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Failure Type Analysis, Mitigation, and Recommendation Using Slope Stability Radar at PT.Kuansing Inti Makmur to Enhance Sustainable Mining

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ABSTRACT

Ensuring slope stability is critical in open-pit coal mining due to its implications for operational safety, infrastructure protection, and environmental impact. This study investigates the implementation of Slope Stability Radar (SSR) technology at PT Kuansing Inti Makmur, focusing on identifying and analyzing three distinct types of slope failures commonly found in mining environments: creep, rilling, and rockfall. By leveraging real-time SSR data—including deformation, velocity, coherence, and range parameters—each failure mechanism is characterized based on its distinct geotechnical signature and temporal behavior. The results show that creep failures exhibit progressive displacement patterns, rilling events are marked by sudden, high-magnitude shifts, and rockfalls manifest as abrupt detachment events with rapid recovery signals. Based on these observations, targeted mitigation strategies are proposed, including slope regrading, drainage control, catchment design, and the application of geotechnical reinforcements. Practical recommendations for safe working distances, inspection intervals, and emergency response protocols are also outlined. This research demonstrates that integrating SSR monitoring with geotechnical analysis significantly enhances failure prediction accuracy and operational safety. These findings highlight the urgency of adopting advanced monitoring systems to support sustainable and resilient open-pit mining practices.

***Keywords**: Slope Stability Radar, Geotechnical Monitoring, Open Pit Mining,*

1. INTRODUCTION

PT Kuansing Inti Makmur (Sinarmasmining Group) operates an open-pit coal mine in Muaro Bungo, Jambi Province. Slope stability is a critical safety concern in such operations due to its potential to endanger personnel, damage equipment, and disrupt production. Failure often results from an imbalance between driving and resisting forces, exacerbated by inadequate slope design or external factors such as rainfall and vibrations. This study aims to evaluate the characteristics of slope failures at the site and develop effective monitoring and mitigation strategies using Slope Stability Radar (SSR). Site data show 149 geotechnical failure events in 2022, dominated by medium and minor incidents. By 2024, this dropped to 8, and only 6 have occurred so far in 2025. As shown in Figure 1.2, this downward trend reflects improved monitoring efforts but also reinforces the need for continuous vigilance and data-driven interventions. SSR technology, introduced by GroundProbe in 2003, enables real-time, high-resolution monitoring of slope movement. PT Kuansing Inti Makmur utilizes SSR at the East Pit to detect deformation patterns, assess slope stability, and support early warning systems for safer, more sustainable mining operations.

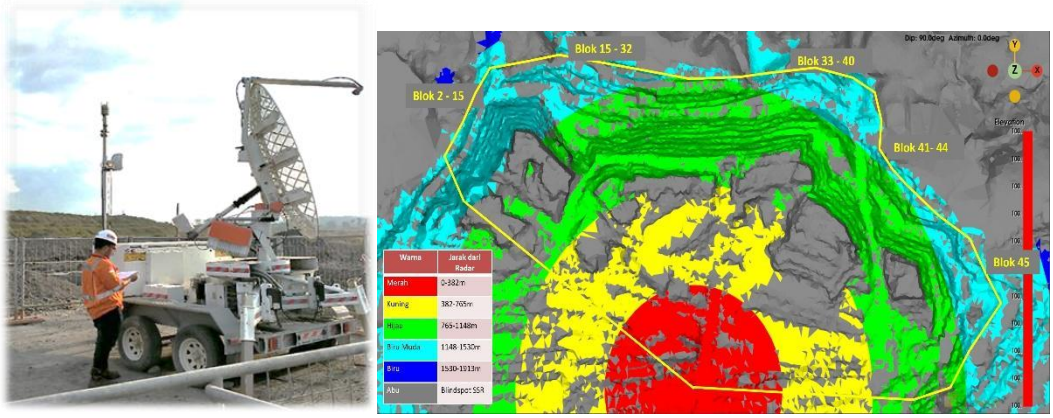

Figure 1.1. The appearance of the Slope Stability Radar tool and the position of the SSR relative to the mining area.

