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Mthembi, Nkiyasi Dolette. (2025). Slope stability review: Through the evaluation of a Klipbankfontein instability case study. [Master's dissertation, University of the Witwatersrand, Johannesburg]. WIReDSpace. https://hdl.handle.net/10539/49816

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School of Mining Engineering



UNIVERSITY OF THE
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JOHANNESBURG

SLOPE STABILITY REVIEW: THROUGH THE EVALUATION OF A KLIPBANKFONTEIN INSTABILITY CASE STUDY

Nkiyasi Mthembi

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I declare that this research is my own unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

Johannesburg, 2025

DECLARATION

I have familiarised myself with the University of the Witwatersrand Student Academic Misconduct Policy (SAMP). I hereby declare that the work I am submitting for assessment is my original work. I affirm that I have not plagiarised, misrepresented, or colluded with any other person or source. I have properly acknowledged, cited and referenced all the sources that I have used in my work. I also declare that where I have used artificial intelligence (AI) tools it has only been as a means of guidance. The ideas and arguments presented in my work are my original thoughts and interpretations. I acknowledge that any academic misconduct, such as plagiarism or collusion will result in serious consequences. According to the SAMP, these consequences may include a reduced grade, a fail mark, or disciplinary action. The Faculty of Engineering and the University of the Witwatersrand have my consent to investigate any potential academic misconduct in my work. This investigation may include the use of similarity and AI detection software to check the originality of my work. I undertake to abide by the decision of any such investigation.



_____

(Signature of Candidate)

25 day of September, 2025

‘It is hard to fail, but it is worse never to have tried to succeed.’

Theodore Roosevelt

ABSTRACT

A slope instability occurred at Kolomela Mine on 16 July 2022. This study analyses the slope instability to determine the rock mass behaviour before, during and after the event. The study describes the process of slope failure and the major indicators of failure as determined from instruments used to monitor the slope at the time of the failure. The contributing elements to the slope failure were investigated, including both the physical conditions and the deformations that were monitored before and during the slope failure. The findings showed that slope failure occurred on the banded ironstone formation (BIF) and gabbro contact, with lateral release given by orthogonal faults. The limit equilibrium analysis indicated that under dry conditions, the BIF–gabbro contact was within acceptable criteria. Implementing a robust monitoring system, including real-time pore pressure sensors, can provide early warning signs of instability and help guide operational decisions. Proactive management of these variables is essential to reducing geotechnical risk and ensuring the continued safety and efficiency of mining operations. TARP effectiveness evaluation calls for the study of response timing as well as monitoring data. The evacuation time at the onset of the failure was within the 13-minute evacuation time. Possibilities for TARP improvement were exposed through several data sources. Combining GeoMoS trends with radar displacement data could have shown warning signals hours before the displacement triggers, according to correlation analysis. While keeping the early warning system with its proven efficacy for personnel safety in place, the implementation of these improved triggers, together with an automated correlation of rainfall intensity and pore pressure changes, would strengthen the usefulness of the current system.

ACKNOWLEDGMENTS

I would like to thank my family for their unwavering support throughout this process. I am also deeply grateful to my supervisor, Bryan Watson, for his guidance and assistance in reviewing this research project. My sincere appreciation goes to Kumba Iron Ore (Anglo American) for granting me access to the necessary resources, which made it possible to complete this work as part of my degree submission.

I dedicate this report to the memory of my daughter, Masingita Ebenezer Mthembi, whose spirit continues to inspire me every day.

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LIST OF ABBREVIATIONS

BIF	Banded Ironstone Formation
FDM	Finite Difference Method
FoG	Fall of Ground
FoS	Factor of Safety
HIRA	Hazard Identification and Risk Assessment
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection and Ranging
PoF	Probability of Failure
PoO	Probability of Occurrence
SSR	Shear Strength Reduction
TARP	Trigger Action Response Plan

Definitions

TERM	DEFINITION
Aquifer	Geological formation saturated with groundwater.
Banded ironstone formation (BIF)	A sedimentary rock consisting of alternating bands of chert and ironstone.
Bedding	Layering parallel to original sedimentary deposition surfaces.
Bench	Horizontal step or level within a mine excavation, currently mined or scheduled for extraction.
Chert	Fine-grained silica is commonly found as nodules or bands within sedimentary formations.
Cohesion	Intrinsic shear resistance within geological materials in the absence of normal stress.
Compressive stress	Axial stress causes shortening in a material.
Controlled blasting	Techniques used to minimise unintended rock fragmentation and vibration effects during excavation blasting.
Creep	Slow, time-dependent deformation, typically occurring in mine floors.
Deformation	Change in shape or dimensions of a solid object under stress.
Dip	Angle of inclination of geological planes relative to the horizontal.
Dolomite	Carbonate rock containing significant magnesium carbonate content.
Factor of safety	Ratio comparing resisting forces against forces promoting failure.
Fault	Rock fracture with observable displacement along its plane.

TERM	DEFINITION
Footwall/floor	Rock mass beneath a structural discontinuity or ore body.
Force	An interaction capable of changing an object's motion or position.
Friction	The resistance force opposing relative motion between contacting surfaces.
Geology	Science examining Earth's physical structure, composition and developmental processes.
Haematite	Iron-rich mineral serving as a key iron ore.
Haul road	Road constructed for the transportation of ore, waste rock and personnel.
Hazard	Potential source or exposure to danger or harm.
Highwall	Nearly vertical excavation face in rock or overburden.
Joint	Rock fracture without observable displacement.
Karst topography	Landforms resulting from chemical erosion of limestone or dolomite by groundwater.
Lithological unit	Sedimentary rock layer defined by uniform mineralogical properties.
Normal stress	Stress component perpendicular to the plane of application.
Ore body	A concentrated mineral deposit which is economically viable for mining.
Outcrop	Natural exposure of rock at Earth's surface.
Permeability	The capacity of a rock formation to transmit fluids through its interconnected pores or fractures.

