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Optimizing Nickel Mine Slope Designs: Integrating Geotechnical Data and Limit Equilibrium Methods

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ABSTRACT

Slope stability in nickel laterite mines is critically influenced by the distinct geotechnical properties of limonite and saprolite weathering profiles. These materials, prevalent in tropical mining regions, exhibit significantly different responses to hydrological and mechanical stresses, necessitating detailed stability assessments for safe mine operations. This study combines field investigations, laboratory testing, and Limit Equilibrium Method (LEM) analysis to evaluate slope stability. Geotechnical parameters were determined through standardized tests and slope stability analyses examined both single-slope (40°-60° angles) and overall-slope configurations with varying bench geometries (widths 3-5m, angles 29°-60°). The analysis demonstrated: (1) Safety factors (SF) decreased 25-30% as slope angles increased from 40° to 60°, with limonite (SF=2.8-2.1) consistently outperforming saprolite (SF=2.4-1.9); (2) Bench width significantly influenced stability, with 5m widths improving SF by 15-20% compared to 3m widths; (3) Optimal stability (SF=1.85) was achieved with gentler geometries (29° slope, 40° bench, 5m width), while steeper configurations approached critical conditions (SF=1.22). The study provides critical insights for designing stable slopes in nickel laterite mines, emphasizing: (1) material-specific slope angles, (2) wider bench designs, and (3) integrated geotechnical-LEM approaches. These findings directly address operational challenges in tropical mining environments, offering practical solutions to enhance safety while maintaining productivity. The methodology establishes a replicable framework for slope stability assessment in weathered geological profiles.

1. Introduction

Slope stability is a fundamental aspect of geotechnical engineering, particularly in mining operations where unstable slopes can lead to significant safety hazards, economic losses, and environmental damage [1]. The stability of slopes is influenced by a complex interplay of geological, hydrological, and anthropogenic factors, making it a critical area of study for engineers and researchers [2], [3]. In open-pit mining, where slopes are continuously modified to access mineral resources, understanding and predicting slope behavior becomes even more crucial. The consequences of slope failure can be catastrophic, ranging from equipment damage and production delays to loss of human life and long-term environmental degradation. Therefore, accurate assessment and proactive management of slope stability are essential components of safe and sustainable mining practices. The tropical climate prevalent in many mining regions, such as Southeast Asia, introduces additional challenges to slope stability [4]. Intense rainfall events can rapidly saturate slope materials, reducing their shear strength and increasing pore water pressures [5]. This phenomenon is particularly problematic for weathered materials like saprolite, which exhibit significant changes in mechanical properties with varying moisture content. Furthermore, the cyclic nature of wet and dry seasons in these regions leads to repeated swelling and shrinking of clay minerals, potentially creating progressive failure surfaces [6]. These environmental factors, combined with the mechanical stresses induced by mining activities, create a dynamic and challenging environment for maintaining stable slopes throughout the mine's operational life.

The Limit Equilibrium Method (LEM) has emerged as the most widely used approach for slope stability analysis due to its conceptual simplicity and practical applicability. This method evaluates the balance between resisting forces, which prevent slope failure, and driving forces, which promote it, to determine the factor of safety (SF) [7], [8]. The development of LEM can be traced back to the early 20th century, with significant contributions from pioneers like Bishop, Janbu, Spencer and Morgenstern [9]–[12]. Over time, various LEM techniques have been developed to address different geological conditions and failure mechanisms, making it a versatile tool for engineers. Its popularity in mining applications stems from its ability to provide quick and reasonably accurate assessments of slope stability, which is crucial for operational decision-making in dynamic mining environments [13].

