Ranah Research
Journal of Multidisciplinary Research and Development
E-ISSN: 2655-0865
082170743613 ranahresearch@gmail.com https://jurnal.ranahresearch.com
DINASTI RESEARCH

DOI: https://doi.org/10.38035/rrj.v8i1

The Use of Aerial Drone Technology for Landslide Investigation in Nickel Mining PT. KLM

Hendy Baehaqi[1], Maulahikmah Galinium[2], Yunita Umniyati[3]
[1]Engineering Management Mechanical Engineering, Faculty of Engineering & Information Technology, Swiss German University, hendy.baehaqi@student.sgu.ac.id
[2]Engineering Management Mechanical Engineering, Faculty of Engineering & Information Technology, Swiss German University, maulahikmah.galinium@sgu.ac.id
[3]Engineering Management Mechanical Engineering, Faculty of Engineering & Information Technology, Swiss German University, yunita.umniyati@sgu.ac.id

Corresponding Author: hendy.baehaqi@student.sgu.ac.id [1]

Abstract: This study explores the use of drone technology to assess landslides within PT. KLM's nickel mining area. Key challenges in collecting geotechnical data include difficult terrain, landslide risks, and limitations of conventional survey methods. The research applies the Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) approach to identify issues, collect and analyze drone data, and develop solutions to reduce landslide risks. Drone flights were conducted at altitudes of 100 m, 150 m, and 200 m, producing maps that evaluate each flight's image resolution, collision risk, photo coverage, flight area, and suitability. Based on these results, the 150 m altitude was selected as optimal. Using Real Time Kinematic (RTK) processing, the drone data showed an average accuracy variance of about 0.317 meters. Findings indicate that drone data effectively produces high-resolution orthophotos, contour maps, and 3D models to monitor terrain changes before and after landslides. Overall, drone technology improves efficiency, enhances safety, and increases data quality for better landslide risk management in nickel mining.

Keywords: Drone Technology, Landslide Assessment, Nickel Mining, Six Sigma DMAIC, Orthophoto and 3D modeling, Real Time Kinematic (RTK).

INTRODUCTION

Indonesia's mining industry is undergoing a major transition as companies diversify away from coal and into mineral resources, particularly nickel, to address coal price fluctuations and meet rising environmental, social and governance (ESG) expectations (World Bank, 2023; Sari, Widodo and Nugroho, 2022). Nickel is increasingly recognised as a critical mineral, not only for stainless steel production but also for the rapidly expanding electric vehicle battery market (International Energy Agency, 2022). However, this strategic shift introduces operational and geotechnical challenges, particularly in open-pit nickel mines where slope instability and landslides pose significant threats to safety, productivity and the environment (Rahardjo, Santoso and Leong, 2019; Fathani and Karnawati, 2021).

Conventional approaches to field data collection for landslide analysis—such as ground surveys, manual measurements and direct visual observations—remain important but are constrained by accessibility, coverage and safety risks (Duncan and Wright, 2014). These methods often require personnel to enter hazardous areas, exposing them to unstable terrain and potential slope collapse. Such limitations highlight the need for innovative, technology-driven solutions to improve both the safety and effectiveness of geotechnical investigations.

Unmanned aerial vehicles (UAVs), commonly known as drones, have emerged as a promising alternative. Equipped with high-resolution imaging and sensor technologies, UAVs can rapidly capture spatial and topographic data, create three-dimensional slope models and detect morphological changes in near real time (Colomina and Molina, 2014; Nex and Remondino, 2014). Compared to conventional methods, drones deliver greater accuracy, broader coverage and lower operational risks. Furthermore, their integration into geotechnical monitoring aligns with ESG objectives by minimising worker exposure to dangerous conditions and enabling more responsive environmental management (Salamí, Barrado and Pastor, 2014).

This study explores the application of drone technology for landslide investigations in PT KLM's nickel mining project in Southeast Sulawesi, Indonesia. Specifically, it examines the role of UAVs in slope stability monitoring, landslide cause identification and risk mitigation (Figure 1). It also evaluates how flight parameters affect data quality and compares UAV-based methods with traditional survey techniques.

The research aims to demonstrate that UAVs provide a safer, faster and more accurate alternative to conventional approaches, while also supporting sustainable mining practices. By integrating drone-based data collection into hazard analysis and slope monitoring, this study contributes to the digital transformation of the mining industry and offers practical insights for improving safety and operational efficiency in mineral resource development.

Figure 1. Drone Imagery Slope Failure in Nickel Mining

METHOD

This research employed the Six Sigma approach through the DMAIC (Define–Measure–Analyze–Improve - Control) framework, which provides a structured methodology for problem-solving and continuous improvement (George et al., 2004). The framework was adapted to design, test, and validate the use of aerial drones in landslide investigations within nickel mining operations.

Research Framework

The Define stage identified limitations of conventional survey methods, including high accident risk, poor accessibility, and the inefficiency of heavy geodetic equipment (Fiorucci et al., 2019). The Measure stage deployed drones to acquire high-resolution orthophotos, Digital Elevation Models (DEM/DTM), and pre-/post-event imagery (Niethammer et al., 2012).

In the Analyze stage, aerial data were processed using photogrammetric software to generate orthomosaics, 3D models, and volumetric assessments. Root cause analysis revealed that unstable terrain and hazardous conditions render manual surveys ineffective, highlighting the need for drone-based alternatives (Turner et al., 2015).