TERM	DEFINITION
Risk	Potential for harm or injury occurring.
Rock	Naturally occurring solid composed of minerals or mineral aggregates.
Rockfall (fall of ground)	Unplanned detachment and descent of rock fragments independent of seismic events.
Rock mass	In-situ rock, including structural discontinuities such as joints, fractures and faults.
Rock mass rating	Systematic evaluation of rock mass quality using recognised classification methods (e.g., Laubscher or Bieniawski).
Rock mass strength	The maximum stress a rock mass can withstand without failure under specific loading conditions.
Rock mechanics	The scientific discipline concerned with the behaviour and mechanical properties of rock materials under various stress conditions.
Scaling	Removal of unstable or loose rock fragments from excavation surfaces to enhance safety.
Seismic event	Seismic occurrence resulting from the sudden release of accumulated stress energy within rocks.
Shale	A sedimentary rock characterised by fissility and distinctive bedding planes.
Shear strength	The highest shear stress that a material can sustain.
Shear stress	Force component causing displacement along planes within a material.
Slope	An inclined surface formed due to mining excavation,

TERM	DEFINITION
	angled less than 90 degrees from horizontal.
Slope instability	A condition where mining slopes or benches become unstable, potentially leading to failure.
Special areas	Zones requiring enhanced monitoring and specific safety precautions due to increased geotechnical risk.
Stack failure	Slope failure involving multiple excavation benches.
Strength	The maximum stress level a material can sustain without failing.
Stress	Force is distributed over an area.
Strike	Horizontal direction of intersection between an inclined geological layer and a horizontal reference plane.
Subsidence	Vertical settlement or downward displacement of the ground surface above underground or adjacent to open excavations.
Thickness	Distance measured perpendicularly between geological boundary layers.
Uniaxial compressive strength	The highest compressive stress a material can resist when no lateral confinement is present.
Weathering	Breakdown of rocks and minerals due to environmental conditions such as temperature variations, water and chemical reactions.

1 INTRODUCTION

1.1 Research Background and Context

This report discusses a case study of a slope failure at the Kolomela open-pit mine. The mine is situated in the Northern Cape Province near Postmasburg and is a producer of direct shipping iron ore, with proven reserves of 101.3 million tonnes. The mine consists of four deposits: Kapstevel North, Kapstevel South, Leeuwfontein and Klipbankfontein. The iron ore is predominantly located at the summit of the Asbestos Hills Subgroup inside the Kuruman Formation. Figure 1.1 illustrates the location of Kolomela Mine.

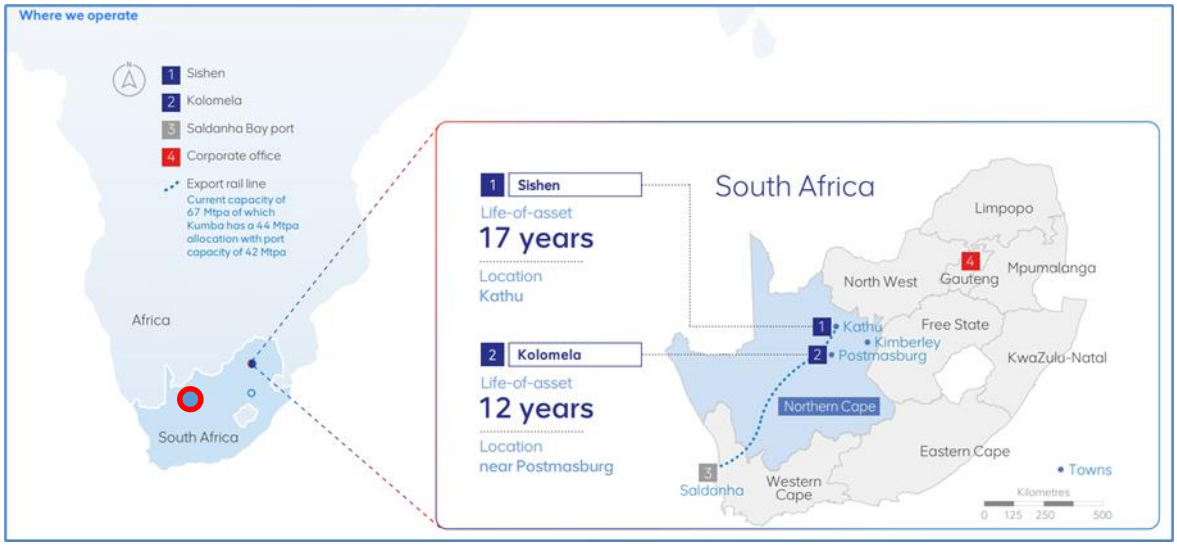


Figure 1.1. Location of Kolomela Mine (Anglo American, 2022)

This study concentrates on the Klipbankfontein pit, located within the Northern Cape region. The area is underlain by unique remnants of the Proterozoic Transvaal Supergroup, consisting of both chemical and clastic sedimentary formations. These geological units mark the western edge of the Kaapvaal Craton in the Northern Cape Province. Over time, the rock layers have experienced significant deformation due to westward-directed thrusting and have undergone notable karst development.

The thrusting activity has led to the development of a series of open, north–south–oriented anticlines and synclines, along with graben structures. Extensive karstification in the area has also contributed to the formation of deep sinkholes. These structural features have played a crucial role in preserving the iron ore deposits at Kolomela Mine from erosion. A plan view of the Klipbankfontein pit is illustrated in Figure 1.2.



Figure 1.2. Plan view of the Klipbankfontein pit (Google 2025)

Klipbankfontein is part of Kolomela, an open-pit operation. Kolomela Mine's run-of-mine was planned for extraction from four pits via conventional truck and shovel operations for loading and hauling, and conventional drilling and blasting methods. Klipbankfontein pit was mined in three pushbacks. The instability occurred in Pushback 1 (Phase 1), which is towards the north of Klipbankfontein pit (Figure 1.2).

1.2 Problem Statement

In the third quarter of 2022, a slope failure was triggered by the interaction between an underlying fault system and a geological contact zone. The incident affected seven mining benches and involved the displacement of approximately 250,000 tonnes of material, as illustrated in Figure 1.3.

