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Evaluation of Slope Stability in Mining Areas Using the Morgenstern Price Method

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Abstract

Indonesia's mining sector, particularly in areas like Morowali Regency, Central Sulawesi, faces significant geotechnical challenges due to its location in the Pacific Ring of Fire. One of the key concerns in open-pit mining operations is slope instability, which can lead to landslides, threaten worker safety, damage infrastructure, and disrupt production. This study evaluates the slope stability in the Sambalagi site of PT. Wosindo Berkat Abadi using the Morgenstern-Price method, a limit equilibrium approach known for its accuracy in heterogeneous slope conditions. Field data were collected, including slope geometry, geological conditions, material strength, and hydrogeological factors. The safety factor (FK) was calculated based on geotechnical parameters such as cohesion, internal friction angle, and unit weight of the slope materials primarily saprolite and limonite. The actual slope FK value at PIT D was found to be 0.974, below the standard requirement (≥1.3) set by the Ministerial Decree No. 1827K/30/MEM/2018. To improve stability, a revised slope design was proposed, including reducing slope angles to 35°, increasing bench widths to 2 meters, and decreasing slope height per bench to 4 meters. The simulation of this revised geometry showed that it could achieve the required FK value. The study contributes to safer and more efficient mine planning by demonstrating the importance of integrating detailed geotechnical analysis in slope design, especially in tropical high-rainfall mining regions.

Introduction

Indonesia lies within the Pacific Ring of Fire, making it highly vulnerable to earthquakes. However, beyond its negative impacts, Indonesia's location offers the potential for mineralization of base and precious metals in several locations due to its proximity to active magmatic pathways. This is evident in the numerous mining areas scattered across almost all of Indonesia's islands. Morowali Regency, Central Sulawesi Province, is one of Indonesia's regencies known for its numerous mining areas, including the Bungku Pesisir sub-district (Nurhidayah et al., 2023; Junaidi, 2022; Ya'la et al., 2025). Nickel ore is mined here using open-pit mining methods.

Open-pit nickel ore mining involves cutting slopes, causing changes in slope forces that disrupt slope stability. Slope instability during excavation can disrupt production, damage

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surrounding buildings, and even result in loss of life (Kolapo et al., 2022; Le Roux et al., 2025; Raza et al., 2025).

Slopes in mining areas, particularly open-pit mines, often face stability challenges, potentially posing safety risks to workers, damaging equipment, and disrupting operational activities that can hamper productivity and production targets (Tsachouridis et al., 2025; Timchenko, 2021). Slope stability is crucial in open-pit mine planning, as unstable slopes can cause significant production disruptions. Therefore, accurate analysis is required to determine recommendations for safe and stable slope geometry, in accordance with the geotechnical and hydrogeological characteristics of the mining area (Saputra et al., 2024).

Unstable slopes can lead to disasters, such as soil and/or rock mass movement. Soil rock mass movement on slopes can occur due to the interaction of several conditions, including morphology, geology, geological structure, hydrogeology, and land use (Jaiswal et al., 2024; McColl, 2022). These conditions influence each other, creating a slope with a tendency or potential for movement. Human activities affecting slope stability include excavation or cutting at the toe of the slope, which increases the slope height, and excavation, which increases the slope gradient. The study area, which has slopes ranging from gentle to very steep, has a high potential for soil or rock mass movement, necessitating engineering measures in these areas.

Mining area of PT. Wosindo Berkat Abadi, located at the Sambalagi site in Bungku Pesisir District, Morowali Regency, faces slope stability issues related to geotechnical conditions and high rainfall in the area, increasing the risk of slope instability that can lead to landslides. Landslides not only impact the safety of field workers but can also damage mining infrastructure and disrupt overall mining operations and productivity. The interplay between controlling and triggering factors leads to slope instability and high potential for landslides.

Figure 1. Landslide conditions at PIT D, PT. Wosindo Berkat Abadi mining area at the Sambalagi site

In recent years, the mining site at PIT D has experienced several small landslide incidents, most of which were triggered by rainfall and slope geometry. Furthermore, hydrogeological factors in this area cause high pore water pressure in the soil during the rainy season, which has the potential to weaken the cohesion of slope materials and accelerate slope failure.

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Previous research has extensively addressed slope stability using various methods. For example, research by Atika (2019) examined slope stability using the Rock Mass Rating (RMR) method to assess the weight of rock mass on open-pit mine slopes and used the Bishop Simplified method to estimate the factor of safety using Slide v6.0 software. Meanwhile, research by Farhan et al. (2020) adopted the Morgenstern-Price limit equilibrium method with the Mohr-Coulomb criterion to analyze slope stability based on geotechnical parameters such as cohesion, internal friction angle, and material density.

Although previous research has addressed slope stability using a variety of methods, several limitations provide compelling reasons to pursue this research. In Atika (2019) study, the approach used tended to be limited to the Simplified Bishop method, which has certain assumptions in force calculations that may be less accurate in more complex geotechnical conditions. On the other hand, research by Farhan et al. (2020) used the more comprehensive Morgenstern-Price method, but did not focus on variations in slope geometry and hydrogeological parameters in specific mining areas, such as PT. Wosindo Berkat Abadi, which has specific geotechnical characteristics.

Furthermore, there are still few studies that integrate detailed variations in field geotechnical data into slope stability simulations for mining conditions in Indonesia (Raza et al., 2025; Zulfahmi, 2022; Rusydy et al., 2021). Given the importance of designing safe and optimal slope geometry, this study seeks to broaden our understanding of the influence of bench geometry and variations in geotechnical parameters on slope stability, using the Morgenstern-Price method, which is considered capable of providing more accurate analysis results than other conventional methods.