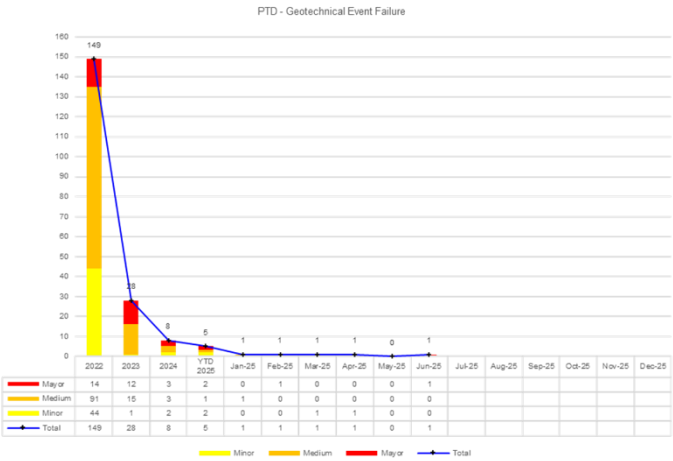

Figure 1.2. PTD – Geotechnical Event Failure Trend (2022–2025) by Severity Category (Minor, Medium, Major).

2. METHODS

2.1 Slope Stability Radar (SSR)

Slope Stability Radar (SSR) is a real-time monitoring system designed to detect slope deformation with high precision. It operates using differential interferometry, transmitting radar waves to a slope surface and analyzing the phase differences of returning signals between successive scans. This enables millimeter-scale detection of movement across broad slope areas without disrupting mining activities. The SSR continuously scans in two dimensions (azimuth and elevation), generating independent pixel data to visualize and analyze slope behavior over time. The data in this study were collected from the East Pit of PT Kuansing Inti Makmur, Jambi Province, covering the monitoring period from January 2022 to July 2025. Observations were conducted under normal operational conditions, including active excavation, rainfall events, and post-blasting phases. Monitoring was carried out continuously

using a fixed SSR-XT unit positioned on a stable platform with a clear line of sight to the monitored slopes.

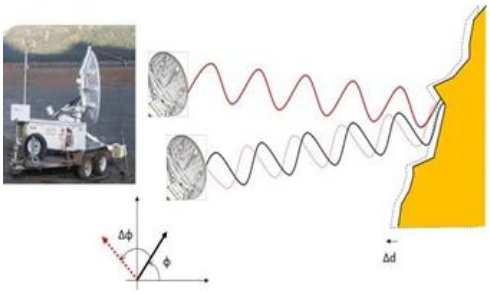

Figure 2.1. SSR Interferometry Technique (Indriastuty et al., 2021)

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Data acquisition occurs through repeated automated scans, and results are transmitted via wireless networks to a centralized monitoring office. There, the *Primary Monitoring Point* (PMP) computer receives, interprets, and stores the data, enabling remote analysis. Visualization and data analysis are performed using SSR Viewer (Monitor IQ), which includes tools for deformation mapping, coherence, amplitude, range, velocity, and inverse velocity.

- **Deformation**: Captures slope displacement by measuring phase differences between scans. Higher intensity (redder) pixels indicate more significant movement.

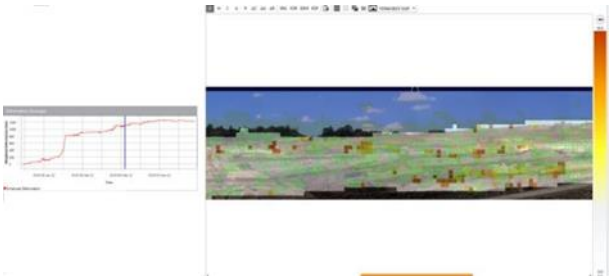

Figure 2.2. Deformation.

- **Coherence and Delta Coherence**: Show changes in signal consistency; lower values may indicate increased deformation or noise in radar returns.