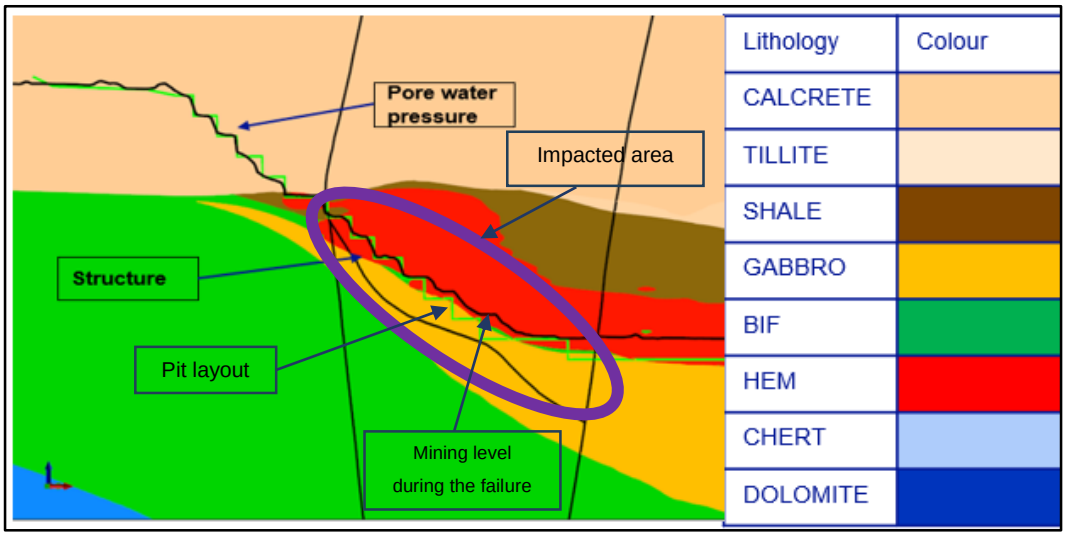


Figure 1.3. Section view of the Klipbankfontein failure area

The geological model developed for the Klipbankfontein pit identifies a total of 29 significant faults within the defined model boundary, 14 of which intersect the final pit design. Two dominant fault orientations are present: one trending northwest–southeast (NW–SE) and the other northeast–southwest (NE–SW). A limit equilibrium analysis conducted for the area yielded factors of safety (FoS) of 1.88 for global stability and 1.33 for localised failure scenarios, both indicating a low overall probability of failure (PoF).

A fault system was confirmed on the eastern highwall of Phase 1, which interacted with an unfavourable dipping geological contact. Hazard identification and risk assessment (HIRA) analysis associated with the potential slope failure fell within the acceptable 0–20 risk rating category. In areas of acceptable risk, normal day-to-day controls, as assumed in the fault tree analysis, are maintained to ensure that the slope stability risk is managed throughout the life of the slope in question. The catchment below the area was deemed sufficient according to the rule of

thumb and an evaluation of the structural model. However, a slope failure occurred, and Figure 1.4 shows the collapse.

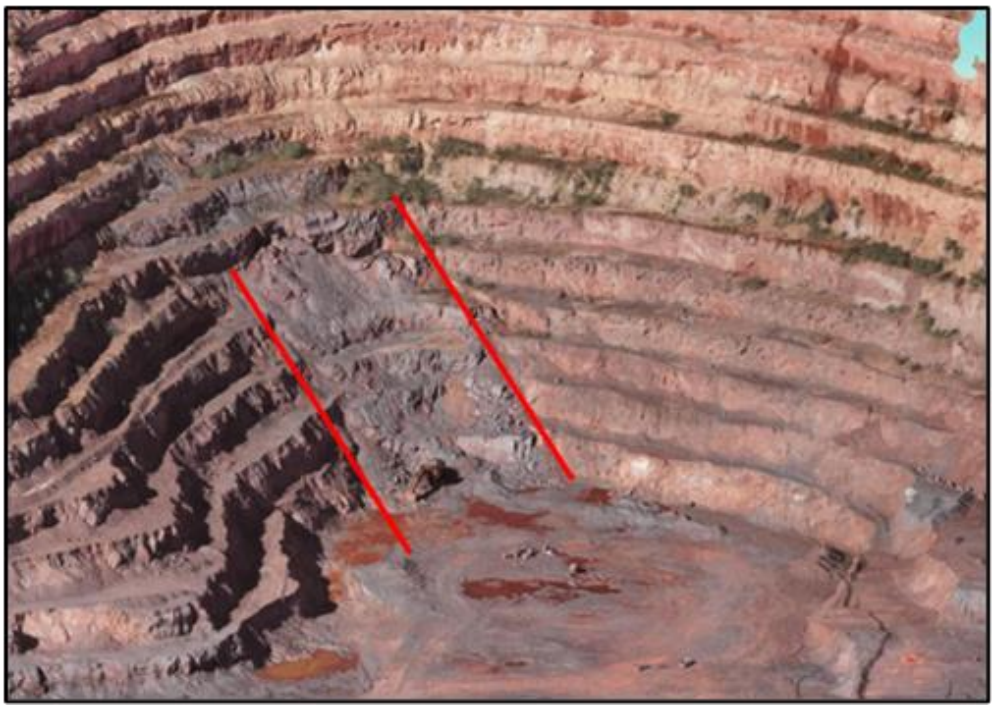


Figure 1.4. Klipbankfontein failure area

During the previous quarter before the instability, no unusual movement was measured in the area. However, after increased rainfall and blasting of an area relatively close to the slope, the GeoMoS system detected an increase in movement. This warning was subsequently validated by the Interferometric Synthetic Aperture Radar (InSAR). A loading vehicle was being repaired beneath the slope at the time the area was evacuated and was left behind. Figure 1.5 shows the slope monitoring strategy that was utilised to monitor the area of concern.

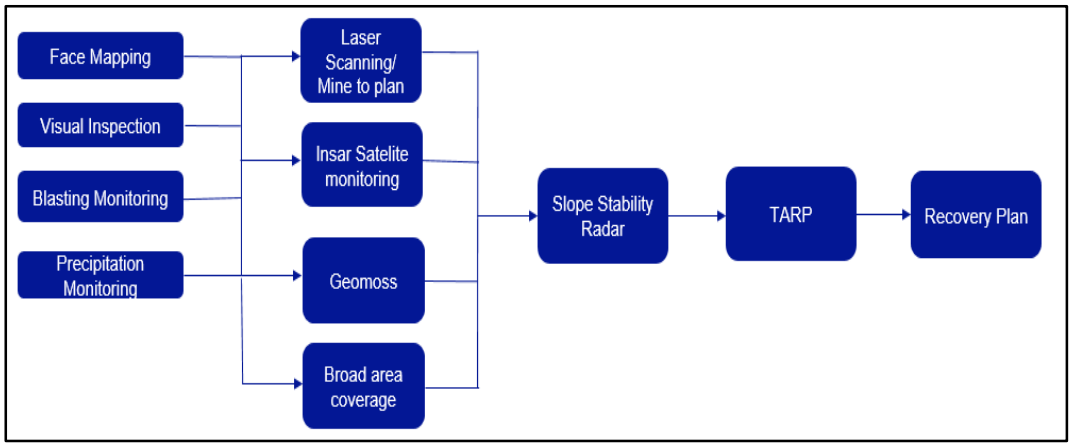


Figure 1.5. Slope monitoring strategy for Kolomela Mine (Malesa et al., 2022)

This instability resulted in a halt in production for approximately a month. Approximately 400,000,000 kg of iron ore were left behind to provide confinement to the instability.