Based on the problems and research gaps mentioned above, this study aims to evaluate slope stability in the mining area of PT. Wosindo Berkat Abadi at the Sambalagi Site, Bungku Pesisir District, Morowali Regency (Chen et al., 2025; Haundi & Okonta, 2025). This evaluation will be conducted using the Morgenstern-Price method to analyze slope safety factors and determine stable and safe bench geometry configurations. Through this approach, the study is expected to provide recommendations for optimal slope geometry according to the specific geotechnical and hydrogeological conditions in the mining area.

Methods

Type of Research

The type of research conducted by the author is applied research, which is careful, systematic, and continuous research on a problem with the aim of immediate use for a specific purpose. The results of the research do not need to be new discoveries, but rather new applications of existing research.

Research Location and Time

Research Location

This study was carried out at the Sambalagi site of PT. Wosindo Berkat Abadi in Bungku Pesisir District, Morowali Regency in Central Sulawesi Province. The site is located in a geomorphological environment that is characterized by undulating to steep slopes (25-60%), elevation of 510 to 780 meters above sea level. High annual rainfall, together with heterogeneity in the lithology of this topography, increases the potential slope instability. The slope materials are mainly limonite and saprolite, which are supported by peridotite, which vary significantly in mechanical strength. Specifically, Saprolite has low cohesion and is highly vulnerable to weathering, therefore it is susceptible to mass movement when conditions are saturated. Such geomorphology and lithology in combination with active hydrological

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processes that increase pore water pressure during rainy seasons render the Sambalagi an important area to study landslide susceptibility. Within this particular geology context, the work creates awareness of undertaking effective slope stability studies to enable viable and safe open-pit mining activities.

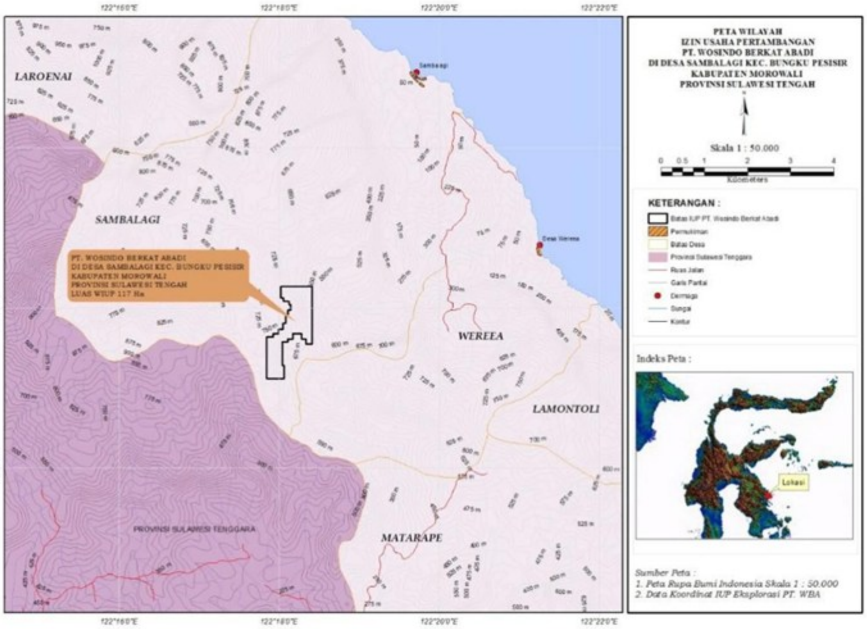

Figure 2. Research Location (source: Primary Data 2024)

Research Tools and Materials

In this study, the author used the following tools and materials to collect and process data obtained from the field. The tools and materials used in this study were:

In this study, special geotechnical instrumentation and spatial data were used to gather and process high-quality field information. Spatial referencing of slope locations was conducted through a Garmin 64s GPS that has a horizontal positioning accuracy of less than 3 m, and slope angle measurements through a clinometer with an accuracy of less than 1o. To measure slope geometry accurately at the centimeter level, a total station survey was carried out to capture the slope dimensions with good accuracy. Terrain models, slope classification, and spatial analysis were calculated using ArcGIS 10.8 and Global Mapper, as both have proved to be able to process geotechnical data.

Research data were a topographic and DEM resolution 30 m high-resolution Digital Elevation Model (acquired by the USGS), topographic and DEM-derived slope maps, and topographic and DEM-derived geological maps (1:50,000). The DEM was adequate to the slope stability evaluation of the region but failed to capture the differences between micro-topographical features; this was overcome by incorporating GPS-enabled field measurements. Geological maps provided lithological and structural information that were necessary to describe the slope materials, and slope maps created in ArcGIS were confirmed by field observation to maximize reliability.

The methodology allows determining the strength of the spatial and geotechnical data and also justifies the choice of each tool and material used to respond to the research goal of assessing slope stability in a geologically complex and highly rainfall-prone mining setting.

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Table 1: Research Tools and Their Descriptions

Research Tool	Description
Laptop	Used to run mapping application programs; the study used an HP laptop.
Mapping Software	Used to process spatial and field data; includes ArcGIS 10.8 and Global Mapper.
GPS (Global Positioning System)	Determines the position or coordinates of the bench location at PT. WBA.
Clinometer	Measures slope angle indirectly.
Tape Measure	Measures aiming distance to determine slope angle.
Smartphone	Used for documentation purposes during fieldwork.
Stationery	Used for taking notes and temporary documentation in the field.

Research Materials

Table 2: Research Materials and Their Descriptions

Research Material	Description
Satellite Imagery	Digital data of the Earth's surface captured from space; used to create regional maps through digitization and to verify the research location.
DEM (Digital Elevation Model)	Represents the surface geometry using coordinate points; used to create slope maps for the study area.
Administrative Map	Shows the location of PT. WBA; used for determining zoning of the research area in Sambalagi Village, Bungku Pesisir District, Morowali Regency.
Slope Map	Displays slope conditions in the area; utilized to analyze landslide susceptibility.
Geological Maps	Contains geological condition data, including rock types; used for analyzing the study area's geologic structure and rock composition.