The effectiveness of LEM depends heavily on the selection of an appropriate analysis variant, each with its own assumptions and limitations. For relatively homogeneous slopes with circular failure surfaces, the simplified Bishop method often provides satisfactory results while maintaining computational efficiency [14]. In cases where non-circular failure surfaces are anticipated, the Janbu method may be more appropriate as it considers force equilibrium conditions [15]. For more complex scenarios involving irregular geometries or heterogeneous materials, the Morgenstern-Price and Spencer method offers greater accuracy by accounting for interslice forces, though at the cost of increased computational complexity [16]. These methodological choices must be carefully considered in relation to site-specific conditions, including material properties, groundwater conditions, and the presence of structural discontinuities.

This study focuses on the stability of slopes composed of limonite and saprolite layers, which are commonly encountered in nickel laterite mining operations. These weathering products present unique challenges for slope design due to their contrasting engineering behaviours. Limonite, forming in the upper zones of weathering profiles, typically exhibits higher density and better cementation between particles due to its iron oxide content. Saprolite, found in deeper weathering zones, retains more of the parent rock's structure but with significantly reduced strength due to chemical alteration. The distinct behaviors of these materials under different stress and moisture conditions necessitate careful consideration in slope design to ensure both operational safety and economic viability of mining operations. The main objective of this study was to analyze slope stability under various slope angles to determine the optimal configuration that ensures both safety and operational efficiency in mining activities. Field investigations and laboratory testing formed the foundation of this research, providing essential data on the geotechnical properties of the slope materials. Standard procedures were followed to determine key parameters including unit weight, cohesion, and angle of internal friction for both limonite and saprolite samples. These material properties were then incorporated into stability analyses examining both single-slope and overall-slope configurations. By systematically varying geometric parameters such as slope angle, bench height, and bench width, the study aimed to identify optimal designs that satisfy safety requirements while maximizing operational efficiency. The findings contribute to the growing body of knowledge on tropical weathering profile behavior and provide practical guidance for engineers working in similar geological settings.

2. Literature Review

2.1 Limit Equilibrium Method

The Limit Equilibrium Method (LEM) is a widely used approach for analyzing slope stability, particularly in geotechnical engineering. It involves evaluating the balance of forces on a potential sliding mass to determine the factor of safety, which indicates the stability of the slope. This method is versatile and can be applied under various conditions, such as different rainfall intensities, seismic activities, and geological settings. The following sections explore key aspects of LEM in slope stability analysis.

In terms of application in different conditions, LEM is used to assess the impact of rainfall on slope stability, as seen in loess slopes where increased rainfall intensity reduces the slope safety factor, indicating higher instability risks [17]. In seismic and fault conditions, particularly in fault-controlled metal mines, LEM helps in identifying slip surfaces with the lowest safety coefficients, crucial for safe mining operations [18]. The method is also applied to evaluate the effect of groundwater levels on slope stability, as demonstrated in areas prone to landslides where rising water tables can lead to critical conditions [19], [20]. While LEM is a robust tool for slope stability analysis, it is important to consider its limitations, such as the assumption of rigid body mechanics and the potential for indeterminacy in complex scenarios. These factors necessitate careful selection of the appropriate LEM variant and consideration of additional methods or technologies to ensure comprehensive risk assessments.

2.2 Safety Factor

The safety factor in slope stability analysis a critical measure that assesses the stability of slopes by comparing resisting forces to driving forces. It is defined as the ratio of the shear strength of the soil to the shear stress acting on a potential slip surface. This ratio helps determine whether a slope is stable ($SF > 1$) or unstable ($SF < 1$) [21]. There are several definitions of the safety factor based on different perspectives. One common approach defines it as the ratio of the soil's shear strength to the shear stress required for equilibrium on the slip surface. Another interpretation views it as the margin of safety, or the factor by which the shear strength must be reduced to bring the slope to a critical equilibrium state—essentially indicating how much reserve strength exists before failure occurs [8]. Additionally, the safety factor can be seen as the ratio of the resisting sliding force to the driving sliding force on the most dangerous slip surface [22].