The Improve stage operationalised the system by training mining personnel in drone handling and geospatial data interpretation. Finally, the Control stage established continuous monitoring via scheduled drone surveys and accuracy validation, enabling early hazard detection (Lucieer et al., 2014).

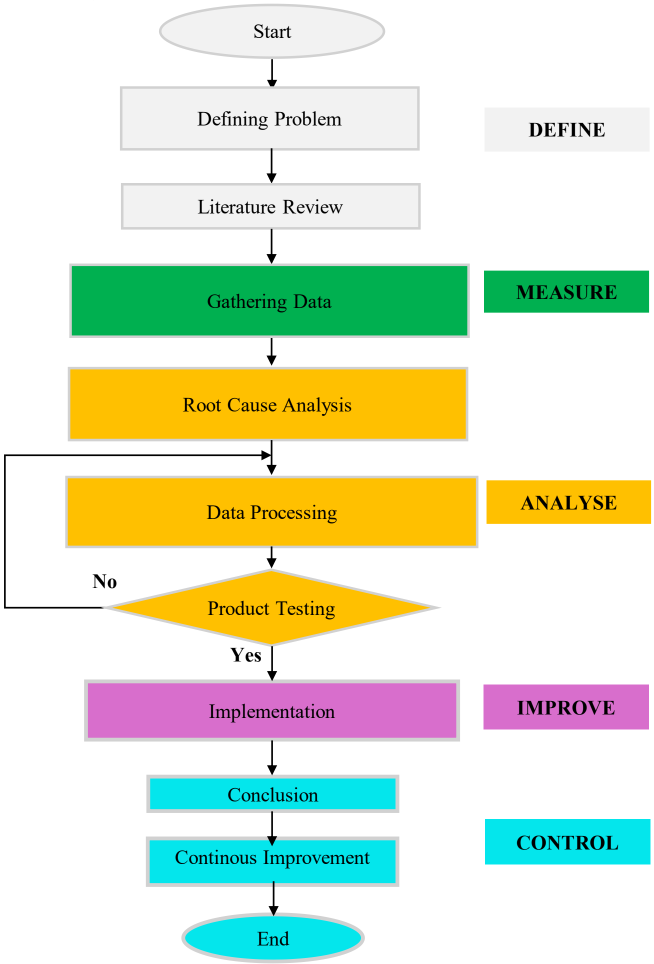


Figure 2. Research Frameworks

Define Phase

The primary issue addressed in this research was the limitation of conventional survey methods for landslide investigation in nickel mining areas. Traditional techniques such as total stations and geodetic GPS are constrained by several factors:

1. High safety risks for personnel working in unstable and landslide-prone areas.
2. Limited accessibility due to steep and slippery terrain.
3. Prolonged setup and calibration times for heavy equipment.
4. Restricted spatial coverage and temporal resolution of acquired data.

These constraints necessitated the exploration of alternative technologies capable of delivering faster, safer, and more comprehensive data collection. UAV-based photogrammetry was identified as a potential solution due to its ability to rapidly acquire high-resolution topographical and morphological data across hazardous terrains.

Literature Review

A literature review was conducted to examine the state of UAV applications in geotechnical engineering, mining operations, and natural hazard monitoring. Previous studies have reported UAV effectiveness in slope stability assessment, digital elevation modeling, and landslide monitoring across various geological contexts. However, few studies have systematically examined UAV deployment in nickel mining environments, where soil characteristics differ significantly from coal or hard rock settings. This identified research gap reinforced the need to evaluate UAV-based methods under such conditions.

Data Collection (Measure Phase)

Study Area

The study was conducted at PT. KLM's nickel mining concession in Southeast Sulawesi, Indonesia. The site is characterized by highly weathered ultrabasic igneous material with low shear strength, making slopes susceptible to failure during intense rainfall.

UAV Platform

Data acquisition was carried out using the DJI Mavic 3 Enterprise UAV, equipped with:
1. A high-resolution optical camera (20 MP sensor, 4/3 CMOS).
2. GNSS navigation with RTK positioning.
3. Autonomous flight control system with pre-programmed mission capability.

Flight Operations

Each survey followed a standardized six-step protocol:
1. Pre-flight inspection (battery, propellers, and calibration).
2. Take-off preparation and safety clearance.
3. Flight path determination using mission planning software.
4. Automated aerial data acquisition (imagery and video).
5. Landing and post-flight inspection.
6. Data transfer to ground station.

Each flight mission lasted approximately 27 minutes, with an additional 5 minutes allocated for equipment checks. Flight altitudes varied between 50–120 m above ground level, depending on site conditions, to balance spatial coverage and resolution.

Data Acquired

The UAV surveys generated:
1. High-resolution orthophotos.
2. Digital Elevation Models (DEM) and Digital Terrain Models (DTM).
3. Dense point clouds for 3D reconstruction.
4. Time-series imagery for pre- and post-event comparison.

Data Processing and Analysis (Analyze Phase)

Collected UAV imagery was processed using photogrammetry software (Red ToolBox) and GIS-based rectification tools. The workflow included:
1. Image alignment and georeferencing.
2. Dense point cloud generation.
3. DEM and DTM construction.

4. Orthomosaic generation.
5. Coordinate corrections and transformation to a consistent spatial reference system.

Analytical procedures consisted of:
1. Comparative accuracy assessment between UAV-derived datasets and conventional survey outputs.
2. Slope stability evaluation, using DEM differencing to identify surface displacement and volumetric changes.
3. Landslide causation analysi, integrating morphological evidence with field observations and rainfall records.