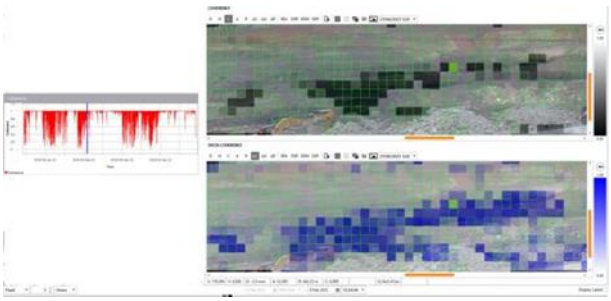

Figure 2.3. Coherence and delta coherence.

- **Range and Delta Range**: Measure the distance from the radar to the reflecting surface; variations signal geometric slope changes.

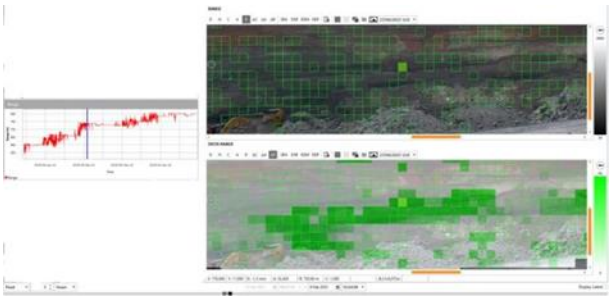

Figure 2.4. Range data and delta range.

- **Velocity and Inverse Velocity**: Indicate the rate of movement (mm/h). Inverse velocity is critical for predicting failure time using linear extrapolation methods.

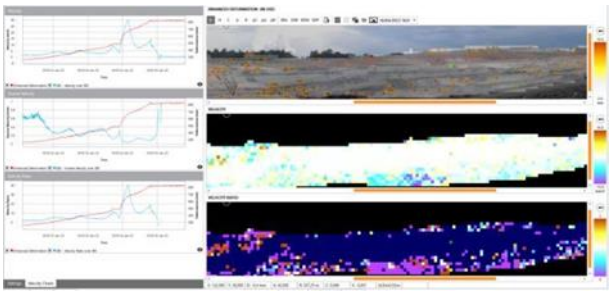

Figure 2.5. Velocity and inverse velocity.

The SSR system allows mining operators to continuously evaluate slope integrity and detect early-warning signs of failure. This capability is crucial for preventive decision-making and risk mitigation in open-pit mining environments.

2.2 Slope Failure Classification

Mass movement, also known as slope movement or landsliding, refers to the downslope transport of soil, rock, or debris under the influence of gravity. The classification of mass movement is based on the type of material involved (rock, debris, earth) and the mode of movement (fall, slide, flow, spread, or creep). Varnes (1978), later refined by Cruden and Varnes (1996), proposed a widely accepted framework that groups slope failures into categories depending on their mechanical behavior. Understanding these types is critical for accurate slope hazard assessment and designing effective monitoring and mitigation strategies.

2.2.1 CREEP

Creep is the slow, progressive, and imperceptible downslope movement of soil or rock over long periods. It typically affects the upper soil layers and manifests through subtle indicators like bent tree trunks, tilted fences or poles, and cracked walls. Creep is driven by repeated expansion and contraction cycles, such as freeze-thaw or wet-dry variations, which gradually

overcome the shear strength of slope materials. Although not catastrophic, creep poses a persistent threat to infrastructure stability.

2.2.2 RILLING

Rilling refers to the formation of small, narrow channels caused by surface runoff on unprotected or loosely packed slopes. These channels can evolve into larger gullies if not stabilized. While rilling is often considered an erosion process rather than a mass movement per se, it significantly contributes to slope instability by concentrating water flow and removing support materials. In mining areas or overburden dumps, rilling can precede larger slope failures.

2.2.3 ROCKFALL

Rockfall is a sudden and high-velocity detachment of rock blocks from steep or vertical slopes, typically triggered by rainfall, blasting, or natural weathering along existing joints or fractures. Unlike creep, rockfall occurs abruptly without gradual warning signs and poses immediate hazards in mining areas.

