining area in Tanggetada District, Kolaka Regency, Southeast Sulawesi Province. The study objects included open-pit mine slopes composed of laterite material, particularly limonite and saprolite zones, as well as overburden and ore embankment slopes.

Data Collection

The data used consisted of field and laboratory data. Field data included topography, morphology, geological structure, slope geometry, groundwater level conditions, and sampling locations. Laboratory data includes the physical and mechanical properties of laterite materials, such as water content, specific gravity, unit weight, cohesion, angle of internal friction, and compressive strength. Geotechnical samples are obtained through core or ring sample drilling, then prepared and tested in a soil mechanics laboratory.

Testing the Physical and Mechanical Properties of Materials

Physical property testing is conducted to obtain values for air content, specific gravity, saturated density, and dry density. Mechanical property testing is conducted through compressive strength and direct shear strength tests. Shear strength test results are used to determine cohesion and angle of internal friction, while compressive strength test results are used to determine the material's ability to withstand compressive loads.

Digability and Scratchability Analysis

Dugability and scratchability analysis were conducted to determine the laterite material demolition method. Parameters used included compressive strength values, Point Load Index (PLI) estimates, and discontinuous plane spacing. The analysis results were used to assess whether the material could be excavated directly with mechanical equipment or required additional demolition methods.

Slope Stability Analysis

Slope stability analysis was conducted using the Limit Equilibrium Method under static and dynamic conditions. The slopes analyzed included a single limonite slope, a single saprolite slope, an overall slope, an overburden embankment slope, an ore embankment slope, and an overall embankment slope. Input





parameters used included slope geometry, material density, cohesion, angle of internal friction, groundwater level conditions, and slope saturation assumptions.

Safety Factor Evaluation

Modeling results were evaluated based on safety factor values and landslide probability. These values were compared with applicable mine slope safety criteria to determine whether the analyzed slope geometry met safety conditions. Evaluations were conducted for both mine slope and embankment slope conditions.

Preparation of Recommendations for Safe Slope Geometry

Recommendations for slope geometry were prepared based on the results of stability analyses under static and dynamic conditions. Recommendations include slope height, berm width, slope angle, overall slope height, overall slope width, terrace width, haul road width, and embankment slope geometry. These recommendations were developed to ensure the slope design can be implemented safely and support the smooth operation of mining activities.

Research Flow

The research flow includes: literature review, field mapping, geotechnical sampling, laboratory testing, processing of physical and mechanical material parameters, digging ability analysis, slope stability modeling using LEM, safety factor evaluation, preparation of recommendations for safe slope geometry, and geotechnical monitoring planning.

RESULTS AND DISCUSSION

Physical and Mechanical Characteristics of Laterite Material

Laboratory test results indicate that the slope material consists of limonite and saprolite zones, each with distinct physical and mechanical characteristics. The saprolite zone has a higher water content, at 41.75%, compared to limonite at 37.61%. The saturated density of saprolite is also higher, at 15.49 kN/m³, while that of limonite is 14.31 kN/m³. This difference indicates that saprolite tends to have a heavier mass when saturated, so the influence of water needs to be taken into account in slope stability analysis.

Mechanically, limonite has a higher cohesion of 45.11 kN/m², compared to saprolite at 39.23 kN/m². Conversely, saprolite has a slightly higher angle of internal friction, at 26.86°, compared to limonite at 26.19°. The compressive strength values for both materials were relatively low, at 4.41 kN/m² for limonite and 4.51 kN/m² for saprolite. This indicates that the laterite material in the study area is characterized by relatively weak weathering, requiring a conservative safety margin in slope geometry design.

