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Engineering Geology Characteristics in Landslide Mitigation at Nickel Mining Sites for Mining and Environmental Safety

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ABSTRACT
This study investigates the geological characteristics and soil movement types associated with landslide mitigation at nickel mining sites, focusing on PT IFISHDECO Tbk in Southeast Sulawesi. The primary objective is to analyze factors influencing slope stability and develop effective mitigation strategies. The research employs a combination of field observations, geotechnical drilling, and literature reviews to identify key contributors to landslide risk, such as geomorphology, rock types, and hydrological conditions. Findings reveal that wedge sliding is the predominant soil movement type, with Safety Factor (FK) values ranging from 0.91 to 1.37, indicating varying degrees of slope stability. The study addresses critical research gaps by providing a detailed understanding of the geological dynamics specific to nickel mining sites—a subject insufficiently explored in current literature. The research implications extend to mining safety practices, suggesting that tailored mitigation strategies, such as slope reinforcement and hydrological control, could significantly improve site stability. Furthermore, the study offers practical recommendations for integrating landslide hazard mapping into mining operations, enhancing both safety and environmental sustainability. This research holds substantial policy and environmental relevance, urging policymakers to adopt more stringent geological assessment protocols and invest in advanced soil stability measures. Ultimately, the study contributes to both scientific understanding and the practical enhancement of mining operations by offering valuable insights into preventing landslides in mining areas.
Keywords: Landslide, Nickel Mining, Slope Stability, Soil Movement, Geology.

INTRODUCTION

Nickel mining companies that have been operating from 2010 to 2024 hold an Exploration IUP License No. 2249 of 2008, which was upgraded to a Production Operation License Decree No. 132 of 2010 issued by the Regent of South Konawe. They also possess a license from the Ministry of Energy and Mineral Resources Number 210/DPMPTSP/III/2019 under the *KEPMEN of Energy and Mineral Resources of the Republic of Indonesia* No. 1827 K/30/MEM/2018 concerning Guidelines for the Implementation of Good Mining Engineering Principles.

Laterite nickel is one of the abundant mineral resources in the Sulawesi region, particularly in Southeast Sulawesi (Arif, 2016; Bogor & Barat, 2011; Capoeira et al., 2021; Crozier & Glade, 2012; Somptan, 2012). This metal has significant economic value due to its wide range of uses, including in the production of stainless steel, laboratory equipment, medical devices, household appliances, and other applications (ESDM, 2018; Fikri et al., 2022; Gloria et al., 2020; Hedianto et al., 2023; Indriani et al., 2017).

Laterite nickel deposits are formed through the weathering of ultramafic rocks rich in minerals such as olivine, pyroxene, and amphibole, leading to mineral enrichment with nickel (Ni) levels ranging from 0.2% to 0.4%. The formation of these deposits is influenced by several factors, including topography that tends to be sloping (<25°), fracture density in rocks, high rainfall, and nickel content derived from the parent rock (Ikram & Yuliadi, 2022; Jaya Saputra Iman et al., 2022; Komadja et al., 2021; Manullang, 2020; Matius Sesa et al., 2024).

Laterite nickel mining activities are carried out by adjusting to the characteristics of cracks typically exposed on the surface, especially in hilly and sloping areas (GeoDept Ifishdeco, 2024). Therefore, the open-pit mining method was selected as the most effective approach under these conditions. This method transforms the original topography into basin- or valley-like forms with stepped mining slopes (Pasha et al., 2018; PUPR, 2021; Putrilia et al., 2022; Rahmatullah et al., 2024; Widianita, 2023). However, these changes can increase the risk of landslides or soil movements due to unstable slope conditions.

Direct field observations in the mining area, particularly in the North Block, Green Pit Sub-Block, revealed land movement in the form of landslides caused by slope instability. Indirect information gathered from research journals supports this observation. For instance, Nugroho et al. (2022) reported 58 mass movement incidents, including landslides, sinkings, rock falls, and creeps, at PT Aneka Tambang UBPE Pongkor between 2017 and 2022, some of which disrupted mining operations. The gap between their study and this one lies in the lithological factors analyzed; Nugroho focused on gold, while this study examines laterite nickel deposits. Similarly, Giffari et al. (2020) studied slope deformation at PT Bukit Asam Tbk, reporting seven landslides between 2022 and 2023 with a focus on dynamic Safety Factors (FK), whereas this study analyzes static FK using different materials. Azizi (2019) explored rainwater-triggered landslides at PT X's mining pit but did not address soil movement types, slope safety factors, or mitigation mapping—elements included in this research. Lastly, unlike reports of illegal mining landslides in North Sulawesi related to gold, this study focuses on legal nickel mining operations.