3. RESULTS AND DISCUSSION

3.1 FAILURE TYPE

3.1.1 NORMAL

A stable slope with no potential for landslides is characterized by a combination of favorable geotechnical and hydrological conditions. These include an adequate factor of safety (typically above 1.3 for static conditions), well-compacted and cohesive materials, proper drainage to prevent water infiltration, and gentle slope angles within the recommended design limits based on the rock or soil type. Vegetation cover can also contribute to slope stability by reinforcing surface materials and reducing erosion. Additionally, the absence of geological discontinuities, such as faults, joints, or weak bedding planes, further minimizes the risk of failure. Regular monitoring and maintenance, along with adherence to engineering design standards, help ensure the slope remains stable under both natural and operational conditions.

Figure 3.1. Normal bench with no potential slope failure.

3.1.2 CREEP

Creep is a slow and continuous movement of soil or rock downslope over time. Visually, this type of failure is identified by subtle surface indicators such as tilted trees or poles, cracks near the crest, distorted drainage lines, and bulging at the toe of the slope. Creep is commonly triggered by natural factors like seasonal moisture changes, wet-dry cycles, or minor seismic vibrations. In mining operations, it may also be caused by repetitive equipment loading or poor drainage, which gradually weaken slope materials. . Though creep is a slow process, its accumulation can signal the potential for more rapid and dangerous slope failures if not monitored and addressed properly.

Figure 3.2. Creep landslide.

3.1.3 RILLING

Rilling refers to surface erosion caused by concentrated water flow, resulting in the formation of narrow, linear channels or rills along the slope face. These rills often start small but can deepen and widen over time if not addressed, potentially leading to more severe erosion or gully formation. Rilling typically occurs after heavy rainfall or due to inadequate surface water management, especially on slopes with loose, unconsolidated material or poor vegetation cover. In operational settings, it is often found on overburden dumps, working benches, or haul roads with insufficient drainage control. Rilling is most common on steep, poorly vegetated slopes with loose, unconsolidated material, and can be exacerbated by heavy rainfall or improper water drainage. While Rilling progresses slowly, if left unmanaged, it can significantly weaken the slope over time and contribute to larger, more rapid landslide events.

Figure 3.3. Rilling material.

3.1.4 ROCKFALL

Rockfall is the sudden detachment and free fall of rock fragments or blocks from steep or vertical slopes. It is visually identified by fresh scarp surfaces, accumulated debris at the slope toe, and open joints or tension cracks near the crest. Affected slopes often exhibit scattered boulders, exposed fractures, and areas of loose, unstable rock with sharp edges and uneven textures.Natural triggers include weathering, rain infiltration, and freeze-thaw cycles, while operational causes may involve blasting vibrations or undercutting during excavation. Rockfalls typically occur without warning and pose serious safety risks, particularly in highwall areas and active pit faces. Although some events are minor, frequent or large-scale rockfalls can significantly compromise slope stability and operational safety.

Figure 3.4. Rockfall.

3.2 FAILURE ANALYSIS

3.2.1 NORMAL

The slope stability radar (SSR) data presented in the figure represents a typical case of normal deformation behavior. The deformation graph shows a gradual and consistent increase over time, without any abrupt spikes or anomalies, indicating a stable slope condition. The range data remains flat, suggesting no significant displacement or shifts in the monitored target area. Furthermore, the velocity graph displays minor fluctuations within acceptable thresholds, with no sudden acceleration that would suggest unstable ground movement. The coherence values remain high and consistent throughout the monitoring period, which implies a reliable radar return signal and a lack of substantial changes on the slope surface. Collectively, these parameters confirm the absence of critical deformation and highlight a condition of slope stability. This pattern is characteristic of normal deformation, where no warning signs of potential failure are detected.