Data Types and Sources

Primary Data

Primary data is data obtained from direct observations and measurements by the author. Primary data is data obtained directly from sources observed and recorded for the first time. Primary data is obtained from interviews and direct observations in the field. These data include: 1) Slope Geometry; 2) HW Slope Material Thickness; 3) Topographic Map; 4) IUP Geological Map; 5) Slope Morphology Data.

Secondary Data

Secondary data is data concerning the general conditions of the research location obtained from literature studies, relevant institutions or agencies, satellite imagery, and other data directly or indirectly related to the research. The secondary data used in this research consists of administrative boundary maps, topographic conditions, and geological conditions related to slope stability analysis. These data include: 1) Coordinates of the Mining Business License (IUP) for the Sambalagi Site of PT WBA; 2) Situation Map.

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Data Processing

Data processing was carried out using several satellite imagery and geographic information system (GIS) software, including Arc.GIS 10.5, ER Mapper v7.1, Global Mapper 15, and Microsoft Excel 2013. All data was converted into the local projection of South Konawe Regency (51 S) using the WGS 1984 coordinate system using the Universal Transverse Mercator (UTM) coordinate system. Geological Characteristics Data Processing

Geological Characteristics Data Processing

In geology, data processing plays a crucial role in understanding the geological characteristics of the research area. Geological data is collected through direct observation of the research area to obtain geological data such as lithology (rock type, topography, and geological structure). The results of the data processing are then interpreted by researchers to understand the geological characteristics, such as rock or soil type, and the geological structures developing in the research area. During field observations, researchers used a Garmin 64s GPS, a geological hammer, and a geological compass.

Land Use Data Processing

Satellite image processing was conducted to analyze land use patterns and the distribution of mining roads within the study area. Several sequential steps were undertaken to ensure the accuracy and clarity of spatial data. First, image enhancement was performed using ArcGIS 10.2 software to sharpen display quality through color balancing and contrast adjustments, thereby improving the interpretability of features. Second, image cropping was applied with ArcGIS 10.5 to isolate the area of interest, ensuring consistency between raster and vector datasets by aligning their projection datums. Third, vegetation density was evaluated using the Normalized Difference Vegetation Index (NDVI), calculated from the red and near-infrared (NIR) bands in ArcGIS 10.5, to differentiate between open and vegetated areas. Finally, the NDVI results were overlaid with Landsat 8 imagery, specifically using band combinations 4-3-2 (natural) and 5-4-3 (thermal), to enable clearer identification of land cover characteristics. This facilitated manual digitization of grassland and low-vegetation areas on-screen, allowing for a more precise interpretation of vegetation distribution in relation to mining activities.

Slope Data Processing

Slope is a crucial parameter in landslide susceptibility zone analysis. Using ArcGIS software, this process can be performed efficiently to produce accurate slope maps based on topographic data. The required topographic data is measured directly using a total station in shapefile form. This data is then analyzed (shp) using ArcGIS 10.5 software using the slope function available in ArcToolbox in the Spatial Analyst Tools > Surface > Slope module to classify slope values in the study area.

Data Collection Techniques

Data collection techniques in this study involved both direct field observations and the use of existing datasets. Field data were obtained through total station surveys to measure slope dimensions and updated mine situation maps, while the thickness of the highwall slope material on the final mining slope was recorded using GPS equipment. Additional data, including geological maps, IUP maps, topographic maps, and accessibility maps, were derived from coordinates provided by the company. Furthermore, situation maps and rainfall records were collected from company archives to support the analysis of hydrogeological conditions in the study area.

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For data analysis, slope safety factors were evaluated using soil parameter data obtained from laboratory tests conducted by PT. Wosindo Berkat Abadi and employed by Geotect Engineering as a reference for pit design in the Sambalagi site. The primary parameters considered included unit weight, internal friction angle, and cohesion, which were then applied to calculate the slope safety factor (FK). The Morgenstern-Price method, based on the limit equilibrium principle introduced in 1965, was used to analyze equilibrium conditions by considering both inter-slice shear and normal forces acting along the failure plane. The calculations were performed using Plaxis software to ensure accuracy and reliability. The resulting FK values were then evaluated against the regulatory standards outlined in Ministerial Decree No. 1827K/30/MEM/2018, which stipulates a minimum FK of 1.3 for slope stability. This combined approach provided a comprehensive framework for assessing the stability of the Sambalagi mine slopes under site-specific geotechnical and hydrogeological conditions.

Ideal Slope Dimensional Design Analysis

The ideal slope design method is achieved by reducing destabilizing forces while simultaneously increasing resistance along the slope. This can be accomplished by modifying the actual slope dimensions through three key engineering adjustments: lowering the overall slope height, widening the bench to provide greater stability, and reducing the slope angle to decrease driving forces. Once these dimensional modifications are applied, the revised slope configuration is tested or simulated to calculate the new safety factor (FK) using the geotechnical parameters of the soil samples, including unit weight, internal friction angle, and cohesion. This process ensures that the redesigned slope geometry meets the required stability standards and minimizes the risk of failure under site-specific conditions.

Results and Discussion

This chapter will describe the area, physical conditions, and population of the study area, along with the research data presented in tables and maps, and the results of the descriptive analysis of the research findings.

Research Area Conditions

PT. Wosindo Berkat Abadi has been involved in the production of nickel and it is under Nickel Production Operation Mining Business Permit (IUP) of the Governor of Central Sulawesi. The permit is grounded on Decree No. 540/518/IUP-OP/DPMPTSP/2020 dated 27 October 2020 that gives the company the right to operate in a land area of 117 hectares in Sambalagi Village, Bungku Pesisir District, Morowali Regency, Central Sulawesi Province. Nickel is the major product that is mined in this region and is one of the main components that are used in various industrial activities especially in the manufacture of stainless steel and batteries.