Geological exploration and modeling in the Green Pit area revealed potential nickel deposits suitable for economic exploitation. However, from a geological perspective, this area is vulnerable to soil movement, particularly under open-pit mining methods (Anatoly & Rofikoh, 2022). To reduce these risks, mitigation measures, including slope stability analyses and landslide hazard mapping, are necessary.

Based on field observations in the Green Pit area, literature studies, and online reports about mining-related landslides, the author conducted in-depth research under the theme of *Engineering Geology Characteristics in Landslide Mitigation at Nickel Mining Sites for Mining and Environmental Safety*.

The geological engineering characteristics analyzed in this study refer to geological properties that influence rock behavior from an engineering perspective, especially regarding the potential risk of soil movement in open-pit mining areas. The primary controlling factors identified in the analysis of potential soil movement hazards (Karnawati, 2005) include geomorphology, rock/soil composition, geological and geohydrological structures, and land use.

Previous studies on landslide risk in mining operations have generally been site-specific and focused on particular materials. Nugroho et al. (2022), for example, examined mass movements at PT Aneka Tambang UBPE Pongkor with an emphasis on gold mining. This study fills a gap by focusing on laterite nickel deposits, which present unique geological and movement characteristics. It highlights the challenges typical of nickel mining sites, including the effects of topography, rainfall, and soil composition on slope stability. Giffari et al. (2020) analyzed slope deformation at PT Bukit Asam Tbk, emphasizing deformation behavior prior to landslides. Unlike their dynamic FK analysis, this study investigates static FK values, offering insights into slope stability for nickel mining. By integrating geological characteristics with safety factor analysis, it contributes to the development of landslide hazard mitigation maps specific to nickel mining operations.

This research aims to analyze soil movement types, evaluate slope Safety Factors (FK), and develop hazard and mitigation maps for potential soil movements in the Green Pit area of PT IFISHDECO Tbk. The study's benefits include providing critical data for safer mine design, improving understanding of slope stability, and supporting Occupational Safety and Health (K3) practices. Moreover, it aids in managing mining resources responsibly, ensuring compliance with the environmental and safety standards set by the Ministry of Energy and Mineral Resources. It also contributes to the broader mining industry by reinforcing risk management strategies and promoting sustainable mining in Southeast Sulawesi.

The research objectives are to analyze soil movement types within the Green Pit mine slope area (Hook et al., 1981), determine the Safety Factor (FK) values and landslide probabilities for the Green Pit slope based on the Ministry of Energy and Mineral Resources Regulation No. 1827 K/30/MEM/2018, and design potential soil movement hazard and mitigation maps for the area. The study provides PT IFISHDECO Tbk with information about areas susceptible to landslides in the Green Pit zone, forming a basis for early mitigation and safety measures.

METHOD

The research design was implemented as a systematic process involving data collection and analysis, beginning with observation and evaluation of available information to form a framework requiring further evidence. This served as a guideline for conducting the study so that data could be collected, processed, and analyzed in accordance with the research objectives.

The implementation consisted of several stages, including making observations, selecting measurement variables, determining techniques and procedures, collecting data, using research instruments, analyzing data, determining samples, and compiling research reports. The characteristics of the research design influenced the type of data collected and, consequently, the results obtained.

This study employed a combination of quantitative and observational approaches, which involved collecting numerical data from measurements, analyzing variables, and observing conditions without manipulating existing variables. The research was conducted at the nickel mine of PT IFISHDECO Tbk in the North Block, Roraya Village, Tinanggea District, South Konawe Regency, Southeast Sulawesi Province.

The data used included primary data obtained directly from sources, such as topographic surveys, geological structure measurements, and local geological mapping, as well as secondary data from related documents and reports. Data collection was carried out through field observations and literature studies. Field observations included direct inspections for problem identification and required data collection, while literature studies involved gathering information from relevant publications.

Data analysis was performed using geomorphological, lithological, geological structure, hydrogeological, and geotechnical test results, enhanced with engineering software. The analysis produced an identification of the type of soil movement, recommendations for slope safety factor values, and a map of potential soil movement hazards in the mine pit as a mitigation measure.

RESULTS AND DISCUSSION

Discontinuity Orientation Mapping Results (Sturdy)

The research method consists of observation which is the systematic observation and recording of geological elements seen in the research object, namely the slope using the help of a 10 m long scanline span which is a method of measuring the position of rocks (strike/dip) directly at the research site and carrying out an inductive approach in calculating and processing data.

Drilling Results and Engineering Geological Sample Test (GEOTEK)

Geotechnical drilling is carried out to determine the strata or layers of soil and rocks under the earth's surface, the type, and the condition of the soil and rocks in the area to be studied. GeoTek drilling that has been carried out amounting to 2 points with a space of 50 m by the consultant, is secondary data in this study. The secondary data obtained are the mechanical properties of rocks in the form of rock specific gravity in each layer zone, rock compressive strength (kPa), deep shear angle (Phi) and rock permeability value (Ru). These data are required in the processing process to determine the value of the Safety Factor (FK) of the mine slope. The SPT value obtained shows that at a depth of 12 meters, the hardness coherence of the layer is more stable.