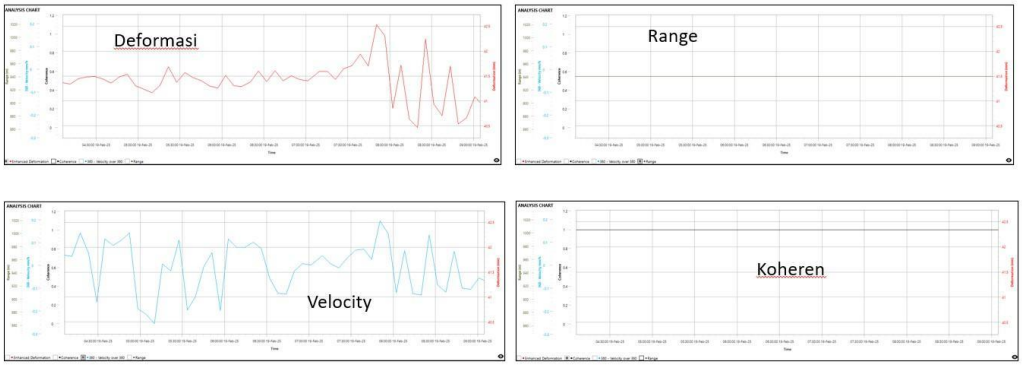

Figure 3.5. Normal Graph

3.2.2 CREEP

The presented slope stability radar (SSR) data illustrates a deformation pattern consistent with creep-type landslide behavior. The deformation graph exhibits a slow and progressive increase over time, which eventually accelerates before stabilizing again. This characteristic pattern indicates a prolonged phase of strain accumulation followed by minor slope adjustment, typical of creep processes. The velocity chart supports this interpretation, showing moderate but sustained velocity peaks that correspond with the acceleration phase in the deformation graph. Additionally, fluctuations in the range data and intermittent drops in coherence suggest slight surface displacements and disturbances, although not severe enough to indicate sudden failure. The coherence values, while occasionally dropping, largely remain recoverable, indicating that the radar still maintained signal quality over time. Overall, this dataset represents a creeping slope movement where deformation occurs gradually and continuously over time, without sudden collapse, which is critical for early warning and long-term monitoring strategies.

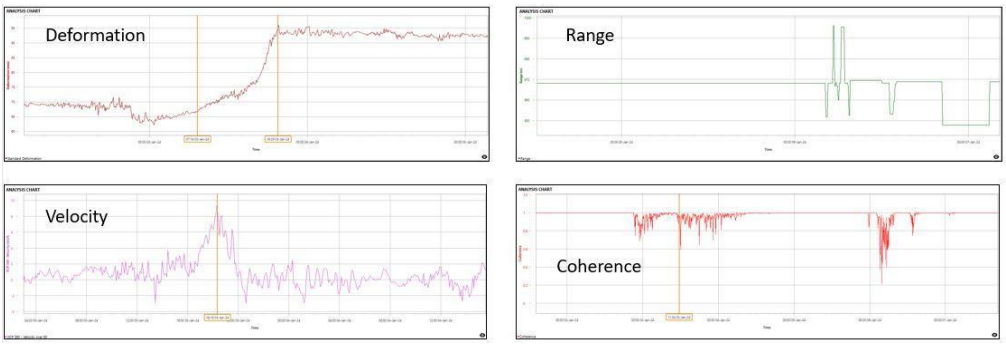

Figure 3.6. Creep Failure Graph

3.2.3 RILLING

The slope stability radar (SSR) data shown in the figure reflects deformation behavior associated with a rilling or guguran event. The deformation chart displays a sudden, sharp increase within a very short time window, which is immediately followed by stabilization, indicating a rapid and localized failure. The velocity graph mirrors this pattern, showing a steep spike that quickly declines, representing a brief high-magnitude displacement. In the range data, an abrupt change is evident, further confirming a physical shift in the monitored slope surface, characteristic of detachment or material loss. Coherence drops momentarily during the event, suggesting signal disruption due to surface roughness or loss of reflectivity caused by the falling debris. However, the coherence recovers quickly afterward, implying that the slope surface returned to a relatively stable state post-event. This dataset typifies a rilling or minor collapse scenario, marked by rapid deformation and short-duration instability, often requiring fast response in early-warning systems. And usually a Rilling event occurs repeatedly until the rock finds its stability point.