The geographical environment of the mining region is complicated and includes a variety of geographical features that affect mining operations. The location lies at a height of 510 to 780 metres above sea level, which also adds to a unique and diverse landscape. This region of Central Sulawesi has medium to high undulating hills as the main landscape, which has both opportunities and challenges to mining activity. The western and the southern boundaries of the area permitted are described by the comparatively flat or sloping land that stretches north-south. Such comparatively flattened areas are more workable in terms of mining and they are less subjected to soil erosion compared to steep areas.

Geologically, the region is concentrated with ultramafic rocks and conglomerates and other lithologies which are vital in the process of nickel deposit formation. These rocks are rich in minerals that are very essential in mining nickel which makes these sectors very important in

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mining activities. Conversely, a large part of the distal IUP area is made up of limestone and this affects the mining methods and processing techniques used in the area. Limestone presence may also require extra processes to recover nickel because it can influence the quality and type of ore that is found in the regions.

The heterogeneity of topography and geology of PT. The mining field of Wosindo Berkat Abadi offers the possibility of a thorough approach to resources mining. However, it also requires careful management of the environment and operations. The mining activities by the company should be undertaken in a way that counteracts the possible environmental effects which include soil erosion, water pollutions, and biodiversity reduction. The minimisation of negative impact on the local ecosystem can be achieved with sustainable mining practices, which are in compliance with the local regulations and environmental guidelines. On-going monitoring would be needed to make sure the environmental standards were met as well as to protect the natural landscape especially in regions where the terrain is flat and the rocks are of ultramafic origin which would sustain the long term life of the mining process.

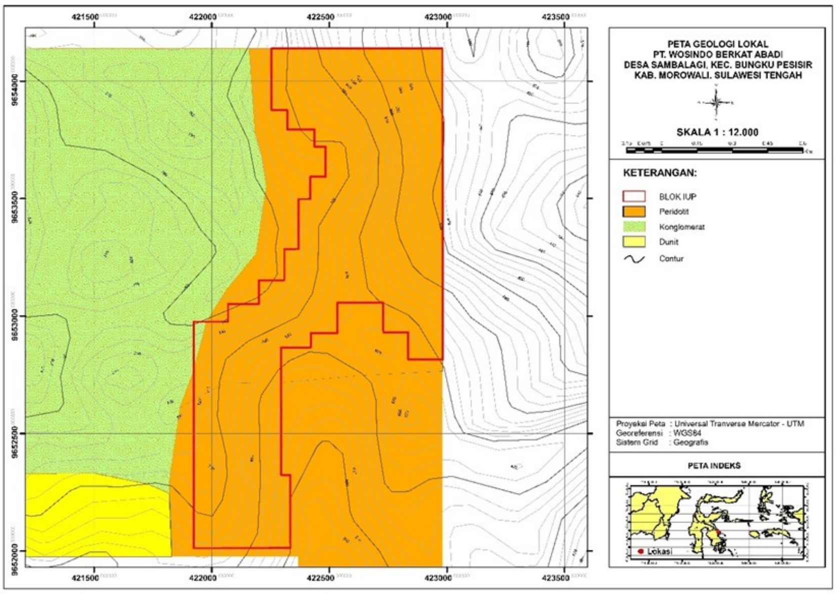

Figure 3. Geological Map of PT. WBA's Mining Business License (Source: PT. WBA Primary Data)

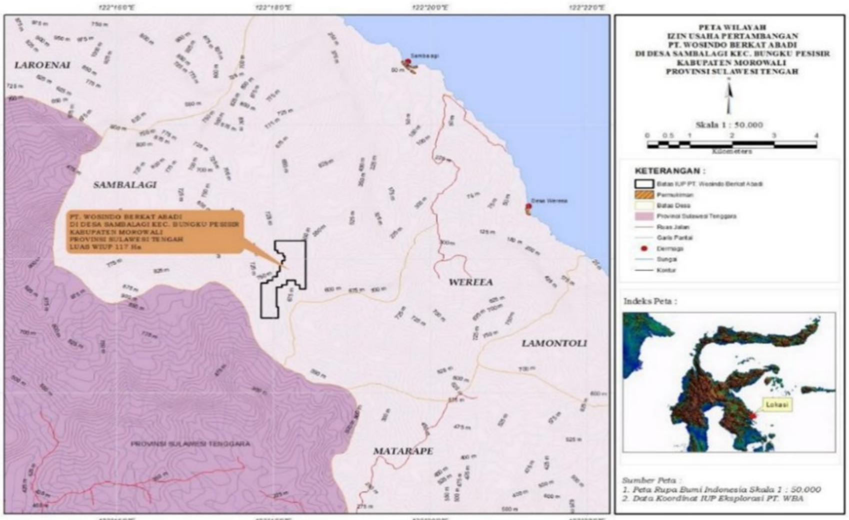

Figure 4. Research Location Map (Source, Primary Data 2024)

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Slope Geometric Characteristics and Geotechnical Parameters Affecting Slope Stability

Mining slope geometry design is necessary because it serves as input data for mine planning activities. It also refers to the Decree of the Minister of Energy and Mineral Resources No. 1827 K/30/MEM/2018 concerning the need for recommendations based on geotechnical data processing that describe the required mining slope geometry and dimensions. Therefore, mining slope geometry design is necessary to determine the height and angle of the slope, both for individual slopes and the entire slope, based on the strength of the slope's constituent materials. Slope geometry involves physical aspects of the slope that influence its stability, including:

Slope Height and Slope Angle

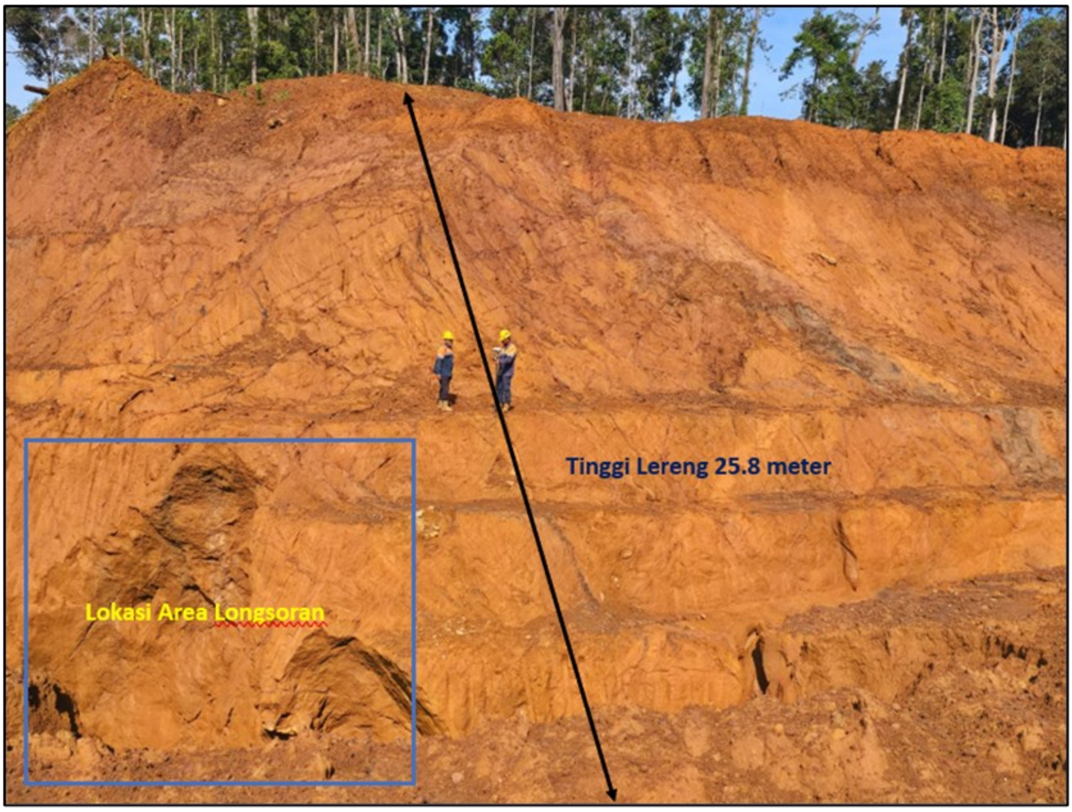

Figure 5. Slope Height of PIT D PT. WBA (Source: Primary Data 2024)

The slope stability analysis revolves around the geotechnical characteristics of the Sambalagi location. Laboratory analysis showed that saprosites and limonites, which are the major slope forming materials, possess low strengths. Saprolite had a cohesion value of 15 kPa and internal friction angle of 35 o and limonite had a cohesion of 10 kPa and same friction angle. The unit weight of both the materials was 17 kN/m 3. These values show that the slopes consist of soils that are relatively weak and are highly susceptible to shear failure when subjected to external loading and hydrological stress.

In addition to the laboratory values, it is of great importance to put these results into perspective in the environmental context of Central Sulawesi. Tropical rainfall in the region is intense, and pressure is raised in the pore water of the slope materials, lowering the effective shear strength of the slope materials. Saprolite and limonite have low permeability which leads to water intrusion that increases ground water levels and reduces adhesion between particles. The small-scale landslides observed in the rainy season in PIT D show how these hydrogeological processes directly play with the soil characteristics. These conditions suggest

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that rainfall is not a passive background process but a force which will enhance slope instabilization by reducing shear resistance.

These problems are combined with geological formation. The slope is made up of discontinuities and weak soil horizons that are located between layers of weathered ultramafic rocks, which are the possible slip surfaces. Together with the high slope geometries with an average slope of 44.4 and bench heights of over 6 meters, the site is such that any moderate external forces can cause the slope to fail.

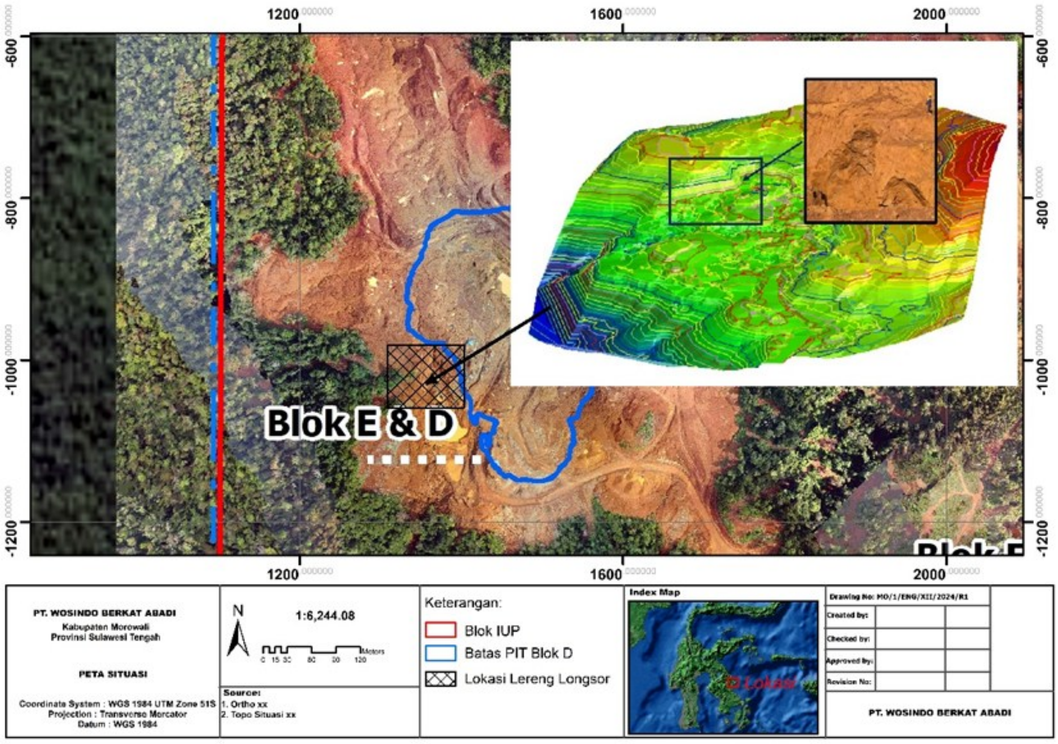

Figure 6. Situation Map of PT. WBA's Mining Business Area (Source: Secondary Data 2024)