In this geotechnical drilling, the full coring method is used per 1 meter and the sampling of rock layers per 2 meters, which is then prepared in an undistrub manner with the aim of maintaining its original condition from nature so that in laboratory testing it obtains the most ideal value possible in the field.

The GeoTek drilling point reference is based on the planning for the development of mining land openings, supporting data is needed for special pit design on slope stability and design for the construction of inpit roads.

Results of data processing of Topographic, Drainage, Morphology, Geohydrology

The primary data processing above uses the Global Mapper application with geological criteria such as the type of contour density to distinguish the height and low of an elevation, slope slope, and interpolation of groundwater level depth based on the water drainage pattern at the ground surface.

The orientation of this soil movement research is based on the researcher's knowledge in the field of geology, as well as data collection that refers to the actual conditions at the location of PT IFISHDECO Tbk's mining green pit in 2024, with the following geological characteristics:

1. Geomorphological conditions: The laterite nickel deposit potential is located in areas with a sloping to steep morphology, with slope slope angles between 10° – 25° and mine slope analysis >45°.
2. Rock Conditions: Laterite nickel deposits in the Limonite and Saprolite zones are covered by sedimentary rocks originating from the Langkowala Formation.
3. Geological Structure Conditions: The uplift of ultramafic bedrock from the ocean floor to the earth's surface due to tectonic processes forms a sloping to steep topography and produces a distribution of geological structures in the form of faults and burrows.
4. Hydrogeological Conditions: The groundwater table in the rock layer affects the binding power of the rocks related to the shape of the rock grains and their porosity. The higher the level of water saturation in the rock layer, the greater the potential for soil movement at a certain slope angle of the cliff.
5. Land Use Conditions: Mining activities can change land use to be unstable to the stability of the slopes around the mining pit, thereby increasing their hazards and vulnerabilities, which can lead to catastrophic soil movements.

Analysis of Soil Movement Type on the Slope of the Green Pit Mine

Analysis of the potential for soil movement or rock slope collapse can be carried out using stereographic techniques. This method is a graphical approach to determining the angle and slope of a plane, which is widely used to identify the type and direction of avalanches or collapses that may occur. By simultaneously plotting the slope and slope and weak fields on the stereonet, the type and direction of the collapse can be identified. The determination of the potential for collapse in rock slope cutting activities is carried out through discontinuity orientation mapping, both before and after the slope is exposed (Hoek., et al. 1981).

Rock mass

Rock mass is the volume of rock that consists of rock material (minerals, texture, and composition) and discontinuous fields that are interconnected and form a unit. The strength of the mass of the rock is affected by the frequency of the discontinuous field, so its strength is lower compared to that of a whole rock. According to Hoek, et all (1981), rock mass is an in-situ rock that is discontinuous due to structural systems such as joints, faults, and layering planes.

Structure Batuan

The structure of the rock describes the appearance and condition of the rock, including its shape and position. Based on the process of its formation, the rock structure is divided into:

1. Primary structure: Structures formed during the rock formation process, such as cross bedding in sedimentary rocks or cooling joints in igneous rocks.
2. Secondary structure: Structures that form after rocks are formed due to deformation or tectonic processes, such as folds, faults, and joints.

a) Areas of Discontinuity

The discontinuity field is generally the field that separates the mass of the rock into separate parts. Priest (1993) defines a discontinuity field as any weak field that occurs in the area with the lowest tensile strength in the rock. Gabrielsen (1990) explained that the occurrence of discontinuity is influenced by changes in stress, strain, temperature, mineralization, and recrystallization that take place in rock masses over a long period of time. The types of discontinuity fields can be grouped according to their size and composition, including: Fault (fracture), Joint (burly), Bedding (layer plane), Fracture and crack.

Of all the types of discontinuity fields, joints are the most often considered, because they are fields of discontinuity that have broken and opened, thus becoming weak fields. Joints are also almost always present in rock masses, making them an important factor in geotechnical analysis compared to other types of discontinuity fields.

b) Kinematics Analysis

Different types of soil movements/slope collapse are related to geological structure and field orientation that result in a discontinuity in a rock mass. One of the methods that is often used to identify and characterize the discontinuity field in rock slope outcrops is the scanline (Hook & Bray, 1981).