Table 1. Physical and mechanical characteristics of laterite materials

Material Zone	Water Content (%)	Saturated Unit Weight (kN/m ³)	Dry Unit Weight (kN/m ³)	Cohesion (kN/m ²)	Internal Friction Angle (°)	UCS (kN/m ²)
Limonite	37.61	14.31	10.39	45.11	26.19	4.41
Saprolite	41.75	15.49	10.98	39.23	26.86	4.51

Diggability and Rippability Analysis

The diggability and rippability analysis shows that the lateritic materials in the study area can be excavated mechanically. The discontinuity spacing ranges from 0 to 1 mm, while the Point Load Index value is within the range of 0–0.000196 MPa. Based on the Franklin et al. (1971) criterion, these conditions





indicate that the material can be freely excavated using excavators and hydraulic breakers without blasting.

This finding is important from an operational perspective because mechanical excavation is more suitable for relatively soft and highly weathered lateritic materials. In addition, avoiding blasting can reduce vibration-induced disturbances that may affect slope stability. Therefore, the recommendation for free digging supports both production efficiency and slope risk control.

Stability of Mine Slopes under Static and Dynamic Conditions

Slope stability analysis was conducted for three main configurations: single limonite slope, single saprolite slope, and overall slope. Under static conditions, the factor of safety of the single limonite slope is 3.49, while the single saprolite slope has a factor of safety of 2.87. These values indicate that the single slopes are stable for a slope height of 5 m, berm width of 3.5 m, and slope angle of 55°. Meanwhile, the overall slope shows a static factor of safety of 1.54 for a slope height of 30 m, slope width of 47 m, and slope angle of 33°.

Under dynamic conditions, the factor of safety decreases. The single limonite slope decreases to 2.89, the single saprolite slope to 2.39, and the overall slope to 1.24. This reduction indicates that dynamic factors, such as equipment vibration or operational loading, can reduce the stability margin of the slope. Nevertheless, the calculated safety factors remain within acceptable criteria for mine slope design based on the technical recommendations used in the study.

Table 2. Factor of safety of mine slopes

Slope Type	Slope Angle (°)	Height (m)	Width (m)	Static FS	Dynamic FS	Probability of Failure
Single Limonite Slope	55	5	3.5	3.49	2.89	0.00%
Single Saprolite Slope	55	5	3.5	2.87	2.39	0.00%
Overall Slope	33	30	47	1.54	1.24	0.00–1.30%

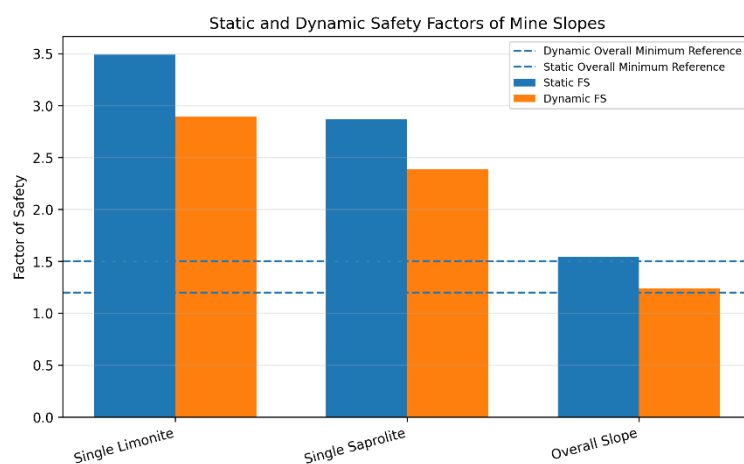


Figure 1. Static and Dynamic Safety Factors of Mine Slopes

Geotechnically, single slopes show higher stability than the overall slope due to their smaller height and more limited potential failure surface. The overall slope has a lower factor of safety because of the



accumulated slope height and wider potential slip surface. Therefore, controlling the geometry of the overall slope is essential for maintaining long-term stability in the mining area.

Stability of Overburden and Ore Dump Slopes

Dump slope stability was analyzed for both overburden and ore materials, including single and overall dump slope configurations. Under static conditions, the factor of safety of the single overburden dump slope is 3.58, while the single ore dump slope has a factor of safety of 2.86. The static factor of safety for the overall overburden dump is 1.76, while the overall ore dump has a value of 1.49.