Slope Materials

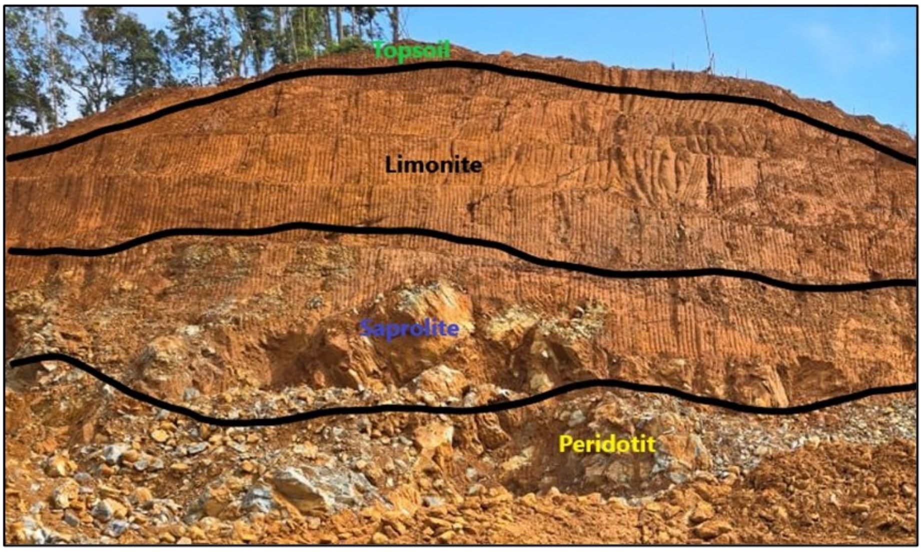

Figure 7. Materials Composing the PIT Area. PT. WBA (Source: Primary Data 2024)

Based on exploration drilling results in the study area, four layers of material were identified: soil (OB), limonite, saprolite, and peridotite. The company plans to mine nickel ore deposits,

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namely limonite and saprolite. However, it is also possible to mine peridotite, which can be used as a road construction material. According to the geotechnical team's analysis, the average compressive strength of each material is 0.563 MPa for limonite, 0.021 MPa for saprolite, and 10.615 MPa for peridotite. According to Bieniawski (1973), materials with a compressive strength of less than 1 MPa are classified as soil. Therefore, it can be concluded that limonite and saprolite are classified as soil, while peridotite is classified as rock.

Geotechnical Parameters Affecting Slope Stability

The stability of a slope is governed by a combination of geotechnical parameters that interact dynamically with site conditions. Soil shear strength, which consists of cohesion (c) and the angle of internal friction (φ), is a primary determinant, as materials with higher shear strength offer greater resistance to failure. While sandy soils typically derive stability from a high internal friction angle, clay-rich soils depend more on cohesion. Unit weight also plays a critical role, as heavier soils or rocks exert greater gravitational forces that can destabilize slopes. Consistency and density further influence stability, with denser and more compacted materials generally providing stronger resistance, though this is highly dependent on geological history. Soil permeability is another crucial factor, as low permeability can trap water within the slope, increasing pore water pressure and reducing shear strength. Relatedly, water content, particularly in saturated conditions, can significantly add to material weight and further elevate pore water pressures, thereby accelerating instability. Geological structures and discontinuities, such as fractures, faults, or weak soil layers, often act as predetermined failure planes, making their orientation and distribution key indicators of landslide potential. Finally, slope geometry interacts with these geotechnical parameters to influence failure mechanisms, whether translational, rotational, or complex ground failures. Recognizing the interplay of these factors is essential for designing effective stabilization strategies, including reinforcement, drainage improvements, or slope geometry adjustments, to ensure long-term stability.

Safety Factor (SF)

Slope stability is the resistance of soil or rock on a sloping surface (measured from the horizontal) to collapse and sliding. To express the level of slope stability, a safety factor is used, which is a value that indicates the ratio of the forces resisting the movement of material, whether soil or rock, to the forces moving the material.

The safety factor is necessary to determine the stability of a slope to prevent future landslides. In this study, the safety factor value set at ≥ 1.3 (Ministerial Decree No. 1827 K/30/MEM/2018) serves as a reference. The main data required to analyze slope stability are the soil unit weight or density (γ) in kN/m3, the cohesion value (c) in kN/m2, the angle of internal friction (θ) in degrees, the slope height (H), and the slope gradient.

The Morgenstern-Price method, supported by Slope/W modeling, was applied to evaluate the slope stability at PIT D. Using the measured geotechnical parameters, the analysis produced a safety factor (FK) of 0.974, which falls significantly below the regulatory minimum of 1.3 set by Ministerial Decree No. 1827K/30/MEM/2018. An FK value below 1 indicates that the slope is inherently unstable under current conditions, with failure likely to occur even under minor external triggers such as intense rainfall, seismic shaking, or blasting vibrations.

This finding has serious operational implications. With FK < 1, slope collapse is not a hypothetical risk but a present hazard that threatens worker safety, mine infrastructure, and production continuity. Without corrective action, further failures may be triggered during the

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rainy season, when increased pore water pressure sharply reduces the residual strength of saprolite and limonite layers.