The results of the plotting are very useful to be able to choose between areas that have the potential to collapse, and those areas that are unlikely to be involved in the avalanche. The kinematic factor of the slope is said to be qualified to cause slope stability when on the slope there is space for the block of rock mass to move on the plane of its slip towards that space (Hoek., et al. 1981).

c) Type of Soil Movement / Collapse on the slope of the green pit mine

From the results of ST-01 stroographic plotting (Appendix 7,) and based on the following values of geological characteristics of rock mass engineering:

1. The position of the weak (burly) field in the ST-01 pair is JS_01 N 330°/68° E and JS_02 N 134°/54° E.
2. The position (strike/dip) of the clay rock that is in contact with the limonite is N 70°/15° E.
3. Mine slope slope at 78°, Dip Direction 120°
4. Friction Angle 37°
5. Wedge sliding direction N 144° E / plunge 14°

The results of the kinematic analysis of the type of soil movement / slope collapse are wedge sliding with the direction of soil movement to the southeast of the open slope of the mine,

From the results of ST-02 stroographic plotting (Appendix 7) and based on the geological characteristics of rock mass engineering as follows:

1. The position of the weak (burly) field in the ST-02 pair is JS_01 N 99°/79° E and JS_02 N 156°/78° E.
2. The position (strike/dip) of the clay rock that is in contact with limonite is N 72°/18° E.
3. Friction Angle 37°
4. Wedge sliding direction N 222° E / plunge 77°

The results of the kinematic analysis of the type of soil movement / slope collapse are wedge sliding with the direction of soil movement to the Southwest. Based on the results of the interpretation of the cararteristic geology, engineering and kinematic analysis in the field of the green pit mine slope, it provides information on the results of the research described below:

1. Erosion type (soil movement); Wedge Collapse (wedge sliding)
2. Wedge collapse occurs in rocks that have more than one free discontinuous (burly) plane, with the angle between the two planes forming an angle (Plunge 14° – 77°) that is greater than the angle of deep shear (37°). The most common phenomenon is that the intersection of two burly planes has a slope of N 144° E / N 222° E) towards the slope (N 120° E / N 200° E). The direction of soil movement to the Southeast - Southwest from the face of the mine slope.

Safety Factor (FK) Value and Probability of Landslide Green Pit Mine Slope Based on the Ministry of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2018

Safety Factor (FK) values and mine slope landslide probabilities are two very important things in slope stability analysis. These two concepts are used to assess whether the mine slope is safe or at risk of landslides. The Indonesian Ministry of Energy and Mineral Resources Standard No.1827 K/30/MEM/2024 provides guidelines and standards for calculating FK and landslide probabilities on mine slopes, which must be complied with by mining companies to ensure the sustainability of operations and safety. Safety Factor (FK) and Probability of landslide on the slope of the green pit mine, using the Bishop Simplified method with Mohr-Coulomb analysis processed in the application of the Slide ver.6

a. The Safety Factor (FK) measures how safe a slope or soil structure is under certain conditions, considering the cohesion strength of the soil, the angle of friction, and the load acting on the slope. The FK value of > 1 indicates that the slope is stable and not at risk of landslides, while the FK value < 1 indicates the potential for landslides. To calculate FK on the slope of a green pit mine, the parameters used include:
    a) Soil cohesion (c), which measures the adhesion strength between soil particles.
    b) Internal friction angle (φ), which indicates the resistance of the soil to shear movement.
    c) The specific gravity of the wet soil (γ), which affects the load acting on the slope.
    d) changes in conditions (Ru), such as rainfall or changes in load due to mining activities.
b. The probability of landslides is measured based on geotechnical conditions in the field. The probability of land movement (landslide) is obtained using the Probability of Failure (Max) PoF (FK<1) in the classification of landslide severity from types of mine slopes (Kepmen of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2024)

The section line of the green pit mine slope is based on the density of the elevation contour line and cuts in the plane of the rock layer from North to South as well as the geological structure.

The orientation of the space between the lines of the section ± 40 meters with a display ± 90 meters. The section is divided into 3 sections that stretch from east to west. The purpose of the section is to identify slope stability.