Under dynamic conditions, the factor of safety decreases to 2.78 for the single overburden dump, 2.23 for the single ore dump, 1.28 for the overall overburden dump, and 1.10 for the overall ore dump.

Table 3. Factor of safety of dump slopes

Dump Slope Type	Slope Angle (°)	Height (m)	Width (m)	Static FS	Dynamic FS	Probability of Failure
Single Overburden Dump	45	5	5	3.58	2.78	0.00%
Single Ore Dump	45	5	5	2.86	2.23	0.00%
Overall Overburden Dump	31	15	25	1.76	1.28	0.00%
Overall Ore Dump	31	15	25	1.49	1.10	0.00%

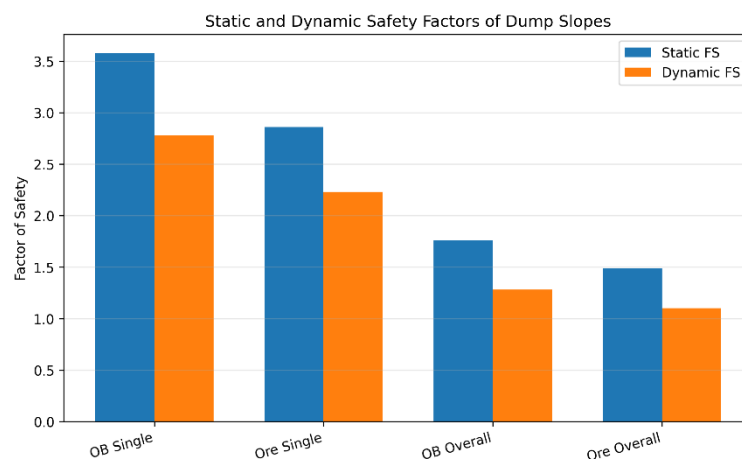


Figure 2. Static and Dynamic Safety Factors of Dump Slopes

These results show that single dump slopes have higher stability than overall dump slopes. The overall ore dump represents the most critical configuration because it has the lowest dynamic factor of safety, namely 1.10. Therefore, strict control of dump height, slope angle, berm width, and drainage is necessary, particularly for ore dump slopes, which show the lowest stability margin compared with other dump configurations.

Recommended Safe Slope Geometry

Based on the slope stability analysis, the recommended slope geometry includes single mine slopes, overall mine slopes, single dump slopes, and overall dump slopes. For single mine slopes, the recommended geometry consists of a maximum slope height of 5 m, minimum berm width of 3.5 m, and maximum slope angle of 55°. For the overall mine slope, the recommended geometry consists of a



maximum height of 30 m, minimum slope width of 47 m, maximum slope angle of 33°, minimum terrace width of 2 m, and minimum haul road width of 10 m.

Table 4. Recommended geometry for mine slopes and dump slopes

Slope Type	Maximum Height	Minimum Width/Berm	Maximum Slope Angle	Additional Notes
Single Mine Slope	≤ 5 m	≥ 3.5 m	≤ 55°	Applicable for static and dynamic conditions
Overall Mine Slope	≤ 30 m	≥ 47 m	≤ 33°	Terrace ≥ 2 m; haul road ≥ 10 m
Single OB/Ore Dump Slope	≤ 5 m	≥ 5 m	≤ 45°	Applicable for static and dynamic conditions
Overall OB/Ore Dump Slope	≤ 15 m	≥ 25 m	≤ 31°	Terrace ≥ 5 m

The recommendations indicate that the design of lateritic nickel mine slopes must distinguish between production slopes and dump slopes. Dump slopes require wider berms and gentler slope angles than single mine slopes because dump materials are generally looser and have lower structural integrity than in-situ materials.