1.3 Justification for Research

The occurrence of slope failure can lead to the loss of human life and damage to property. The examination of causal factors of such failure facilitates the understanding of potential hazards and the implementation of preventative actions. As the lead time associated with slope failures was not known and may be variable, mining equipment was left behind during the evacuation. The evacuation resulted in a halt of production for over a month in the area. Slope failures also have the potential to significantly harm important elements such as haul roads and the ore itself. There are also significant financial implications connected with the rehabilitation of slope failures. In this instance, iron ore, which was already included in the mine plan, needed to be left behind to provide confinement for the failing wall, resulting in an additional financial impact.

Past studies by Sullivan (2013) and Contreras (2015) show that good slope management calls for balancing safety needs with the economic optimisation of ore recovery. The Klipbankfontein case required leaving almost 400,000 tonnes of iron ore behind to provide confinement to stabilise the area. This scenario agrees with Kolapo et al. (2022), which shows that more complex methods of slope

stability risk assessment and management are needed to cater for the growing depth and scale of modern mining activities.

Mining activities must include geotechnical risk factors in their first planning and reserve calculations if they are to meet these difficulties. As Read and Stacey (2009) highlight, this entails a thorough economic risk assessment, including possible ore sterilisation scenarios in financial models. The Klipbankfontein failure behaviour supports Stacey and Hadjigeorgiou's (2021) case study of using a quantified value-created approach in mine design and running decisions. The research was aimed at preventing circumstances whereby valuable ore must be sacrificed for stability; hence, such an approach should include alternative mining sequences for high-risk areas, the development of contingency plans and the regular updating of risk matrices. Such proactive actions fit De Graaf and Wessels' (2016) approach to controlling geotechnical risk across several activities, thereby possibly avoiding the notable financial consequences evidenced in this case study.

Doumbouya et al. (2020) state that there have been numerous instances of catastrophic slope failures or severe deformations worldwide over the previous decade. Klipbankfontein has seen multiple ground collapses, which will be addressed in the subsequent chapters. Considering the escalating trends in depth and catastrophic failures documented in the literature, a comprehensive understanding of the failure causes and potential warning signals of an impending collapse will enhance the industry's value (Doumbouya et al., 2020).

Slope stability failures are a primary cause of fatalities in surface mining operations in the United States (Girard & McHugh, 2000). The examination of slope failures is crucial to the advancement of geotechnical engineering expertise. A comprehensive understanding of the fundamental mechanisms that lead to failures is essential for engineers to improve design techniques, construction processes and predictive modelling. Analysing the causes that lead to slope instability is essential for developing an effective plan for disaster prevention.

1.4 Research Objectives

The primary objective of this report is to investigate the root causes of the slope failure and to establish measures aimed at reducing the likelihood of a similar event in the future. The study involved a comprehensive evaluation of contributing factors, systematic hazard identification, the formulation of trigger action response plans (TARPs) and the design and application of appropriate evacuation protocols.

1.5 Research Methods

The investigation into the slope instability at the failure site involved a detailed assessment of key indicators linked to the event. Several inspection techniques—ranging from traditional visual assessments to more advanced methods such as photogrammetry and drone-based surveys—were evaluated for their efficacy in detecting early signs of instability. In addition, a comprehensive analysis of monitoring datasets was conducted, with a particular focus on the interpretation and reliability of the collected data. This analysis incorporated multiple data sources, including geotechnical laboratory test results and the characterisation of rock mass properties within the affected lithological units.

1.5.1 Qualitative research

This section summarises the methods used to gather data for investigating slope instability at the Klipbankfontein site area. Data was primarily collected using the slope deformation monitoring system, as outlined in the slope monitoring strategy in Figure 1.6.

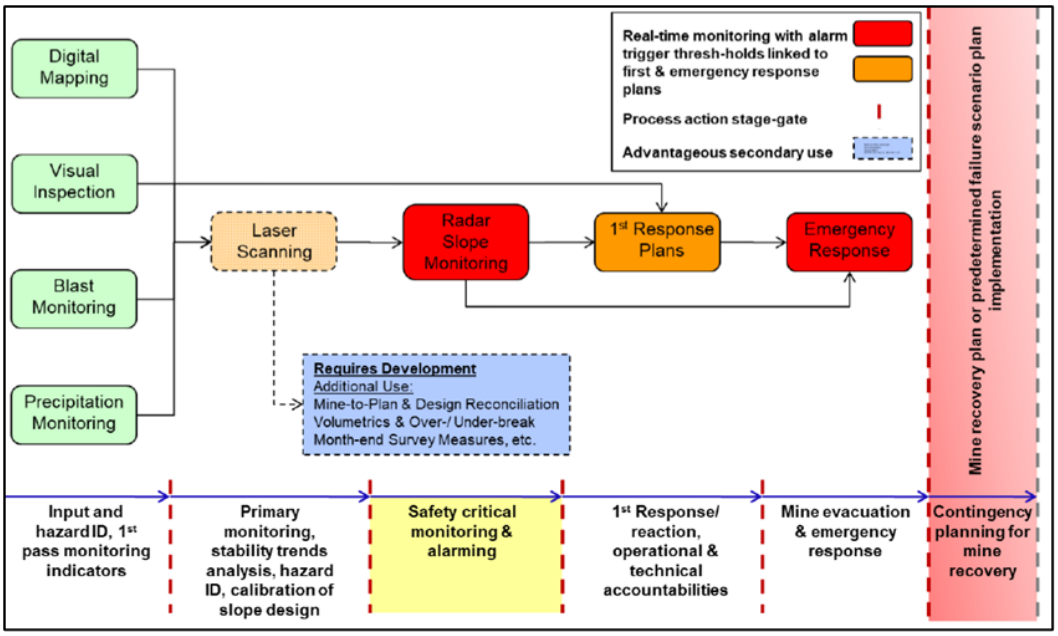


Figure 1.6. Generic slope monitoring strategy (Sekoere et al., 2014)

The methodology included kinematic and slope stability analysis, deformation profile and warning time evaluation.

1.6 Sources of Data

The geological and structural characteristics of this structurally controlled failure were obtained from several sources. The main data consisted of a thorough mapping of discontinuities, especially the orientation. Properties of the haematite/BIF and gabbro contact and intersecting fault systems were also determined. Drill core logging and face mapping allowed for joint roughness coefficients, persistence and infill characteristics to be recorded. Rainfall records, among other hydrogeological data, were gathered to better understand the function of water pressure along these structural paths. Additional data sources included historical drone footage showing increasing development of the failure, blasting records from surrounding areas, and slope monitoring data from radar and prism measurements capturing displacement patterns along the controlling structures.