In practical applications, the safety factor plays an essential role in assessing slope conditions. For instance, in Morowali, safety factors calculated using FEM methods showed values below 1, indicating instability and the need for reinforcement measures [23]. Furthermore, comparative studies of various LEM methods, have shown differing safety factor results, highlighting the importance of selecting the appropriate method for accurate slope stability assessments [24].
While the Limit Equilibrium Method provides a foundational approach to slope stability analysis, it is important to recognize its limitations. The accuracy of the results depends heavily on the chosen method and the assumptions made during calculations, which can lead to varying safety factor outcomes.

3. Research Method

Based on the results of the field investigation using deep boring, the slope materials consist of two main layers, namely limonite and saprolite. These two layers are the focus in the analysis of mine slope stability. The limonite layer is formed from the intensive weathering process of the parent rock while the saprolite layer is the result of advanced weathering of ultramafic rocks with physical characteristics in the form of textures that vary from sandy clay to clayey sand. Based on the results of laboratory tests, the average soil parameters in the limonite and saprolite layers are found in Table 1.

Table 1 Laboratory test results

Soil layer	γ (kN/m3) [25]	c (kPa) [26]	ϕ (...º) [26]
Limonit	22.46	32.65	30.68
Saprolit	21.26	26.52	29.49

Analysis was carried out on single slope conditions and overall slope analysis to determine slope geometric designs that still meet the criteria of safe factors [27], using Slide 6.0 software. The single-slope design is made assuming that the material is homogeneous, so the direction of the single slope is considered uniform. The single-slope geometry is designed by modeling each lithology separately, using a simulation of a single slope height of 6 meters as well as variations in slope angles of 40º, 45º, 50º, 55º, and 60º.

The overall slope geometry design is carried out to determine the optimal slope angle that can be formed in the mining area. The overall slope geometry plan follows the layer profile obtained from the results of the field investigation (Figure 1). Figure 1 shows the profile of the layer consisting of two main layers, namely the limonite layer and the saprolite layer. This profile is the basis for making the geometric design of the mine slope to ensure the efficiency and stability of mining operations. The top layer that is yellow is the layer of limonite. The thickness of the limonite layer varies, ranging from 5 to 10 meters. The second layer which is orange-yellow is the saprolite layer. The thickness of the saprolite layer varies quite a bit, ranging from about 10 meters to 15 meters. A geometric model of a single slope and an overall slope can be seen in Figure 2. The overall workflow of the slope stability analysis carried out in this study is illustrated in Figure 3.

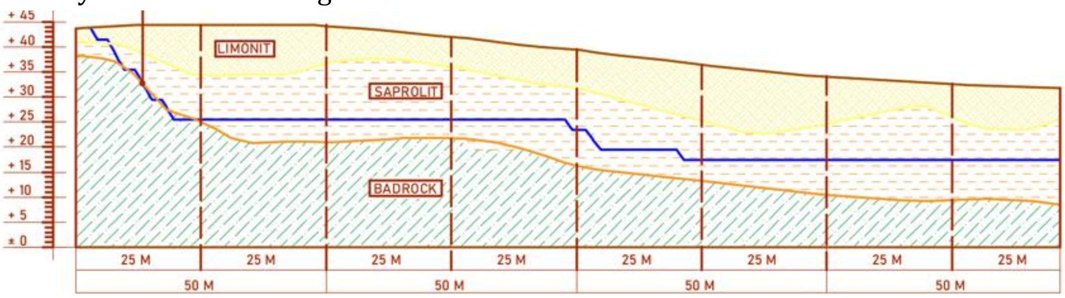
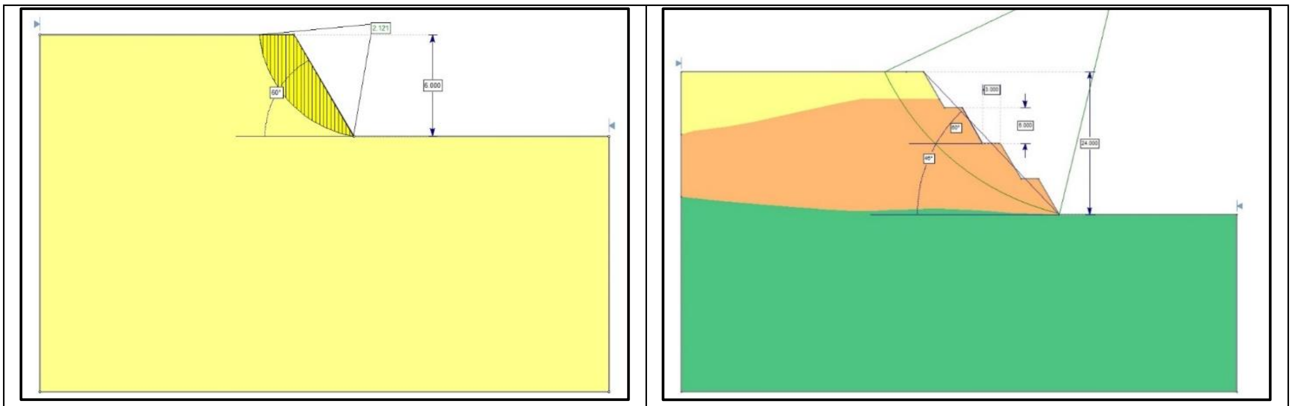