1. Slope Stability Conditions Based on Safety Factors (FK)
   The analysis shows variations in slope stability conditions based on safety factors (FK) for different slope levels:
   FK 0.91 (Single Slope - Unstable): Unstable slope conditions, where the triggering force (such as gravity or pore pressure) has exceeded the ground-retaining force. The potential for landslides is very high and can occur at any time, especially if there are external factors such as heavy rain, earthquakes, or additional loads. A single slope with an FK of 0.91 requires immediate mitigation to prevent collapse.
   FK 1.18 (Single Slope - Balanced): The slope is in a balanced condition, where the holding force is almost the same as the trigger force. Slopes are sensitive to external disturbances such as erosion, increased pore water pressure, or human activities. The stability of this FK can still be maintained if there are no major changes in environmental conditions.
   FK 1.20 (Inter-ramp Slope - Balanced): The stability of the inter-ramp slope indicates balanced conditions but does not fully meet geotechnical design standards (FK ≥ 1.3). These inter-ramp slopes are more stable than single slopes, but they remain susceptible to triggers, especially in extreme weather conditions or slope geometry changes.
   FK 1.37 (Overall Slope - Stable): The overall slope is considered stable, meeting the minimum geotechnical safety threshold for design (FK ≥ 1.3). Although globally stable, local risks may arise in areas with lower FK (such as single slopes and inter-ramps).
2. Avalanche Severity
   High Severity (FK 0.91): The potential for landslides is massive and can cause significant damage. Impacts include the collapse of large volumes of material that have the potential to damage infrastructure around the foot of the slope and jeopardize safety for mine workers
   Medium Severity (FK 1.18 and 1.20): Landslides tend to be local, but still have a significant impact on environmental functions, such as transportation access or operational activities in the area around slopes. The risk is more controlled than the FK 0.91 but requires attention to reduce the potential for ground movement.
   Low Severity (FK 1.37): The overall slope is considered safe from massive landslides, but it is still necessary to anticipate the possibility of minor landslides in critical areas or weak areas.
3. Causes of Instability and Vulnerability
   Single Slope (FK 0.91 and 1.18): Layers of soil or rock with low cohesion and small deep shear angles are the main culprits. High pore water pressure due to poor drainage increases susceptibility to landslides.
   Inter-ramp slope (FK 1.20): The combination of weak layers such as clay or saprolite with a critical shear plane can be the cause of decreased stability. The influence of human activities such as cutting slopes or additional loads magnifies the risk.
   Overall Slope (FK 1.37): Globally, the material is more stable due to a more even distribution of forces. However, it is necessary to pay attention to certain layers that have the potential to weaken local stability.

4. Landslide probabilities

   The probability of landslides on the slopes of the green pit mine as a whole ranges from 10 - 50% with the severity of the landslide classified in the medium category. According to the Ministry of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/2018, the category of moderate landslide severity is when there are consequences for serious human injuries, damage to facilities and infrastructure from 25% to 50%, production stoppage for more than 12 hours to less than 24 hours, buried reserves but can still be taken, and environmental damage still within the scope of the IUP area.

Referring to the FK value in the topological area along the section line – 01, the potential for soil movement is controlled by technical geological characteristic factors in the form of geomorphology of steep slope slopes > 45°, limonite rock layers, highly weathered samples, sandstone with low porosity, the position of the rock layer (strike/dip) intersecting with the discontinuity plane of the geological structure in the form of burly which forms a weak zone of the slip plane, geohydrology in the distribution of groundwater in the rock layer which weakens the density of rock mass, as well as mining activities in the face of external disturbances on the slopes that trigger soil movement.

Based on the input of the technical geological characteristics data of each rock layer using the Bishop method and Mhor-coulomb analysis as well as the actual slope analysis of the section-02 line (appendix.16).

1. Slope Stability Conditions Based on Safety Factors (FK)

   Slope stability analysis based on safety factors (FK) yields the following data:

   FK 1.19 (Single Slope - Balanced): The slope is in a balanced condition, where the ground holding force is almost the same as the trigger force. Although stability can still be maintained, these slopes are highly sensitive to environmental changes, such as increased pore water pressure, erosion, or additional loads. Simple mitigation interventions, such as water management and slope reinforcement, can improve safety factors.

   FK 1.25 (Inter-ramp slope - Balanced): The inter-ramp slope shows balanced conditions but is still close to the minimum limit of geotechnical standards (FK ≥ 1.3). Slopes tend to be safe under normal conditions, but they need to be monitored to ensure there is no deterioration in stability due to human activities or environmental changes.

   FK 1.19 (Inter-ramp Slope - Balanced): On other segments of the inter-ramp slope, stability again shows a balanced value. This slope requires more attention than segments with higher FK, especially to prevent disturbances that can trigger collapse.

   FK 1.37 (Overall Slope - Stable): The overall slope is in stable condition, with safety factors that meet geotechnical design thresholds. Global stability indicates the ability of slope structures to withstand trigger forces under normal conditions and most external disturbances.

2. Avalanche Severity

   Medium Severity: Areas with a FK of 1.19 (single slope and part of inter-ramp slope) have a medium risk of landslides. Landslides that occur are likely to be local and have more impact on operational efficiency than major structural damage.

Low Severity: Areas with a FK of 1.37 on the overall slope have a low risk of landslides, with minimal environmental and operational impact. Global stability helps prevent large-scale collapse.

3. Causes of Stability and Vulnerability

   Single Slope (FK 1.19): Weak material properties or high pore water pressure increase slope susceptibility. Steep slopes without an adequate drainage system worsen stability.

   Inter-ramp slope (FK 1.19 - 1.25): Changes in geometry or additional load (e.g., machine activity) can affect stability. Lithological influences, such as saprolite or clay layers with low shear strength, are important factors.

   Overall Slope (FK 1.37): A combination of more stable rock layers, such as limonite or solid materials, contributes to global stability. A good drainage system helps reduce the water pressure of the pores in the critical layers.