Improve Phase

Based on the validation of UAV-generated outputs, an implementation protocol was developed for operational teams. This included regular UAV deployment following heavy rainfall or upon early indications of slope instability. Training programs were conducted for technical staff to ensure standardized UAV operation and data interpretation.

Control Phase

A long-term monitoring system was established using periodic UAV surveys. The data were systematically compared against baseline conditions to detect deviations in slope geometry. This control mechanism ensured early detection of hazards and enabled timely mitigation planning, thereby enhancing operational safety.

UAV System Architecture

The survey system comprised three key components: drone platform, Ground Control System (GCS), and data link. A DJI Mavic 3 Enterprise equipped with GPS, flight controller, power modules, and sensors was employed (DJI, 2023). Data processing followed established photogrammetric workflows, including image alignment, dense point cloud generation, DEM construction, and orthomosaic production (Agisoft, 2020).

System architecture was organised into mission planning, flight management, control, and sensor–actuator layers, ensuring robust mission execution and real-time operator oversight.

The UAV system was structured around three key components:
1. Aircraft – including flight controller, navigation system, sensors, and power supply.
2. Ground Control Station (GCS) – responsible for mission planning, communication, and operator interface.
3. Data Processing Pipeline– comprising photogrammetry and GIS-based software for data transformation into orthophotos, DEMs, and 3D surface models.
4. The system operated under a hierarchical mission execution structure:
5. Mission layer (task definition).
6. Planning layer (flight path design).
7. Flight management layer (execution of plans).
8. Control layer (signal translation).
9. Sensors and actuators layer (data acquisition and system response).

This multi-layered architecture ensured safe UAV operation and accurate geospatial data generation for landslide investigation in nickel mining areas.

RESULT AND DISCUSSION

UAV Data Products

The UAV surveys produced multiple geospatial outputs including orthophotos, contour maps, 3D surface models, Digital Elevation Models (DEM), Digital Terrain Models (DTM), and time-series datasets. Orthophotos provided geometrically corrected high-resolution imagery suitable for monitoring mine infrastructure, benches, and slope changes. Contour maps facilitated slope gradient and drainage analysis. The 3D models enabled volumetric calculations of displaced material and visualized surface deformations. DEMs and DTMs supported cross-sectional stability analyses and hazard zoning. Collectively, these outputs established a robust foundation for landslide investigation and geotechnical assessment.

Flight Operations and Coverage

Data were acquired following a systematic "lawnmower" flight path covering approximately 24 km in total. Due to UAV battery limitations, surveys were conducted over four days. Each flight lasted ~27 minutes for operational activities and 5 minutes for inspection. Flight altitudes were set at 100 m, 150 m, and 200 m, allowing evaluation of the effect of flight height on spatial accuracy. High overlap between flight lines ensured reliable photogrammetric reconstruction.

Photogrammetric Outputs

Image mosaicking and 3D reconstruction produced orthomosaics with ground resolutions of 2.6–5.2 cm/pixel depending on altitude. DEMs achieved point cloud densities exceeding 200 points/m² at 100 m altitude, decreasing with higher flight altitudes. Elevation profiles generated from DEMs aligned with known topographical features, confirming suitability for slope morphology assessment.

Comparison with Conventional Methods

To validate UAV-derived data, elevations were compared with 20 RTK-GNSS control points distributed across the survey area. Results (Table 1) demonstrated decreasing mean absolute deviations with lower flight altitudes:

Table 1. Deviation Of Elevation Drones Data & Elevation RTK

Name	El RTK	El drone 200	El Drone 150	El Drone 100	Dev 200	Dev 150	Dev 100
POINT 1	43.010	42.491	42.691	42.721	0.519	0.319	0.289
POINT 2	100.450	99.976	100.003	100.021	0.474	0.447	0.429
POINT 3	66.623	66.242	66.326	66.442	0.381	0.297	0.181
POINT 4	58.617	58.108	58.212	58.358	0.509	0.405	0.259
POINT 5	37.185	37.008	37.077	37.106	0.177	0.108	0.079
POINT 6	55.440	55.013	55.123	55.215	0.427	0.317	0.225
POINT 7	47.546	47.076	47.186	47.276	0.470	0.360	0.270
POINT 8	57.753	57.250	57.353	57.449	0.503	0.400	0.304
POINT 9	72.965	72.402	72.582	72.702	0.563	0.383	0.263
POINT 10	39.199	38.788	38.818	38.897	0.411	0.381	0.302
POINT 11	69.199	68.698	68.848	68.948	0.501	0.351	0.251
POINT 12	53.881	53.320	53.430	53.573	0.561	0.451	0.308
POINT 13	68.882	68.640	68.749	68.767	0.242	0.133	0.115
POINT 14	7.004	6.778	6.828	6.858	0.226	0.176	0.146
POINT 15	30.159	30.017	30.039	30.077	0.142	0.120	0.082
POINT 16	26.594	26.027	26.267	26.345	0.567	0.327	0.249
POINT 17	44.284	44.012	44.092	44.098	0.272	0.192	0.186
POINT 18	36.453	36.039	36.187	36.239	0.414	0.266	0.214
POINT 19	17.287	16.790	16.879	16.979	0.497	0.408	0.308
POINT 20	47.974	47.387	47.477	47.577	0.587	0.497	0.397
Average Deviation					**0.422**	**0.317**	**0.243**
Maximum Value					**0.587**	**0.497**	**0.429**
Minimum Value					**0.142**	**0.108**	**0.079**

These values indicate UAV surveys can achieve sub-meter vertical accuracy, comparable to conventional surveying instruments. However, operational efficiency and safety must be considered; 150 m altitude was determined to provide the best compromise between accuracy, area coverage (10–12 ha/flight), and reduced collision risk.