Figure 1 Cross-sectional profile



(a)	(b)

Figure 2 Slope geometry model (a) Single slope analysis; (b) Overall slope analysis

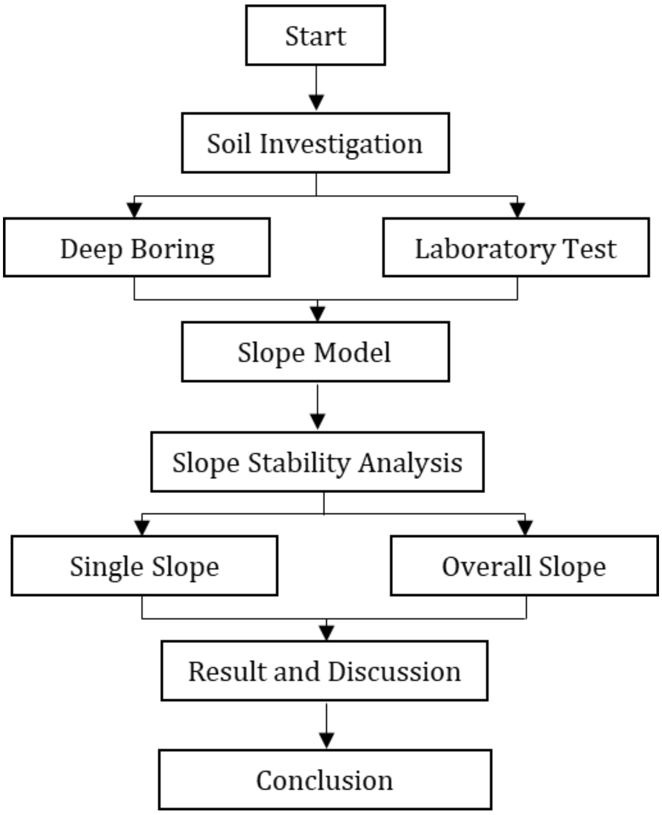


Figure 3 Research flowchart

4. Results and Discussion

4.1 Analysis of Single Slope Stability

The analysis results of the limonite and saprolite layers stability are shown in Figure 4. The results of the analysis showed the relationship between slope angle and Safety Factor (SF) value in the two main types of slope constituent materials, namely limonite and saprolite.