4. Landslide probabilities

   The probability of landslides on the slopes of the green pit mine as a whole ranges from 10 - 25% with the severity of the landslide classified in the medium category. According to the Ministry of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/2018, the category of moderate landslide severity is when there are consequences for serious human injuries, damage to facilities and infrastructure from 25% to 50%, production stoppage for more than 12 hours to less than 24 hours, buried reserves but can still be taken, and environmental damage still within the scope of the IUP area.

Based on the analysis of the value of Safety Factors (FK) in the topographic area along the section-02 line, the potential for soil movement is influenced by a number of engineering geological factors. The main factors include geomorphological characteristics in the form of steep slope slopes with an angle of >45°, the presence of limonite and saprolite rock layers that have experienced high weathering, and sandstone with low porosity. The position of the rock layer (strike/dip) that interacts with the discontinuity plane, such as the burly, forms a weak zone that serves as a potential slip plane.

In addition, geohydrological conditions also play a significant role, especially through the distribution of groundwater that weakens the density of rock masses and affects slope stability. Mining activities in this area are also external factors that accelerate disturbances to the stability of the slopes, thus triggering soil movement. The combination of these factors creates conditions of high vulnerability to soil movement in the area.

Based on the input of the technical geological characteristics of each rock layer, the Bishop method and Mhor-coulomb analysis as well as the actual slope analysis of the section-03 line (appendix. 17).

1. Slope Stability Conditions Based on Safety Factors (FK)

   Slope stability analysis based on safety factors (FK) yields the following data:

   FK 1.13 (Single Slope - Balanced): The slope is in a balanced condition, where the ground retaining force is almost equivalent to the trigger force. These slopes have a high level of susceptibility to external disturbances, such as increased pore water pressure or human activity. This condition requires mitigation measures to avoid potential landslides.

FK 1.26 (Single Slope - Balanced): The stability of the single slope at this value is in the balanced category, although it is close to the geotechnical design standard safety threshold (FK $\geq$ 1.3). These slopes are generally safe under normal conditions but still require regular monitoring to anticipate a decrease in stability due to environmental changes.

FK 1.15 (Inter-ramp Slope - Balanced): Inter-ramp slope exhibits balanced conditions, with susceptibility to pore water pressure or additional load changes. This section requires more attention than other slope segments to ensure its stability is maintained.

FK 1.31 (Overall Slope - Stable): The overall slope is in stable condition, with safety factors that meet geotechnical standards for design. Global stability is quite good, but it still requires anticipation of local risks from slopes with lower FK.

2. Avalanche Severity

   Low Severity (FK 1.26 and FK 1.31): The risk of landslides is relatively low on single slopes (FK 1.26) and overall slopes (FK 1.31). The landslides that occur are local with minimal impact on the structure and the surrounding environment.

   Medium Severity (FK 1.13 and FK 1.15): Areas with FK 1.13 (single slope) and FK 1.15 (inter-ramp slope) have a moderate risk of landslides, especially when affected by external factors such as heavy rain or heavy activity. Landslides in this section can have an impact on operations and have the potential to spread if not handled immediately.

3. Causes of Stability and Vulnerability

   Single Slope (FK 1.13 and FK 1.26): High pore water pressure due to less effective drainage systems can affect stability. Weak materials such as clay layers or saprolite increase the potential for collapse.

   Inter-ramp slope (FK 1.15): A combination of low deep shear angles on certain layers and the influence of additional activities such as machine loads can cause vulnerability.

   Overall Slope (FK 1.31): Global stability is aided by an even distribution of forces, but it is necessary to anticipate local influences from sections with low FS.

4. Landslide probabilities

   The probability of landslides on the slopes of the green pit mine as a whole ranges from 10 - 50% with the severity of the landslide classified in the medium category. According to the Ministry of Energy and Mineral Resources of the Republic of Indonesia Number 1827 K/30/MEM/2018, the category of moderate landslide severity is when there are consequences for serious human injuries, damage to facilities and infrastructure from 25% to 50%, production stoppage for more than 12 hours to less than 24 hours, buried reserves but can still be taken, and environmental damage still within the scope of the IUP area.

Based on the analysis of the value of Safety Factors (FK) in the topographic area along the section-03 line, the potential for soil movement is influenced by a number of engineering geological factors that interact with each other. The main factors include geomorphological characteristics, which include the slope of steep slopes with angles greater than 45°, as well as the presence of layers of limonite and saprolite rocks that are subjected to high weathering. In addition, sandstone that has low porosity also contributes to the reduction of cohesion between rock grains, thereby increasing its susceptibility to the movement of soil masses.