To address these risks, engineering interventions must be prioritized. Potential mitigation measures include: To mitigate the risks associated with slope instability, several engineering interventions are recommended. Geometry modification is the primary measure, involving the reduction of slope angles from 40–51° to a maximum of 35°, coupled with lowering bench heights to 4 meters and widening benches to 2 meters, thereby reducing driving forces acting on the slope. Complementing these structural adjustments, effective drainage control is essential through the installation of both surface and subsurface drainage systems to lower pore water pressures, particularly during periods of intense rainfall. Reinforcement measures such as shotcrete application, soil nailing, or the installation of rock bolts should be applied in critical zones to strengthen weak planes and enhance overall slope resistance. Finally, continuous monitoring systems, including real-time extensometers or advanced remote sensing techniques such as InSAR, are crucial to detect early signs of displacement and provide timely warnings for preventive action. Collectively, these measures not only address the immediate geotechnical challenges of PIT D but also contribute to safer and more sustainable mining operations.

The following values are used to determine the safety factor and analyze slope stability:

Soil Bulk Density (γ)

The greater the bulk density of a rock or soil, the greater the driving force causing a landslide. Thus, the slope's stability is reduced. Based on testing and calculations, the bulk density values for the materials were found to be 17 kN/m3 for saprolite and 17 kN/m3 for limonite.

Cohesion (c)

Cohesion is the attractive force between particles in soil or rock, expressed as weight per unit area. Soil cohesion increases with increasing shear strength. The cohesion value is obtained from the liquid limit and plastic limit calculations. These calculations yielded a cohesion value of 15 kPa for saprolite and 10 kPa for limonite.

Internal Friction Angle

The internal friction angle (ϕ) is the angle formed by the relationship between the normal stress and shear stress within the soil or rock material. The greater the internal friction angle of a material, the more resistant it is to external stress. The internal friction angle of the slope material can be determined from the liquid limit and plastic limit calculations. From these calculations, the internal friction angle values for Saprolite are 35° and Limonite are 35°. The slope safety factor was determined manually using the Morgenstern-Price method and Geostudio/Slope W software.

Table 3. Soil parameters

Material	Model	Unit Weight (kN/m^3)	Cohession (kPa)	Friction Angle (^{o})
Peridotite	Bed Rock	Impenetrable		
Saprolite	Mohr Coulomb	17	15	35
Limonite	Mohr Coulomb	17	10	35

Morgenstern-Price Method

To process the data using the Morgenstern-Price method, researchers used the total slope height and average slope gradient of the soil or rock at the PT Wosindo Berkat Abadi nickel

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mine. The total height obtained from direct field measurements was 25.8 meters and the average slope was 44.4°. For material properties such as cohesion, internal friction angle, and bulk density, the researchers used the hardest and softest materials.

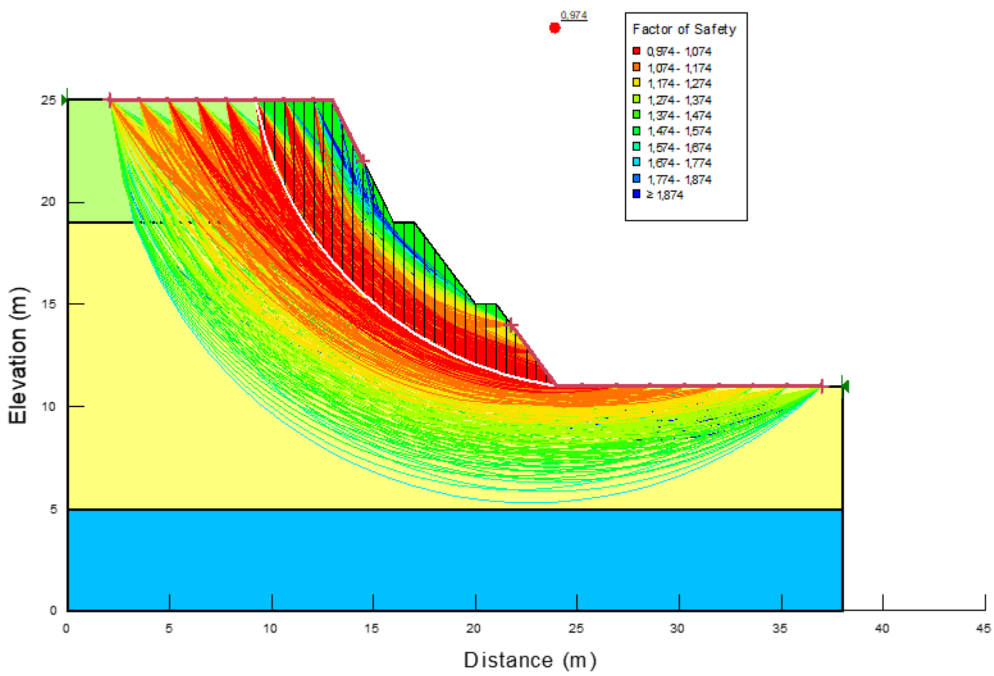

Figure 8. Safety Factor Calculation Results

Based on Figure 8, the safety factor calculation was assisted by slope modeling and safety factor calculation software. The safety factor calculation utilizes the limit equilibrium method, with more detail using the Morgestern-Price method and the Mohr-Columb failure criterion. The Morgestern-Price method analyzes the equilibrium results of each normal force and moment acting on each slice of the slope failure plane. This method makes simplifying assumptions about the relationship between the shear forces around the slice and the normal forces around the slice.

Compared to other limit equilibrium methods, this method is one of the most accurate in slope stability analysis. This method is highly flexible and can be used for all types of slopes, with homogeneous or heterogeneous materials, and all types of landslides. This is the basis for using the Morgestern-Price method in this study.