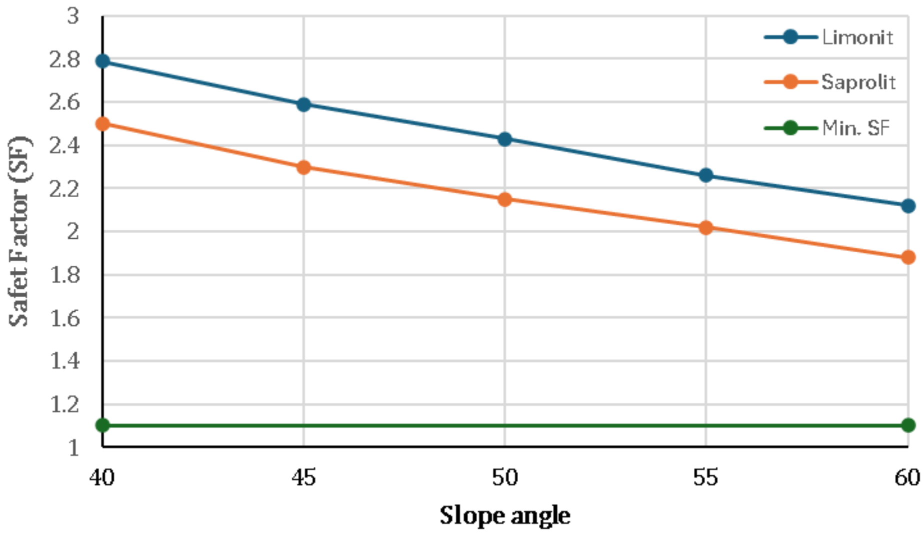


Figure 4 Single slope stability analysis result

The results of the analysis showed that the value of the safety factor decreased as the slope angle increased. At a slope angle of 40°, the SF value for the limonite layer reaches about 2.8 and decreases to about 2.1 at an angle of 60°. As for the saprolite layer, the SF value is in the range of 2.4 at an angle of

40° and drops to about 1.9 at an angle of 60°. This decrease in SF value is in accordance with the principle of slope mechanics, where an increase in slope angle leads to an increase in the shear force component that drives collapse, while the retaining force remains, thereby reducing the stability of the slope [23].

In comparison, limonite material shows better performance in terms of slope stability than saprolites. This is in line with the technical characteristics of both types of materials. Limonite formed from the oxidation and precipitation processes of iron has a denser and consolidated structure, as well as a high iron oxide content that acts as a binder between soil particles. In contrast, saprolites, which are the result of advanced weathering of the parent rock, have a looser structure and shaft, and are highly sensitive to changes in moisture content, so their shear strength is relatively lower [28]–[31].

Although the SF values for both types of materials are still above the minimum safety factor requirement, it can be seen that the saprolite layer is closer to the critical limit, particularly at greater slope angles. This shows that slope geometry planning needs to consider the dominance of the types of materials present in the field. In areas dominated by saprolites, the slope angle design should not be too steep to maintain long-term slope stability.

4.2 Analysis of Overall Slope Stability

The calculation results (Table 2) show that the safety factor decreases consistently along with the increase in slope and level angle. In the level configuration with a height of 6 meters and a width of 3 meters, the increase in slope angle from 33° to 46° led to a decrease in the value of the safety factor from 1.65 to 1.22. A similar pattern of decline was also found in configurations with a width of 4 meters and 5 meters, which indicates that the increase in slope driving force, thereby decreasing the stability of the slope.

However, the increase in level width has been proven to make a positive contribution to the stability of the slope. In the combination of slope angles and level angles, the value of the safety factor increases as the width of the level increases. For example, for a slope angle of 36° and a slope angle of 45°, the value of the safety factor increases from 1.51 (width 3 m), to 1.62 (width 4 m), and 1.73 (width 5 m). This shows that level widening is able to extend the potential slip field and reduce the shear stress acting on the slope body. The geometry of the slope, which includes the height and slope of the overall slope, has a dominant influence on stability. The higher and steeper a slope, the greater the force that drives the potential for avalanches, so the value of the safety factor tends to decrease [23]. For example, at a level width of 3 meters, increasing the slope angle from 33° to 46° lowers the safety factor from 1.65 to 1.22.