The position of the rock layer, determined by the direction of the dip strike, intersects with various areas of geological discontinuity, such as burrows or cracks, that form weak zones. This zone serves as a potential slip field, which can facilitate the movement of soil masses along the field. In addition, geohydrological factors, especially the distribution of groundwater, also play an important role in weakening the density of rock masses, which in turn affects slope stability. Mining activities that occur in this area are external factors that worsen geotechnical conditions, by increasing disturbances to slope stability. These disturbances, which include changes in load distribution, increased groundwater pore pressure, and changes in geological structure due to mining activities, have the potential to trigger soil movement. Overall, the interaction between these geological factors creates conditions of high vulnerability to soil movements in the area.

Design of Potential Land Movement Hazard Map (Landslide) and Mitigation Map Based on the Ministry of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2018

THE MINISTRY OF ENERGY AND MINERAL RESOURCES OF THE REPUBLIC OF INDONESIA 1827 K/30/MEM/2018 provides guidance to improve mine safety through the identification of potential hazards of soil movement and mitigation strategies based on technical data. The design of potential hazard maps of land movements (landslides) and mitigation maps allow for measurable risk management. The implementation of technical mitigation measures, monitoring, and operational management provides maximum protection against soil movement risks, improves mine efficiency, and ensures worker safety. This map is an important tool to support the sustainability of mine operations.

The design of a map of potential land movement hazards (landslides) involves processing technical data that includes geology, mechanical properties of rocks, topography, and hydrology, where maps of structures, rock formations, and fault zones are important components. This mapping methodology begins with modeling slope stability using the boundary balance method to calculate the Safety Factor (FK), which classifies landslide potential zones into high, medium, and low based on FK values. Risk analysis is also carried out by considering slope slope angles, pore water pressure, and material properties to determine the classification of landslide severity in accordance with the Ministry of Energy and Mineral Resources of the Republic of Indonesia No. 1827 K/30/MEM/2018, which provides guidelines for mitigating soil movement hazards in mines. The design of the ground movement hazard mitigation map includes danger zones, safe zones, evacuation routes, and gathering points, where hazard zones are determined based on slope stability analysis indicating high landslide potential, as well as mitigation measures necessary to protect workers. The 2 Ha safe zone is located outside the potential for landslides, with mitigation measures to ensure worker safety, while the evacuation route is designed for accessibility and safety, with additional measures such as lighting and clear markings. The gathering point is in a safe location and accessible to all workers, equipped with communication facilities and first aid equipment. Structural mitigation is carried out to improve slope geometry and the creation of mitigation maps serves as a safety analysis tool in identifying danger zones and designing mitigation measures and evacuation planning.

CONCLUSION

In the Green Pit area, the identified type of ground movement was a wedge collapse, with plunge angles of 14°–77° exceeding the deep shear angle of 37° and intersection slopes oriented N 144° E / N 222° E, causing movement toward the southeast–southwest. Slope stability analysis showed single slopes with FK values of 0.91–1.26 (unstable to balanced), inter-ramp slopes with FK 1.15–1.25 (balanced), and overall slopes with FK 1.31–1.37 (stable). The probability of landslides across the area was 10–25%, categorized as medium severity, with hazard classification based on FK values: <1.0 (high), 1.0–1.3 (moderate), and >1.3 (low). The mitigation map identified a potential danger zone covering 0.33 ha, a safe zone of 2 ha, an evacuation route of 68–267 m, and a muster point equipped with emergency response facilities. Future research should examine the long-term effects of rainfall intensity and seasonal weather variations on wedge collapse mechanisms to refine slope stability predictions and enhance mitigation planning.

REFERENCES

Anatoly, N., & Rofikoh, S. (2022). *The Effect of Geological Structures on the Slope Stability of the South Wall Slopes of Open Pit ABC , PT XYZ Gold Mine in Central Kalimantan*. 1–5.

Arif, I. (2016). *Mewujudkan Produksi Tambang yang Berkelanjutan dengan Menjaga Kestabilan Lereng*.

Bogor, K., & Barat, J. (2011). Kajian Geoteknik Kestabilan Lereng Di Daerah Quarry Hambalang , Kecamatan Citeureup. *Jurnal Teknik*, *18*(1), 34–42.

Capoeira, Paripurno, E. T., & Kusumayudha, S. B. (2021). Geologi Dan Analisis Kestabilan Lereng Desa Ngaglik Dan Sekitarnya, Gebang, Purworejo, Jawa Tengah. *Jurnal Ilmiah Geologi Pangea*, *8*(2356-024X), 55–72.

Crozier, M. J., & Glade, T. (2012). Landslide Hazard and Risk: Issues, Concepts and Approach. In *Landslide Hazard and Risk*. https://doi.org/10.1002/9780470012659.ch1

ESDM, K. (2018). *KepMen ESDM RI No. 1827 K/30/MEM/2018 Tentang Pedoman Pelaksanaan Kaidah Teknik Pertambangan yang Baik*.