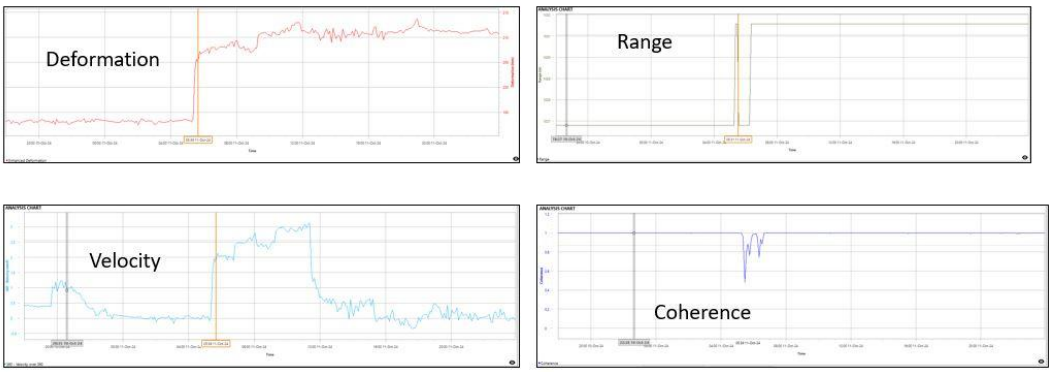

Figure 3.7. Rilling Failure Graph

3.2.4 ROCKFALL

The slope stability radar (SSR) data in this figure captures a deformation event typical of a rockfall or sudden detachment. The deformation graph reveals an abrupt and substantial increase in displacement within a very short time, followed by stabilization, indicating the occurrence of a sudden mass movement. The velocity chart further supports this, showing a

distinct, sharp spike that quickly diminishes—signifying a rapid movement rather than a progressive slope failure. The range plot also indicates an instantaneous change, suggesting a physical shift or detachment of material from the slope surface. Additionally, coherence values drop temporarily during the event, which is common in rockfall incidents due to disruption in radar signal reflection caused by fragmented or dislodged materials. The signal subsequently recovers, reflecting the end of active movement and stabilization of the slope surface. This pattern is characteristic of rockfall-type landslides, which are generally localized but high-energy events that require immediate detection and rapid response for hazard mitigation.

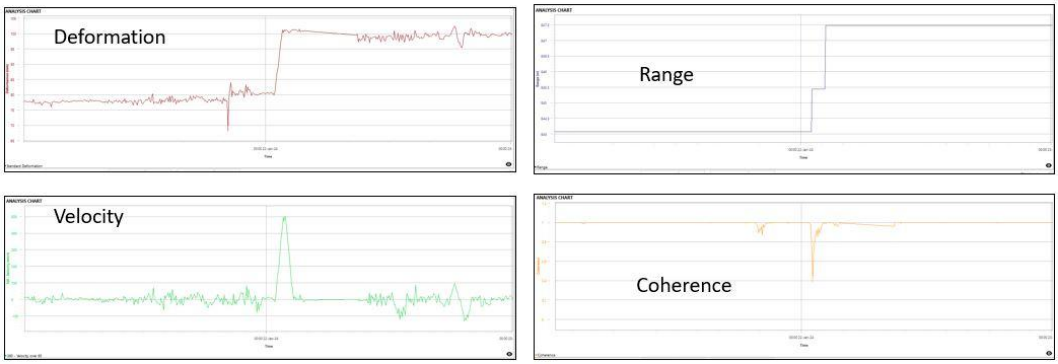

Figure 3.8. Rockfall Failure Graph

3.3 FAILURE MITIGATION AND RECOMMENDATION

The safety parameters presented in this study—such as minimum safe distances, re-entry times, and inspection intervals—were developed based on actual field observations and historical event analysis at the East Pit of PT Kuansing Inti Makmur between 2022 and 2025. These parameters were adapted to local geological conditions, slope geometries, and recorded deformation behavior observed during routine geotechnical monitoring. Effective mitigation of such deformation begins with continuous geotechnical monitoring using tools such as slope stability radar (SSR), inclinometers, and ground-based survey systems to detect subtle movements over time:

3.3.1 CREEP

Mitigation of creep-related deformation focuses on long-term slope management. Recommended actions include:

- Slope regrading to reduce overall inclination and minimize shear stress,
- Surface and subsurface drainage control to prevent water accumulation and reduce pore pressure,
- Installation of geosynthetics or retaining structures to improve slope resistance,
- Erosion control and vegetative cover to protect surface layers.