Conventional surveys using total stations and RTK-GNSS deliver point accuracies of <0.1 m but are limited by (i) line-of-sight constraints, (ii) slow coverage of large areas, and (iii) safety risks due to personnel exposure on unstable slopes. UAV mapping achieved comparable accuracy (<0.5 m deviation) with far greater spatial coverage, reduced manpower requirements, and eliminated the need for surveyors to enter hazardous zones. This validates UAVs as effective replacements for conventional methods in landslide-prone mining sites.

Table 2. Differences In Drone Flight Parameters at Altitudes of 100 m, 150 m, and 200 m

Parameter	100 m	150 m	200 m
Image Resolution	2,5–3 cm/pixel	3–4cm/pixel	5–8 cm/pixel
Area Coverage per Photo	Smaller, high detail	Wider, medium detail	Widest, lowest detail
Area per Flight (20 minutes)	6 - 9 Ha	10 - 12 Ha	13-15
Number of Photos for the Same Area	More, longer processing time	Less time, more efficiency	At the very least, highly efficient
Collision Risk	Higher because it is closer to the object	Medium	Lower
Ideal Use	Detailed mapping, stockpile volume, precision inspection	General mapping, medium-range monitoring	Quick survey of a large area, rough monitoring

Referring to Table 2, this section explains the differences in parameters and optimal applications for drone mapping or surveying at altitudes of 100, 150, and 200 meters. The table demonstrates how varying flight heights impact data quality, operational effectiveness, and associated risks.

Forum Group Discussions (FGD) and Root Cause Analysis

An FGD involving engineers, surveyors, safety officers, and management stakeholders confirmed the operational advantages of UAV deployment. Participants emphasised enhanced worker safety, particularly in inaccessible or hazardous terrain, and recognised UAVs as superior in producing orthophotos, 3D models, and pre- and post-failure imagery for landslide analysis. Key challenges identified included limited battery endurance, adverse weather, and the need for skilled data processing personnel. These challenges echo barriers reported in other UAV-based mining studies (Gülci et al., 2022).

Root Cause Analysis (RCA) revealed that conventional surveying constraints including high manpower demands, exposure to secondary landslides, and limited access to unstable slopes were critical factors necessitating UAV adoption. Such constraints have also been reported in slope hazard investigations globally (Casagli et al., 2017).

A fishbone diagram analysis categorized contributing factors:

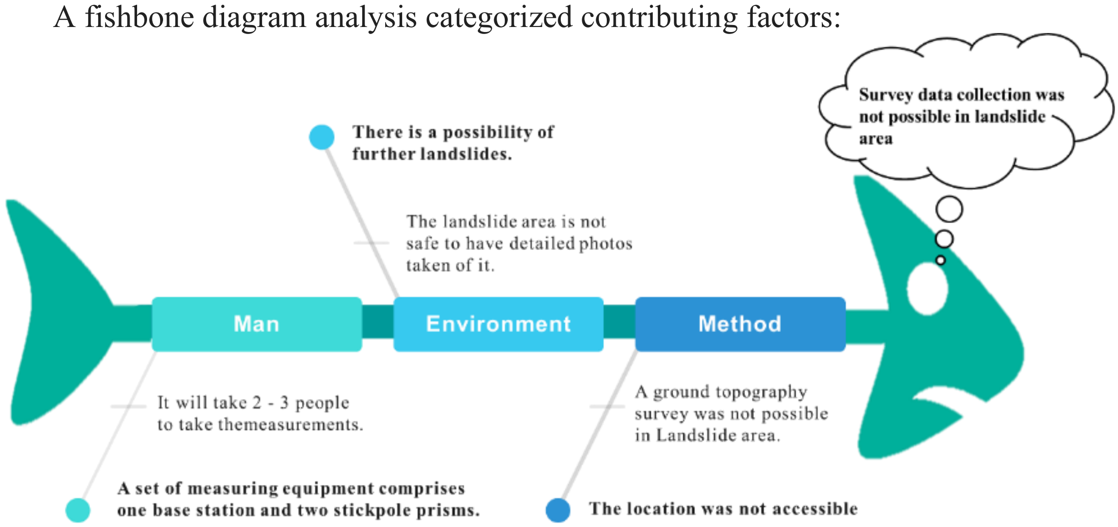


Figure 4. Fish Bone Diagram

Categories of Contributing Factors:

a. **Human Factors**

Two main issues are associated with personnel:

1) Manpower requirements: Conventional field surveys typically require 2–3 personnel, which creates shortages and increases exposure to safety risks, particularly in disaster-prone areas.
2) Equipment limitations: The available tools, consisting of a single base station and two prism poles, demand considerable effort and coordination when deployed in rugged terrain, thereby elevating operational hazards.

b. Environmental Factors

The natural environment presents several challenges:

1) Risk of secondary failures: Ongoing or subsequent landslides may occur during survey activities, directly endangering field crews.
2) Unstable terrain conditions: The affected zone is often insecure, hindering the acquisition of detailed imagery and resulting in incomplete or unreliable datasets.

c. Methodological Factors

Two principal methodological constraints were identified:

1) Survey infeasibility: Adverse field conditions render conventional topographic surveying impractical.
2) Restricted accessibility: Limited access routes prevent both personnel and equipment from reaching the landslide site, obstructing comprehensive data collection.