1.7 Research Validation

The information used in this report forms part of the QAQC process and periodic reviews of data and processes that are carried out on all the site information. The information was also reviewed against literature data, such as the TAMU database (Timchenko & Briaud, 2023).

1.8 Structure of the Research Report

This report consists of six chapters, as outlined below.

Chapter 1 outlines the research background, including the geographical context, motivation for the study, problem statement, research objectives, research questions, methodology and the layout of the report.

Chapter 2 presents a comprehensive literature review of the subject matter, offering insights to foster a deeper understanding of slope failure and instabilities as well as elucidating key debates and controversies.

Chapter 3 delineates the research methodology employed in the study, detailing the approach, methods and techniques utilised to address the research objectives comprehensively.

Chapter 4 presents a description and analysis of the collected data to answer the research questions.

Chapter 5 presents a thorough discussion of the report findings while giving insights and analysis derived from the report outcomes.

Chapter 6 encapsulates the conclusions drawn from the report and provides recommendations for further actions and considerations.

2 LITERATURE REVIEW

2.1 Introduction

Open-pit mining entails the extraction of minerals or other geological substances from an uncovered excavation or quarry. Slope failure, also known as slope collapse or landslide, represents a persistent risk in open-pit mining operations. Slope collapses may result from various sources, such as geological conditions, weathering processes, mining activity and human error (Sjoberg, 1996).

Kolapo et al. (2022) assert that empirical evidence from rock slope project designs has continuously highlighted the necessity of a rigorous design methodology. In open-pit mining, several measures can be utilised to improve slope stability, such as slope angle optimisation, benching and drainage management.

Important consequences for both safety and production follow from the differences in the failure mechanisms and warning times of slope failures in open-pit mines. With 145 million tonnes of material involved, the 2013 Manefay slope failure at Bingham Canyon Mine is a prime example of a large-scale circular failure mechanism with clearly visible precursor movements that allowed for evacuation (Williams et al., 2021). While smaller in scope, the Klipbankfontein failure showed traits of a structurally controlled failure along geological contacts and fault intersections, typical of the mechanisms described by Sjoberg (1996). A progressive displacement prompts the need for a close look at the slopes. As the slopes move faster, it is important to make predictions of a possible slope failure timeously (Kothari & Momayez, 2017).

This chapter examines the core principles and theoretical frameworks that underpin the investigation of slope failures. By analysing the complex interplay between slope geometry, material properties, shear strength and external influencing factors, engineers can deepen their understanding of slope instability mechanisms. Such insights are critical for developing robust evaluation methodologies and mitigation strategies, ultimately contributing to the design of safer and more resilient engineered environments.

Slope collapses have an economic effect beyond the immediate loss of material. They can include prolonged mine closures and production delays. As with Klipbankfontein's month-long closure, the Bingham Canyon Mine remained closed for several months during repairs; the main difference between the two mines was the detection and response times. Osasan and Stacey (2014) claim that various failure mechanisms call for appropriate monitoring techniques and response plans.

Structured geological controls used in the Klipbankfontein experience support Stacey and Hadjigeorgiou's (2021) emphasis on the need for thorough monitoring systems capable of identifying both gradual deformation and rapid structural failures. This requirement is especially true in areas where geological structures could encourage accelerated failure development.

Monitoring systems primarily capture data related to temporal changes and ground deformation or displacement. These systems typically record increasing deformation trends up to the point of slope failure or until the displacement exceeds the operational limits of the monitoring equipment (Chandarana et al., 2016). The temporal and deformation datasets are critical in characterising the nature of slope movement—whether it is progressive, steady, or diminishing over time—as illustrated in Figure 2.1. Zavodni and Broadbent (1978) demonstrated the use of empirical data from various open-pit mining operations to differentiate between progressive and regressive deformation behaviours.

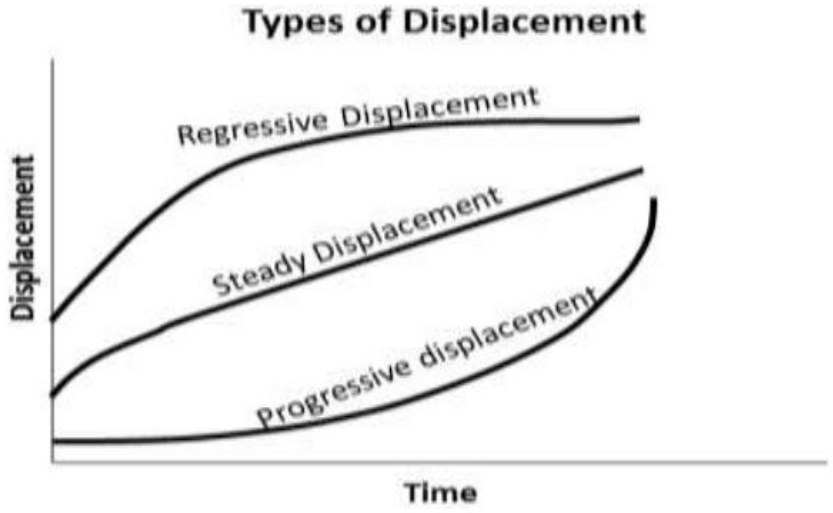


Figure 2.1. Progressive, steady and regressive displacement (Kothari & Momayez, 2017)

Radar monitoring data provide valuable insights into the evolution of slope movement from the onset of minor displacements through to eventual failure. This pre-failure deformation process is typically divided into three distinct phases: primary, secondary and tertiary—an approach analogous to creep behaviour observed in geomaterials (Crosta & Agliardi, 2003; Federico et al., 2012; Saito, 1996; Xu et al., 2011). The primary stage is characterised by a decreasing strain rate, the secondary stage by a near-constant strain rate, and the tertiary stage by a rapidly accelerating strain rate that culminates in failure, as illustrated in Figure 2.2. These phases correspond to regressive, stable and progressive deformation patterns, respectively, in the movement of a rock mass. A displacement-time curve exhibiting a sharp, exponential increase in the tertiary phase is indicative of imminent slope failure (Nie et al., 2016).