Table 4. FK values on the actual Highwall slope of PIT D

Sayatan *(Section)*	Nilai FK Aktual
PIT D	0.974

This work demonstrates that slope stability in mining ceases to be seen as a technical engineering question, but a concern of the mining management, and can directly affect the sustainability of operations, financial performance, and legal adherence. A safety ratio of less than one (FK < 1) at the Sambalagi location is not merely an engineering exception, but a deep management issue that reflects an organisational weakness in its governance systems and decision-making processes. Homyack (2024) claims that geotechnical risk is constantly one of the most urgent operational risks that mine operators have to face and address regardless of the level: both technical and corporate. Poor consideration of such risks has

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already been associated with disastrous failures and resultant financial damage (Salisbury & Salisbury, 2022).

Slope instability is directly related to financial strategy and risk governance as a managerial issue. According to research conducted by Salisbury & Salisbury (2022), inadequate early geotechnical data assembly causes costs in redesign, production delays, and in certain instances the mining project may be suspended. According to Sun et al. (2022), the financial risk associated with the downstream instability is greatly mitigated during the feasibility stage through the investment in solid geotechnical datasets. This is consistent with the general management literature which highlights the importance of risk anticipation as a strategic asset in asset-intensive industry (Nakhli et al., 2024). The mining manager implication is obvious: slope stability needs to be a strategy investment that is budgeted and controlled rather than a discretionary technical cost.

The relevance of ensuring slope stability is incorporated in formal management systems in the recent changes in the corporate geotechnical governance has been highlighted. one of the most successful examples of multi-site slope risk aggregation into a coherent framework that informs local activity and corporate control is the Rio Tinto Geotechnical Management System (GMS). These structures enshrine technical vigilance and make it part of managerial accountability systems (Read & Stacey, 2009). The current research confirms this management requirement: an FK of 0.974 does not only pass a regulatory stress test, but it reveals the insufficiency of the existing practices in integrating geotechnical control into executive decision-making procedures.

Monitoring and adaptive management can also play an important role. TARPs have been identified as the key tool in bridging the divide between technical risk evaluation and operation practice (Lawal et al., 2024; Pruvot et al., 2023). TARPs make slope monitoring no longer a passive data-collection operation by connecting thresholds to managerial actions. As the case of Victor Diamond Mine demonstrates, adaptive monitoring frameworks can not only contribute to the increase in the safety of closure but also reduce long-term liabilities. The introduction of such systems in Sambalagi would make the instability signals converted into managerial responses instead of delayed technical responses.

This study has a methodological implication which can be considered a managerial value. Limit equilibrium is a useful tool, but it is only able to provide a partial picture of slope performance, because of the traditional deterministic character of the technique. Recent publications suggest the combination of probabilistic and multi-criteria decision making schemes, including Monte Carlo simulations, fuzzy logic and TOPSIS structures, to be more representative of uncertainty (Pellegrino et al., 2024; Williams et al., 2024; Hoek & Bray, 1981). These approaches are complementary to traditional practices and may be used to support managerial decisions by contextualizing the geotechnical risk in probabilistic and strategic terms (Agrawal et al., 2024). Not only does the managers receive a pass/fail output but also has an informed risk distribution that can help them in investment and contingency planning.

Technology innovation also redefines managerial capacity to manage geotechnical risks. Early-warning capability has been demonstrated to significantly increase with the implementation of the real-time monitoring system, such as InSAR, movement radar, or even IoT-enabled sensor networks (Kumar, 2024). Wireless sensor networks are also becoming widely available at lower prices and in combination with inertial measurement devices (IMUs), which can be used to monitor the slope. These technologies expand geotechnical monitoring beyond periodic testing to constant monitoring and change the managerial

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paradigm, where managers are interested in anticipating and governing the organization and its processes instead of responding to crisis. These tools, when adopted in Sambalagi, would bring local practice at par with international best practice in risk-based mining operations.

The overall implication is both cultural and organizational beyond technology. According to Ayeh & Bleicher (2021), to integrate geotechnical vigilance into the governance culture of mining companies, it is impossible to do without qualitative risk assessment and external geotechnical review boards. This coincides with management research pointing to the role of risk culture and not just the use of formal procedures that defines the outcomes of organizational responses to new threats. According to Sambalagi, the evidence indicates that there is a need to change the culture, where slope stability is not seen as a technical value, but as a long-term management focus that is directly related to the safety of workers, social license to operate, and shareholder value.

Conclusion

The landslide vulnerability zone, based on geological characteristics in the PT. Wosindo Berkat Abadi mining area, has steep topography (25-60%) and is composed of laterite soil, a weathered form of ultramafic rock, which is highly susceptible to landslides. This is evidenced by the landslide at PIT D. The actual static slope safety factor of PIT D, based on each section, still does not meet the criteria stipulated in the Decree of the Minister of Energy and Mineral Resources No. 1827K/30/MEM/2018. A landslide mitigation method is needed, namely by recommending changes to the actual slope geometry design of PIT D. This recommendation includes reducing the slope angle, widening, and reducing the height at each slope level. The slope angle is tapered to 35º from the original 40º - 51º for all sections, widening the steps to 2 meters from the original 1 meter, and reducing the height of the steps to 4 meters from the original 4.5 - 6.6 meters. From the recommendations for changes to the actual slope geometry of Highwall PIT D, the static safety factor value is ≥ 1.3 according to the Decree of the Minister of Energy and Mineral Resources number 1827K / 30 / MEM / 2018.

Recommendations

A landslide hazard assessment of the PIT D mining area of PT. Wosindo Berkat Abadi is an important strategic step in identifying potential hazards and developing effective mitigation measures. This assessment provides scientific data that can be used to improve mine operational safety and prevent losses due to landslides. With an assessment-based approach, mining companies can ensure sustainable environmental management and protect employees and surrounding communities.

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