Orthophotos for Landslide Investigation

Orthophotos proved instrumental in landslide causation analysis. Sequential imagery between 2023–2025 demonstrated progressive water saturation in waste dump toes and drainage outlets, culminating in slope failure. Laboratory validation of soil samples showed average moisture content exceeding 40%, reinforcing UAV observations. These findings confirm the importance of UAV time-series monitoring in detecting hydrological precursors of slope instability (Niethammer et al., 2012; Rossi et al., 2018).

Compared to conventional ground photography, UAV orthophotos provided superior coverage, reduced operator risk, and enabled volumetric estimations of displaced material. Similar advantages have been reported in post-failure assessments of open-pit mines (Peppa et al., 2019).

Table 3. Comparisson of Conventional photo & Drone's Photo

No.	Aspect	Conventional Photo (Regular Camera)	Orthophoto Using Drone
1	Viewing Perspective	Limited angle (usually horizontal/panorama)	Birds eye view (top-down perspective)
2	Coverage Area	Limited, difficult to cover wide and steep terrain	Wide, capable of accessing difficult and steep areas
3	Visual Detail	Real visual details at the photo point	High spatial detail with contour and boundary information
4	Data Accuracy	Less accurate for area and volume analysis	Accurate for analysis of area, distance, and landslide volume
5	Measurement Capability	Difficult for precise direct measurements	Easy to perform distance and area measurements using software
6	Operator Safety	High risk especially in landslide zones and hazardous terrain	Safe, as the drone captures images from the air without direct risk
7	Speed of Data Collection	Relatively slow, dependent on field access	Fast, can capture many points in a short time
8	Main Function	Visual documentation of real-time field conditions	Monitoring, risk analysis, and landslide mitigation planning

The comparison in table 3 shows the big differences between standard images taken with a typical camera and orthophotos made with drone technology to document landslide regions in nickel mining sites. Regular images provide you a limited perspective from the ground that shows you real-time visual information, but they don't cover a lot of ground, are not very accurate, and can't estimate distances or regions very well. They also put operators who work in dangerous and hard-to-reach areas at greater risk, and data collection is usually slower because it's harder to get to.

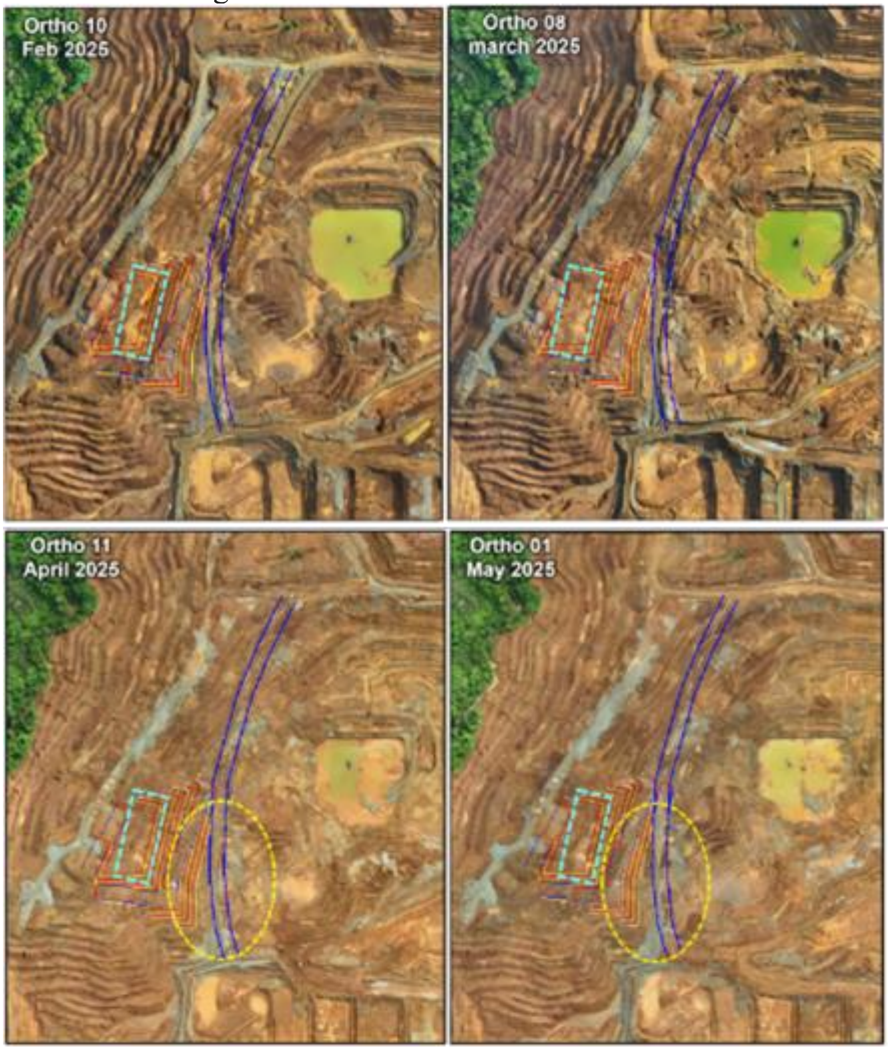


Figure 5. Imagery Drone Photo Of Saturated Area

Figure 5 which shows that the light blue areas are saturated. This saturation is caused by rainwater in these areas not being discharged or not being properly drained, for example by the construction of drainage channels or ditches.