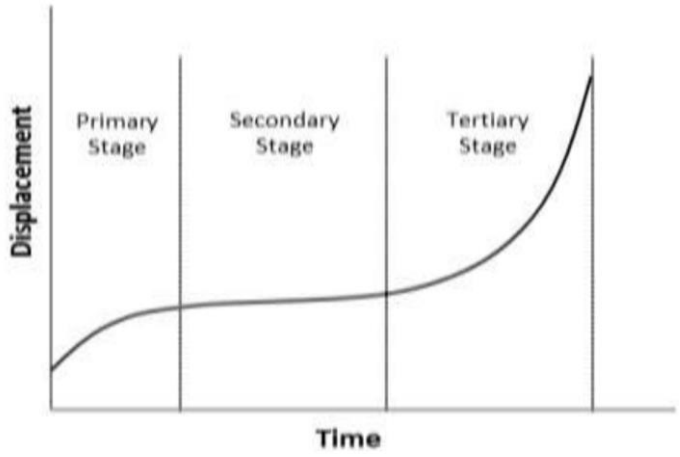


Figure 2.2. Primary stages of pre-failure evolution (Kothari & Momayez, 2017)

In open-pit mining, protection against rockfalls requires carefully designed containment structures. A bund (also known as a rockfall berm or protective embankment) is an engineered earthen barrier constructed to intercept and contain falling rocks before they reach active mining areas or infrastructure. According to Read and Stacey (2009), an effective bund design must consider the potential energy and trajectory of falling material, with typical heights being one-third to one-half of the cumulative bench height they protect.

Ritchie (1963) established fundamental criteria for rockfall protection design, demonstrating that bund effectiveness depends on three key parameters: height,

width and catch capacity. Studies by Hungr and Evans (1988) further developed these concepts, showing that bund geometry should be designed based on:

- expected rockfall volume;
- fall height and bench configuration;
- rock fragment size and shape;
- impact energy calculations; and
- required catchment capacity.

At Klipbankfontein, mining activities were restricted to areas west of the protective bund, which was designed to contain potential rockfalls from the unstable eastern highwall. This approach aligns with modern risk management practices described by Wessels and Dixon (2020), where physical barriers serve as critical controls in the hierarchy of rockfall protection measures.

In December 1967, a significant slope failure occurred at the Chuquicamata Mine in Chile, triggered by an earthquake and subsequently aggravated by excavation and blasting operations. The collapse resulted in the deposition of nearly three million tons of rock. Limit equilibrium analysis indicated that the average cohesion involved in the slope movement was relatively low, around 100 kN/m², with friction angles between 20° and 25° (Voight & Kennedy, 1979). Figure 2.3 shows a cross-section of the southeastern slope of the Chuquicamata open pit at N3500, adapted from Kennedy et al. (1971). The diagram compares slope profiles from 1967 and 1968, highlighting a stripped bench crest located above level D-2. The failure surface is illustrated with bold dotted lines. Major geological features, labelled A and B, are shown as thick solid lines. The figure includes a theoretical cylindrical failure surface based on a friction angle (φ) of 25°, along with planar failure surfaces at ψ = 25° and 30° (inclination angle of a potential failure surface), which are constrained at the rear by steeply inclined fractures. Regions labelled a and b represent segments of the northern and central slope blocks that were involved in the collapse. The zone of deformation extends to a depth of at least 123 m. Centres of rotation for the cylindrical failure models are also indicated for various combinations of height (H) and friction angle (φ).

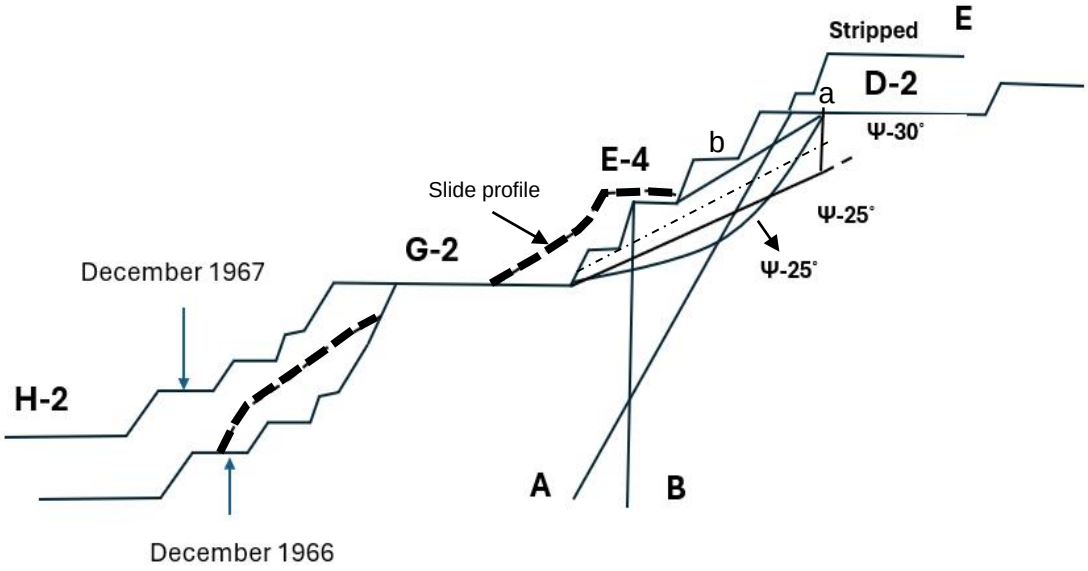


Figure 2.3. Section profile of the southern face at Chuquicamata Mine (Voight & Kennedy, 1979)

Voight and Kennedy (1979) indicate that the low strength values suggest failure occurred on smooth joint surfaces coated with silicate. The surfaces in question are not represented in published statistical assessments of rock fabric but are instead interpreted through analysis. The incident resulted in the death of one miner and caused considerable damage to the mine's infrastructure.

These instances exemplify a restricted quantity of slope failures in the annals of open-pit mining. Kolapo et al. (2022) indicate that substantial advancements have occurred in slope stability monitoring and analysis in the mining sector in recent years. There is an increasing acknowledgement of the necessity to mitigate the dangers linked to open-pit mining to avert possible disasters.

The presence of two distinct profiles, dated December 1966 and December 1967, illustrates a temporal comparison of geological or structural conditions. This allows for the assessment of changes over time, likely resulting from mining activities, natural erosion, or slope instability. Such comparisons are essential for evaluating excavation progress, identifying potential failure zones and informing future operational planning.

Slope stability is essential in open-pit mining operations, as it affects employee and equipment safety, along with the mine's economic viability. Slope stability is often assessed using various geotechnical investigations, monitoring and management methodologies.

Geotechnical engineers employ many approaches, such as geological mapping, ground characterisation and slope monitoring to ascertain probable reasons leading to instability. This encompasses geological formations, material characteristics and aquifer conditions to guarantee slope stability. These characteristics are utilised to construct a suitable slope design and management strategy, encompassing benching, drainage systems and stabilisation strategies to reduce the risk of slope failure (Silva et al., 2021).