Operational adjustments, such as limiting heavy equipment traffic near affected areas, are also necessary. All decisions should be based on geotechnical risk assessment supported by real-time monitoring.

Safety Protocols for Creep Failure:

- Minimum Safe Distance (Barricade) : 1.5 times the height of the affected slope, measured from the crest.
- Safe Re-entry Time After Initial Movement: 2 hours after slope failure and SSR reading had linear phase deformation
- Inspection Interval: Every 30 minutes.

3.3.2 RILLING

Rilling mitigation targets surface erosion and water flow control. Recommended actions include:

- Scaling or removal of loose material, particularly on overburden slopes,
- Construction of catch benches and berms to intercept dislodged material,
- Surface protection using mesh netting or erosion-control blankets,
- Installation of contour drains and check dams to manage runoff.

Regular inspections are essential following rainfall events or blasting activities to detect early rill development and prevent progression into deeper gullies.

Safety Protocols for Rilling:

- Minimum Safe Distance: 30 meters from rill-prone zones
- Safe Re-entry Time After Initial Impact: 1 hours after slope failure and SSR reading had linear deformation
- Inspection Interval: Every 1 hour .

3.3.3 ROCKFALL

Rockfall mitigation emphasizes structural stabilization and hazard containment. Recommended measures include:

- Geotechnical mapping and structural analysis to identify unstable blocks (Kinematic analysis),
- Installation of rock bolts, wire mesh, or shotcrete to stabilize potential failure zones,
- Construction of catchment systems, such as rockfall ditches and protective berms,

- Implementation of exclusion zones and controlled access near active highwalls.

Routine scaling operations are advised, especially following rainfall or blasting, to remove unstable rock fragments before failure occurs.

Safety Protocols for Rockfall:

- Minimum Safe Distance: 40 meters from the base of exposed slopes
- Safe Re-entry Time After Rock Detachment: 30 minutes and SSR reading had linear deformation
- Inspection Interval: Every 1 hour

4. CONCLUSION

This study classifies three dominant types of slope failure in the East Pit area—creep, rilling, and rockfall—each with distinct visual characteristics, triggering mechanisms, and operational implications. Effective mitigation requires tailored strategies, including slope regrading, drainage control, surface protection, structural reinforcement, and routine inspection. Safety protocols were developed based on historical field data and include minimum safe distances, re-entry times, and inspection intervals.The integration of geotechnical monitoring tools, particularly Slope Stability Radar (SSR), has proven critical in guiding timely interventions and supporting operational safety. By analyzing the temporal deformation behavior and geotechnical signals of each failure type, more precise and proactive strategies can be implemented. SSR monitoring enhances predictive capabilities and enables data-driven decisions, contributing to safer and more sustainable open-pit mining operations.

Failure Type	Minimum Safe Distance (Barricade Area)	Safe Re-entry Time	Inspection Interval
Creep	1.5× slope height from crest	2 hours after failure event + linear SSR phase	Every 30 minutes
Rilling	30 meters from rill-prone zones	1 hour after failure + linear SSR phase	Every 1 hour
Rockfall	40 meters from slope toe	30 minutes after failure event + linear SSR phase	Every 1 hour

Table 4.1. summarizes the site-specific safety protocol at PT Kuansing Inti Makmur (Jambi), used to manage slope failure risks:Summary of Safety Parameters by Failure Type.

Future research should explore the integration of real-time SSR data with machine learning algorithms to enable automated, predictive early-warning systems. Additionally, investigating the correlation between meteorological changes, groundwater behavior, and slope response could further refine risk mitigation frameworks. This study confirms that monitoring slope conditions using Slope Stability Radar (SSR) technology effectively identifies and differentiates the characteristics of three main types of slope failures in open-pit mining: creep, rilling, and rockfall. Creep failures are characterized by gradual and progressive deformation, indicating soft and slowly shifting materials. Rilling failures display rapid deformation and velocity, often occurring repeatedly until the slope stabilizes. In contrast, rockfall events occur suddenly, with sharp increases in deformation and velocity, and typically appear only once in the range and coherence graphs.

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