The position of the water in the same area indicates that the capacity or absorption of the material has reached its threshold. Which indicates that the material inside is no longer void. It is in a fully saturated state.

Sequential UAV orthophotos revealed progressive deterioration of the landfill slope. Historical imagery showed the landfill toe was utilized as a dewatering discharge outlet, causing persistent water saturation. Rainfall events intensified soil saturation, reducing effective stress and shear strength. Laboratory tests confirmed soil water contents of 42.95–53.44% (Figure 6), indicating critical saturation levels.

A. Uji Kadar air

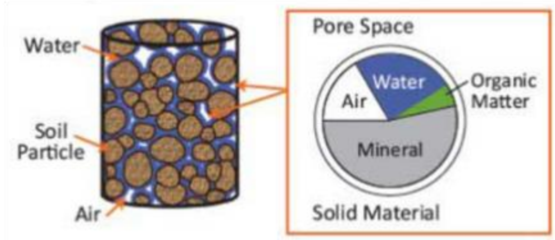
No Cawan	Satuan	a	b
Berat Cawan	gram	12.68	76.88
Berat Cawan + Tanah Basah	gram	51.45	188.06
Berat Cawan + Tanah Kering	gram	39.58	153.64
Berat air	gram	11.87	34.42
Berat tanah kering	gram	26.90	76.76
Kadar air	%	44.13	44.84
Kadar air rata-rata	%	44.48	

A. Uji Kadar air

No Cawan	Satuan	a	b
Berat Cawan	gram	21.98	21.96
Berat Cawan + Tanah Basah	gram	104.49	70.58
Berat Cawan + Tanah Kering	gram	79.70	55.97
Berat air	gram	24.79	14.61
Berat tanah kering	gram	57.72	34.01
Kadar air	%	42.95	42.96
Kadar air rata-rata	%	42.95	

A. Uji Kadar air

No Cawan	Satuan	a	b
Berat Cawan	gram	12.99	12.70
Berat Cawan + Tanah Basah	gram	131.14	136.70
Berat Cawan + Tanah Kering	gram	89.95	93.56
Berat air	gram	41.19	43.14
Berat tanah kering	gram	76.96	80.86
Kadar air	%	53.52	53.35
Kadar air rata-rata	%	53.44	



Average Water Content : 40%

Figure 6. Water content laboratory results and material distribution illustration

Slope Stability Modeling

Cross-sectional analysis using UAV-derived DEMs allowed deterministic and probabilistic stability modeling. Limit equilibrium analysis yielded:

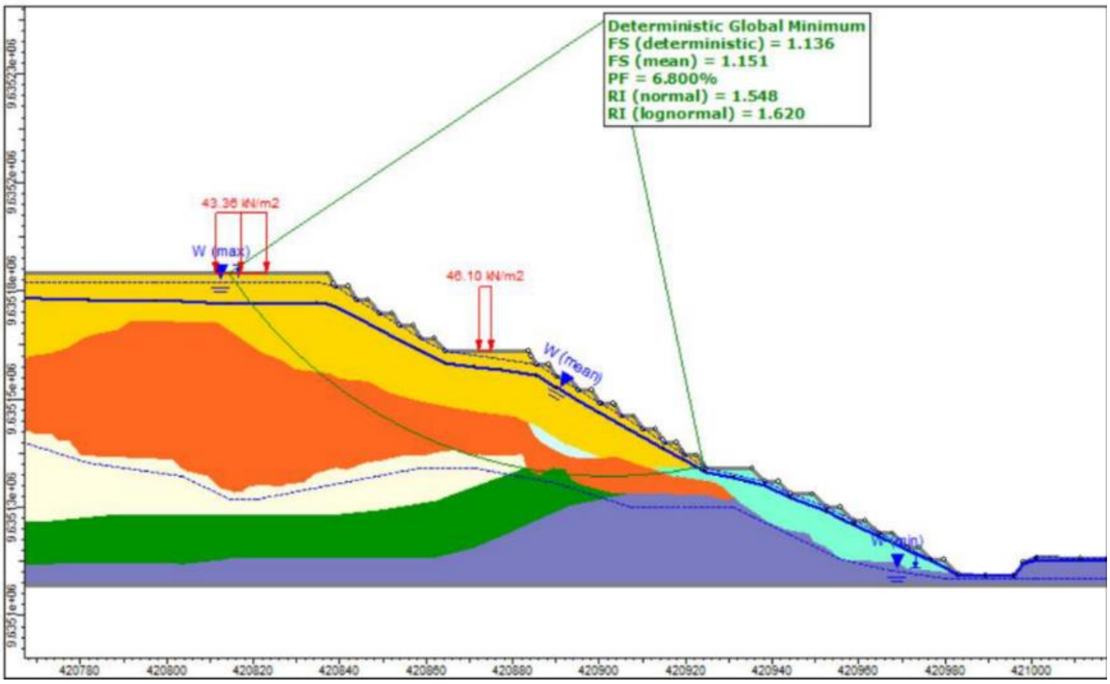


Figure 6. Geotechnical Modelling

Figure 6 presents the outcome of a slope stability assessment conducted using geotechnical software applying the limit equilibrium method. The cross-sectional profile of the embankment is illustrated, with material layers distinguished by different colors and potential slip surfaces clearly marked. The analysis produced a deterministic factor of safety (FS) of

1.136 and a mean FS of 1.151, values that slightly exceed the minimum stability criterion commonly applied in mining geotechnical design (approximately 1.1 under dinamic conditions) (KEPMEN ESDM 1827, 2018). The probability of failure (PF) was calculated at 6.8%, indicating that although the slope is considered broadly stable, a measurable risk of failure remains. These results classify the slope as marginally stable, requiring remediation.