The stability of a slope is affected by the geotechnical characteristics of the rock, slope angle and configuration, weathering processes, groundwater conditions, blasting operations and seismic events. Ensuring stability and preventing accidents requires the execution of efficient monitoring, analysis and mitigation procedures. This encompasses the implementation of benching, drainage systems, reinforcement strategies and optimisation of slope angles (Karam et al., 2015).

2.2 Key Concepts, Theories and Studies

Slope failures manifest through a variety of mechanisms, each governed by distinct geological and geotechnical processes. Commonly identified failure types include translational slides, rotational slides, rockfalls, debris flows and complex failures that involve a combination of multiple failure modes. Understanding and mitigating these events requires a detailed analysis of their defining features and the specific conditions that trigger each failure type. Such analysis is fundamental to developing effective risk reduction strategies in slope stability assessments.

There is much information in geotechnical literature about how water can cause slopes to fail. Braathen et al. (2004) showed that groundwater pressure lowers effective stress along breaks in rock, especially in rock masses that are joined together, which allows water to enter along structural features. This mechanism is especially important where geological contacts and fault intersections make flow

paths that are easier to follow. Read and Stacey's (2009) research shows that heavy rain can cause sudden rises in pore water pressure, which can lead to failures in situations where the structure is controlled, and the rock mass behaviour is based on breaks rather than its strength as a whole.

Much research has been done on how gabbro behaves when it comes to slope stability. Hoek and Brown (1997) assert that gabbro usually has a high intact rock strength (uniaxial compressive strength 150 MPa – 250 MPa), but joint networks can make it much weaker.

A variety of methods are utilised to evaluate slope stability, from basic limit equilibrium approaches to advanced numerical modelling techniques. Limit equilibrium methods, such as Bishop's and Spencer's methods, provide swift evaluations of slope stability, whereas advanced techniques such as finite element analysis yield more thorough and intricate understandings of complex slope behaviours (Matthews et al., 2014).

The assessment of safety issues is essential in the analysis of slope stability. Integrating probabilistic techniques allows for a more comprehensive assessment by accounting for the inherent uncertainties of input parameters. Probabilistic methods provide essential insights into the probability of slope failure events and aid in the development of risk management strategies.

2.3 Key Debates and Controversies

As noted by Mali et al. (2021), the investigation of slope failures represents a complex and interdisciplinary field, integrating scientific, technical and engineering considerations. It remains a topic of considerable discourse among researchers, geotechnical practitioners and industry stakeholders, often giving rise to a range of challenges and differing viewpoints. Numerous ongoing debates within this domain have been identified, several of which are outlined in the following sections.

2.3.1 Safety vs economic viability

Although safe slope angles are crucial for preventing slope failure and ensuring worker safety, adhering to these angles may diminish ore extraction, hence

impacting profitability. Should the risk appetite be higher, accepting a higher risk means ensuring that an adequate early warning monitoring system is in place. Important to note that the failure mechanism should be well understood, ensuring minimum unknowns. The risk can also be reduced by ensuring that a dual ramp system is in place. This, however, is costly; hence, the balance between safety and profitability is frequently contentious.

2.3.2 Empirical vs numerical modelling approaches

Empirical approaches, grounded in historical experiences, may be constrained by the distinct geological and geotechnical characteristics present at each location. Numerical models are intricate and costly and necessitate comprehensive data, which may not always be accessible (Corominas et al., 2013). Different schools of thought exist on whether empirical methods or numerical models provide more reliable slope stability predictions.

2.3.3 Accuracy of geotechnical data

The collection and interpretation of data remain central themes in ongoing discussions surrounding slope failure investigations, particularly regarding the challenge of acquiring data that is both accurate and sufficiently comprehensive. A frequent point of contention arises from the need to balance the high costs—both financial and labour-related—associated with extensive data acquisition, against the necessity for detailed and reliable information (Read & Stacey, 2009).

Obtaining precise geotechnical data is essential for dependable slope stability research; however, acquiring extensive data is difficult, particularly in deep excavations and intricate geological environments. There is frequently a trade-off between the expense of comprehensive geotechnical studies and the quality of the data, prompting inquiries on the sufficiency of information for making informed stability judgments. Inaccuracies may result in the underestimation of slope instability hazards.

2.3.4 Triggering mechanisms

The identification of the primary triggering mechanisms of slope failures is a contentious issue. Precise forecasting and alleviation require an in-depth comprehension of the principal drivers, which may encompass precipitation,

seismic events, anthropogenic actions, or a combination thereof (Kolapo et al., 2022).

Kolapo et al. (2022) emphasise that the transition of a slope from a stable condition to an active failure is typically initiated either by an external triggering force or when shear stress surpasses the inherent strength of the rock mass. Slope failure mechanisms are often governed by a complex interplay of contributing factors. One key process involves the redistribution of loads that leads to elevated shear stress, prompting downward movement of slope segments, particularly when the applied stress exceeds the rock mass's shear strength. Eberhardt et al. (2004) further argue that even in the absence of a distinct triggering event, progressive failure can occur due to the gradual deterioration of rock strength over time, indicating a time-dependent weakening mechanism. Such failures may manifest in various forms, including planar, wedge, rotational and toppling failures.

2.3.5 Human-induced contributions

The evaluation of the respective roles of anthropogenic activities—such as excavation, construction and mining—and natural geological processes in triggering slope failures has become an increasingly prominent area of discussion. Accurately distinguishing between these causative factors is critical, as it influences the assignment of accountability, informs regulatory and legal responsibilities, and shapes the formulation of appropriate mitigation strategies (Kolapo et al., 2022).

2.3.6 Predictive models

The precision and dependability of forecast models for slope failures are topics of continuous contention within the academic community. The range of models includes basic empirical methods and sophisticated numerical simulations, with discussions often focusing on model calibration, data requirements and the inherent limitations of each approach (Wang et al., 2023).

According to Osasan and Stacey (2014), academics have made multiple efforts over the years to establish reliable techniques for estimating the duration before open-cast mine slopes collapse. However, no single method is universally acceptable for mine slope failure prediction. The duration until failure of slopes is

contingent upon the function that is chosen. The linear, exponential and power law functions are the most frequently utilised.

2.3.7 Monitoring

Different technologies, including classic inclinometers, GPS, LiDAR and remote sensing methods, possess unique advantages and limitations, with the choice dependent on factors such as accuracy, cost and accessibility (Mohammed, 2021). The creation of effective early warning systems to swiftly alert authorities and communities to imminent slope failures is a multifaceted and controversial issue. The identification of alert activation thresholds, the formulation of response protocols, and the intricate equilibrium between false positives and overlooked warnings are topics of contention (Mohammed, 2021).