Meanwhile, the geometry of the level, which includes the height, width, and angle of the bench face angle, also affects local and global stability. The wider level allows the avalanche energy to be dissipated better, as well as lowering the overall slope. For example, at a slope angle of 36° and a level angle of 45°, the value of the safety factor increased significantly from 1.51 (width 3 m) to 1.73 (width 5 m). This improvement shows that modifications to the geometry of the level can be an effective strategy to increase stability without having to lower the overall height of the slope. In addition to the width of the level, the angle of the face of the level also plays an important role. A sloping angle (about 40°–45°) results in a higher safety factor value compared to a steeper angle (50°–60°). Too steep angles lead to the formation of shorter slip trajectories and increased concentrate tension, thus magnifying the potential for failure.

Based on all the geometric variations tested, the most stable configuration was obtained at a combination of slope angle of 29°, angle of 40°, and width of 5 meters, resulting in a safety factor value of 1.85. On the other hand, the most critical combinations occurred at a slope angle of 46°, a slope angle of 60°, and a level width of 3 meters, with a safety factor value of only 1.22. This value indicates that the slope design is at the threshold of stability. Overall, the results of the analysis show that the optimal slope design approach should consider the synergy between slope geometry and level geometry. Adjustment of level width, slope angle control, and moderate selection of level face angles have been shown to be effective in keeping safety factor values above safe limits (≥1,2). This strategy is important in open-pit mine slope planning in order to ensure long-term stability.

Table 2 Overall slope stability analysis result

Slope geometry		Bench geometry			SF
Slope height (m)	Slope angle (^{0})	Bench Slope (^{0})	Height (m)	Width (m)	
24	33	40	6	3	1.65
24	36	45			1.51
24	39	50			1.4
30	42	55			1.22
24	46	60			1.22
24	31	40	6	4	1.75
24	36	45			1.62
24	39	50			1.5
24	43	55			1.41
32	40	60			1.23
24	29	40	6	5	1.85
24	32	45			1.72
24	34	50			1.61
24	37	55			1.51
24	40	60			1.42

5. Conclusion and Recomendation

In conclusion, this study investigated the stability of slopes composed of limonite and saprolite layers using the Limit Equilibrium Method (LEM), revealing critical insights into the influence of material properties and geometric configurations on slope safety. The analysis demonstrated that the safety factor decreases as the slope angle increases for both materials, with limonite exhibiting higher stability due to its denser structure and greater cohesion. Saprolite, on the other hand, showed greater vulnerability to instability, particularly at steeper angles, highlighting the need for material-specific slope designs. The overall-slope analysis further emphasized the importance of bench geometry, where wider benches and gentler angles significantly improved stability by redistributing shear stresses and extending potential slip surfaces. The optimal configuration—combining a slope angle of 29°, a bench angle of 40°, and a bench width of 5 meters—achieved a safety factor of 1.85, well above the critical threshold.

However, several limitations of this study should be noted. First, the assumption of homogeneous conditions within the slope layers may not fully capture the variability of in-situ material properties, especially in weathered geological formations. Second, the analysis did not incorporate dynamic loading factors such as seismic activity or blasting vibrations, which can significantly affect slope stability in active mining operations. Third, the geotechnical data used were based on limited field sampling, which may not represent broader site conditions in highly heterogeneous deposits. These limitations should be considered when applying the findings to other sites or scaling them for operational implementation.

To ensure long-term stability in mining operations, it is recommended to adopt gentler slope angles and wider benches, especially in areas dominated by saprolite. Regular monitoring of slope conditions, particularly during periods of heavy rainfall or seismic activity, is also essential to detect early signs of instability. Future research should aim to address the aforementioned limitations by incorporating advanced numerical modeling, site-wide geotechnical characterization, and the effects of dynamic loading. By integrating these improvements into slope design and management practices, mining operations can enhance safety, reduce the risk of failures, and improve overall efficiency.

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