Hazard Mapping

By integrating UAV DEMs, slope analysis, and geotechnical inputs, a hazard map was developed, classifying the site into five zones:

1. Zone A (High Hazard): active landslide zones, strictly restricted.
2. Zone B (Caution): unstable areas requiring intensive monitoring.
3. Zone C (Fall Risk): ponding and mudflow-prone depressions.
4. Zone D (Moderate Hazard): potential equipment-related risks.
5. Zone E (Low Hazard): stable zones safe for routine operations.

Figure 7 shows the mine area is divided into zones according to the level of potential geotechnical hazard, to support the safety and efficiency of operations.

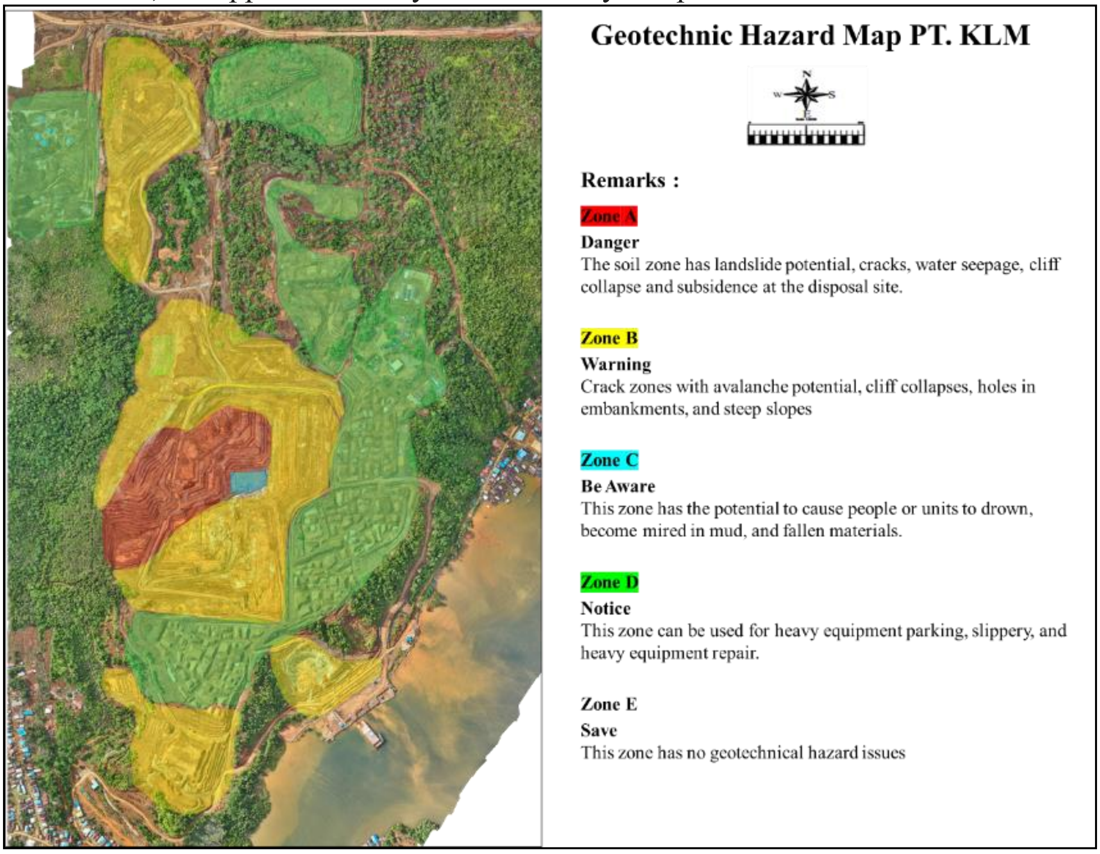


Figure 7. Geotechnic Hazard Map

This hazard map provides a spatial decision-support tool for mine planning, zoning, and evacuation route design.

1. **Zone A (Red):** This zone represents the highest hazard level, where unstable soil conditions create a strong potential for landslides. Typical features include surface cracking, cliff scouring, localized collapses, and subsidence in disposal areas. Strict operational protocols apply: work must be suspended at the first indication of instability, ground movements exceeding 0.05 mm/hour are unacceptable, and any signs of cracking or displacement must be reported immediately. Blasting activities are prohibited unless specifically authorized, and intensive monitoring is required to minimize accident risks.
2. **Zone B (Yellow):** Classified as a cautionary area, Zone B is prone to slope failures and collapse in both disposal and pit walls. Hazards include the presence of voids in disposal

zones, subsidence, and waterlogging. Field crews must carefully observe wall and surface conditions, and any cracking must be reported without delay. Operations may be temporarily suspended if warning signs are identified. Heavy equipment use is restricted in unstable sections, and continuous monitoring is necessary to reduce risk.