Geotechnical Discussion

Overall, the results show that slope stability in the lateritic nickel mining area is controlled by the interaction between material characteristics, slope geometry, saturation condition, and loading scenario. Limonite has higher cohesion than saprolite, resulting in a higher factor of safety under the same slope geometry. Conversely, saprolite has higher saturated unit weight and water content, which may contribute to greater driving forces under wet or saturated conditions.

The decrease in factor of safety from static to dynamic conditions indicates that slope assessment should not rely only on static analysis. Dynamic loads generated by mining operations can reduce the stability margin, particularly for overall slopes and overall dump slopes. Therefore, safe slope geometry must be designed by considering both static and dynamic conditions.

The safest configurations are observed in single mine slopes and single dump slopes, which have relatively high factors of safety. In contrast, the most critical configurations are the overall mine slope and overall ore dump slope, particularly under dynamic conditions. This finding suggests that the larger and more complex the slope configuration, the greater the need for geometry control, drainage management, and geotechnical monitoring.

Technical Implications for Mining Operations

The results provide several important implications for lateritic nickel open-pit mine planning. First, excavation can be conducted mechanically without blasting because the material is classified as freely diggable based on the PLI value and discontinuity spacing. Second, slope geometry must follow the recommended limits to ensure that the factor of safety remains within acceptable criteria. Third, overall slopes and overall dump slopes should be prioritized for geotechnical supervision because they have lower safety factors than single slopes.

Routine geotechnical monitoring is required using Total Station monitoring, slope deformation control points, groundwater monitoring, warning signs, and daily supervision. If slope movement is detected,





mitigation measures may include reducing the slope angle, removing excessive load from the upper slope, adding counterweight at the slope toe, and lowering the groundwater level through drainage control.

Table 5. Synthesis of key findings and technical interpretation

Study Aspect	Main Finding	Technical Interpretation
Lateritic material	Limonite is more cohesive; saprolite has higher water content and saturated unit weight	Material zoning must be considered in slope design
Diggability	Material can be freely excavated	Excavators and hydraulic breakers are adequate; blasting is not required
Mine slope stability	Static FS: 1.54–3.49; Dynamic FS: 1.24–2.89	Slopes are acceptable, but the overall slope is more critical
Dump slope stability	Static FS: 1.49–3.58; Dynamic FS: 1.10–2.78	Overall ore dump is the most critical configuration
Slope geometry	Single slope ≤ 5 m and $\leq 55^\circ$; overall slope ≤ 30 m and $\leq 33^\circ$	Safe geometry must be controlled during operation
Monitoring	Total Station, groundwater monitoring, warning signs, and daily supervision	Required for early detection of deformation and slope failure mitigation

CONCLUSION

The geotechnical analysis indicates that the lateritic nickel mining area in Tanggetada District is generally stable when the slope geometry follows the recommended design limits. The limonite and saprolite materials show different physical and mechanical characteristics, with limonite having higher cohesion and saprolite having higher water content and saturated unit weight. These differences confirm that material zoning must be considered in slope design.

The stability analysis shows that single mine slopes have higher safety factors than overall slopes, while dump slopes, particularly the overall ore dump, represent the most critical configuration under dynamic conditions. Therefore, slope geometry must be controlled by limiting the height, slope angle, berm width, and overall slope dimensions according to the recommended safe design.

The study also shows that the lateritic material can be excavated mechanically using excavators and hydraulic breakers without blasting. To maintain long-term slope stability, the recommended geometry should be supported by routine geotechnical monitoring, groundwater control, daily slope supervision, and early warning measures in areas with potential instability. Overall, the integration of geotechnical characterization, static–dynamic stability analysis, and monitoring is essential to ensure safe, efficient, and sustainable lateritic nickel mining operations.

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Finally, the authors hope that the results of this study can contribute to safer slope design, improved geotechnical risk management, and the implementation of good mining engineering practices in lateritic nickel open-pit mining operations.

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