Fikri, M. A., Imananto, E. I., Yudianto, E. A., & Priskasari, E. (2022). Analisa Penyebab Terjadi Longsoran Ditinjau Dari Stabilitas Tanah Dan Pengurangan Resikonya. *Student Journal Gelagar*, *4*(02), 19–28.

Gloria, E., Sophian, R. I., Zakaria, Z., & Pujiastuti, K. (2020). Stabilitas Lereng Dinding Utara (Section Xy) Desain Fase 7 Tambang Terbuka Batu Hijau Berdasarkan Kinematik. *Padjadjaran Geoscience Journal*, *4*(3), 191–195.

Hedianto, Ma`rief, A. A., Mahyuni, E. T., Sultan, K. El, & Afasedanya, M. (2023). Faktor Geometri Lereng Dalam Simulasi Nilai Ambang Batas Safety of Factor Di Front Penambangan Mahfia Pada PT. ANTAM Tbk, Kabupaten Halmahera Timur, Provinsi Maluku Utara. *Jurnal Teknik Amata*, *4*(2), 9–18.

Ikram, M., & Yuliadi. (2022). Kajian Geoteknik untuk Penentuan Geometri Lereng Front Penambangan di PT. XYZ. *Jurnal Riset Teknik Pertambangan*. https://doi.org/10.29313/jrtp.v2i2.1246

Indriani, Y. N., Kusumayudha, S. B., & Purwanto, H. S. (2017). Analisis Gerakan Massa Berdasarkan Sifat Fisik Tanah. *Jurnal Mineral, Energi Dan Lingkungan*, *1*(2), 39–49.

Jaya Saputra Iman, I., Zam mili, M., Studi Teknik Pertambangan, P., Ilmu dan Teknologi Kebumian, F., & Halu Oleo Kampus Bumi Hijau Tridharma Anduonohu, U. (2022). Kajian Geoteknik Untuk Perencanaan Geometri Lereng Pit Tambang Nikel Menggunakan Metode Bishop Simplified Pada Pt. Riota Jaya Lestari. *Jurnal Riset Teknologi Pertambangan (J-Ristam)*, *2*(2).

Komadja, G. C., Pradhan, S. P., Oluwasegun, A. D., Roul, A. R., Stanislas, T. T., Laïbi, R. A., Adebayo, B., & Onwualu, A. P. (2021). Geotechnical and geological investigation of slope stability of a section of road cut debris-slopes along NH-7, Uttarakhand, India. *Results in Engineering*, *10*. https://doi.org/10.1016/j.rineng.2021.100227

Manullang, P. (2020). Analisis Probabilitas kelongsoran lereng Pada Desain Lereng Tambang Batu Bara dengan Menggunakan Metode Kesetimbangan batas. *Prossiding TPT XXIX Perhapi*.

Matius Sesa, H., Najib, N., Luthfi Dalimunthe, H., & Handietri, Z. (2024). Slope Stability Evaluation and Geometrical Recommendation Using The Morgenstern Price Method. *Jurnal Teknologi*, *16*(1), 53. https://doi.org/10.24853/jurtek.16.1.

Pasha, S., Sunarwan, B., & Syaiful, M. (2018). Analisis Potensi Longsor Menggunakan Metode Kinematik Pada Tambang Terbuka Limestone Narogong Pt Holcim Indonesia Tbk Kecamatan Cileungsi Kabupaten Bogor Jawa Barat. *Jurnal Online Mahasiswa (JOM) Bidang Teknik Geologi*.

PUPR. (2021). *Modul Pengertian Lereng Dan Longsoran*. Kementrian Pekerjaan Umum Dan Perumahan Rakyat Direktorat Jenderal Sumber Pusat Pendidikan Dan Pelatihan Jalan, Perumahan, Permukiman, Dan Pengembangan Infrastruktur Wilayah.

Putrilia, B., Poalahi, S., Rembah, R., & Munir, A. S. (2022). Analisis Kestabilan Lereng pada Pit Bengkirai, Tambang Terbuka Batubara di PT Ghuruh Putra Bersama, Site Gunung Sari, Kecamatan Tabang, Kabupaten Kutai Kartanegara, Kalimantan Timur. Jurnal Geomine, 10(2), 156–167. https://doi.org/10.33536/jg.v10i2.1178

Rahmatullah, A., Siregar, A. D., Wiratama, J., & Denny, A. (2024). *Analisis Deformasi Lereng Yang Mengalami Longsor Menggunakan Slope Stability Radar (SSR) Pada Pit 2 Blok Banko Barat PT Bukit Asam Tbk, Kabupaten Muara Enim, Provinsi Sumatra Selatan*.

Somptan, A. F. (2012). *Struktur Geologi Sulawesi*.

Widianita, D. R. (2023). Analisis Desain Geometri Lereng Tambang PIT X. *AT-TAWASSUTH: Jurnal Ekonomi Islam*, *8*(1).