3. **Zone C (Blue):** This zone is defined by fall and drowning risks, particularly in areas with ponds, sumps, or mud-filled depressions. Workers and equipment face hazards from unstable pond walls, thick mud, or sudden material falls. Machine operation is prohibited near such areas, and workers must exercise heightened caution. Regular inspections of soil and water conditions are required to ensure early detection of changes that could increase accident likelihood.
4. **Zone D (Green):** Although considered relatively safe, Zone D still requires supervision, especially around heavy equipment parking zones, repair workshops, disposal pits, and embankments. Hazards in this zone are typically operational rather than geotechnical, arising from the movement or maintenance of machinery. Preventive oversight is essential to ensure that secondary risks do not compromise safety.
5. **Zone E (White):** This is a designated safe zone where no significant geotechnical hazards have been identified. Normal mining and operational activities can proceed without additional geotechnical restrictions, although standard occupational safety practices remain applicable.

CONCLUSION

1. Based on the findings of this study, several key conclusions can be drawn. First, the use of drones significantly enhances workplace safety by eliminating the need for personnel to physically enter hazardous zones; surveys can instead be performed remotely from safe locations.
2. UAV technology produces a range of critical outputs for landslide investigation. High-resolution orthophotos provide precise visual documentation of the terrain and, when compared over time, reveal landscape changes that help identify triggering factors such as waterlogging from poor drainage or pump discharge. Contour maps derived from drone data accurately represent slope geometry, offering valuable insights for slope stability evaluation. Additionally, UAV surveys enable the generation of 3D models, which allow realistic visualization of site conditions, support monitoring, and help pinpoint areas at risk of failure.
3. Drone deployment effectively addresses major challenges in surveying nickel mine slopes, including restricted access, unstable ground conditions, and the limitations of conventional equipment. While UAV outputs are generally accurate, some deviations may occur, requiring consistent monitoring and calibration for applications demanding high precision.
4. This study highlights the broader analytical potential of UAV technology beyond simple mapping. Drone-based data proved instrumental in identifying the root causes of landslides and in supporting detailed geotechnical assessments, thereby contributing to safer and more informed slope management practices.

REFERENCES

Agisoft (2020) Agisoft Metashape User Manual: Professional Edition, Version 1.6. St. Petersburg: Agisoft LLC.

Colomina, I. and Molina, P. (2014) 'Unmanned aerial systems for photogrammetry and remote sensing: A review', ISPRS Journal of Photogrammetry and Remote Sensing, 92, pp. 79–97.

Casagli, N., Frodella, W., Morelli, S., Tofani, V., Ciampalini, A., Intrieri, E., Raspini, F., Rossi, G. & Tanteri, L. (2017) 'Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning', *Geoenvironmental Disasters*, 4(1), pp. 1–23.

DJI (2023) DJI Mavic 3 Enterprise Series Product Manual. Shenzhen: DJI.

Duncan, J.M. and Wright, S.G. (2014) Soil Strength and Slope Stability. 2nd edn. Hoboken: John Wiley & Sons.

Fathani, T.F. and Karnawati, D. (2021) 'Landslide hazard and risk assessment in tropical mining areas', Natural Hazards, 107(1), pp. 1225–1245.

Fiorucci, F., Giordan, D., Santangelo, M., Dutto, F. and Allasia, P. (2019) 'A UAV-based approach for landslide mapping and monitoring', Natural Hazards and Earth System Sciences, 19(2), pp. 323–343.

George, M.L., Rowlands, D., Price, M. and Maxey, J. (2004) The Lean Six Sigma Pocket Toolbook. New York: McGraw-Hill.

Gülci, S., Kalkan, K., Akay, A. & Toksoy, D. (2022) 'Opportunities and challenges of UAVs in forestry and mining', *Journal of Environmental Management*, 307, p. 114571.

International Energy Agency (IEA) (2022) The Role of Critical Minerals in Clean Energy Transitions. Paris: IEA.

KEPMEN ESDM 1827. (2018). Keputusan Menteri Energi dan Sumber Daya Mineral Nomor 1827 K/30/MEM/2018 Tentang Pedoman Pelaksanaan Kaidah Teknik Pertambangan yang Baik. https://jdih.esdm.go.id/peraturan/Keputusan Menteri ESDM Nomor 1827 K 30 MEM 2018.pdf.

Lucieer, A., de Jong, S.M. and Turner, D. (2014) 'Mapping landslide displacements using Structure from Motion (SfM) and drone data', Remote Sensing of Environment, 150, pp. 93–104.

Nex, F. and Remondino, F. (2014) 'UAV for 3D mapping applications: A review', Applied Geomatics, 6(1), pp. 1–15.

Niethammer, U., James, M.R., Rothmund, S., Travelletti, J. and Joswig, M. (2012) 'UAV-based remote sensing of landslides', International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 39(B1), pp. 1–6.

Peppa, M.V., Hall, J., Mills, J.P. & Smith, M.W. (2019) 'UAV-derived datasets for landslide monitoring: case study from the UK', *Remote Sensing*, 11(6), p. 1432.

Rahardjo, H., Santoso, V.A. and Leong, E.C. (2019) 'Slope stability issues in residual soils of tropical regions', Engineering Geology, 249, pp. 170–185.

Salamí, E., Barrado, C. and Pastor, E. (2014) 'UAV flight experiments applied to the remote sensing of vegetated areas', Remote Sensing, 6(11), pp. 11051–11081.

Sari, A.P., Widodo, B. and Nugroho, A. (2022) 'ESG challenges in Indonesia's coal mining industry', Journal of Sustainable Mining, 21(3), pp. 125–134.

Turner, D., Lucieer, A. and Watson, C. (2015) 'An automated technique for generating landslide inventories from drone imagery', Remote Sensing, 7(6), pp. 6737–6757.

World Bank (2023) Commodity Markets Outlook: The Impact of Energy Transition on Metals and Minerals. Washington DC: World Bank.