2.3.8 Deformation profile

An analysis of the deformation profile of slope failures in open-pit mining is an essential component of geotechnical engineering. This analysis aids in the monitoring and prediction of slope stability. Slope failure is caused by a combination of factors, including material characteristics, geological formations, water pressure and mining operations. The deformation profile captures the time-dependent movement, displacement and strain within a slope, offering critical insights into the progression towards failure. This information is essential for identifying early warning signs and improving predictive models for slope stability in open-pit mining (Lu, 2015).

2.3.9 Climate change

The possible impact of heightened precipitation patterns and temperature variations on slope stability as a result of climate change remains a subject of active discussion among specialists (Wong et al., 2022).

2.3.10 Vegetation

The capacity of vegetation to provide beneficial root stabilisation is recognised; however, the effectiveness and limitations of vegetation in preventing slope failures under diverse conditions remain topics of academic discussion (Tabari et al., 2025).

2.3.11 Trigger action response plan

The evaluation, communication and reaction to hazards related to slope failure are also topics of continuous discussion. Determining acceptable risk levels and successfully conveying uncertainties to stakeholders and the public can provide considerable hurdles (De Graaf & Wessels, 2016). The subject of slope repair solutions often prompts discussions over the most effective and efficient methods for managing slopes prone to failure. The reconciliation of technical interventions, natural stabilisation processes and long-term sustainability is a contentious topic (De Graaf & Wessels, 2016). Engineers must navigate uncertainties in geological models, diverse failure mechanisms and site-specific conditions, which make standardised solutions impractical. Additionally, environmental regulations and stakeholder expectations often conflict with technical recommendations, while the need for continuous monitoring and adaptive management adds further complexity. These factors contribute to ongoing debates about the most effective, efficient and responsible approaches to managing slopes prone to failure.

These discussions emphasise the interdisciplinary nature of slope failure research and the inherent complexity associated with understanding, predicting and mitigating slope instability. The critical need for continuous research, cross-disciplinary collaboration and technological innovation in this domain is also highlighted (De Graaf & Wessels, 2016). Over the past several decades, slope failures commonly referred to as landslides have been extensively studied by geologists, geotechnical engineers and natural hazard specialists. Researchers have examined various failure modes, including planar, rotational, toppling and translational failures, each influenced by factors such as soil composition, slope gradient and moisture content. Both natural triggers, such as earthquakes, volcanic activity, intense rainfall and human activities, including deforestation, overgrazing and excavation, have been identified as key contributors to slope failure (Sjoberg, 1996).

A range of methodologies has been developed by researchers to assess the risk of slope failure, including empirical approaches, numerical modelling techniques and remote sensing technologies. These tools are instrumental in identifying potentially unstable areas and estimating the likelihood of collapse within specific regions (Read & Stacey, 2009). In parallel, a variety of mitigation strategies have

been proposed and implemented to prevent or lessen the impact of slope failures. These include slope reinforcement techniques such as soil nailing, the construction of retaining structures, drainage improvements and overall slope stabilisation efforts (Danish et al., 2017). Numerous case studies, both historical and contemporary, have been conducted to examine the causes, failure mechanisms and consequences of slope instability. These studies also evaluate the effectiveness of different mitigation approaches and offer valuable lessons for future practice. Slope stability remains an active area of research, with ongoing developments aimed at improving predictive models and engineering responses (Danish et al., 2017).

Significant advancements in slope stability research have occurred during the past few decades, focusing on the reasons and factors that can precipitate slope failure. Kolapo et al. (2022) assert that the rising demand for minerals in the 21st century has propelled the worldwide growth of mining activities, leading to the extraction of minerals at greater volumes and deeper depths. Consequently, these operations must be executed safely and economically. Proficient designs and methodologies must therefore be employed to accommodate the always-expanding mining capacity. Notwithstanding the assessment of slope stability by conventional methodologies, miners persist in encountering disastrous and expensive slope failures. There is a need for enhanced comprehension of slope collapse and the creation of precise predictive models to anticipate this hazard (Kolapo et al., 2022).

A TARP generally entails the establishment of triggers or indicators that denote the commencement of a risk event, the definition of suitable reaction measures to mitigate the recognised risk, and the delineation of responsibilities and procedures for executing these activities. With a TARP implemented, mining companies may efficiently monitor risks and swiftly respond to prevent potential negative outcomes (Mosh, 2025).

2.4 Data Collection

The acquisition of field data is a crucial component of slope design in open-pit mining. This involves the acquisition of geological, hydrogeological, geotechnical and other relevant data to facilitate the design and planning of secure and efficient

slopes. Stacey and Hadjigeorgiou (2021) identify numerous critical factors to consider while gathering field data for slope design in open-pit mining, including the following:

- The site's geology significantly influences the slope design, as it determines the kind and properties of the rock or soil present. Geological mapping, drilling and sampling are fundamental techniques utilised to precisely characterise the geological properties of a region.

- The presence of water in a slope can substantially influence slope stability. Consequently, it is imperative to gather hydrogeological data, including groundwater levels and flow direction, to understand the hydrological behaviour of the slope.

- The acquisition of geotechnical data is crucial for assessing the strength and deformation characteristics of rock or soil. This information is often acquired through laboratory analysis of samples collected via drilling.

- The slope's configuration is substantially affected by the site's topography. High-resolution topographic data can be obtained by surveying methods such as total station surveying or LiDAR.

- The weather can also have an impact on the stability of a slope.

- Data regarding the performance of current slopes offers valuable insights into slope dynamics and informs the development of new slopes. After the slope has been designed and executed, it is essential to gather data on its performance over time. This can be achieved through the regular monitoring of slope alterations, groundwater levels and other relevant data.

Geotechnical models are mathematical representations of the subsurface soil and rock properties at a specific site. A variety of geotechnical investigations, including borehole logs, laboratory analyses and field tests, are employed to construct the model. The model is applicable for simulating the behaviour of soil and rock under

diverse loading conditions and for assessing ground stability (Read & Stacey, 2009).

Geotechnical models are developed to replicate real-world conditions and support various engineering evaluations of slope stability assessments. These models enhance engineers' understanding of the expected behaviour of the ground under diverse loads, stresses and environmental conditions. As a result, engineers are equipped to make informed decisions and design structures that exhibit safety and stability. Multiple factors influence the geotechnical model, as seen in Figure 2.4 (Read & Stacey, 2009).

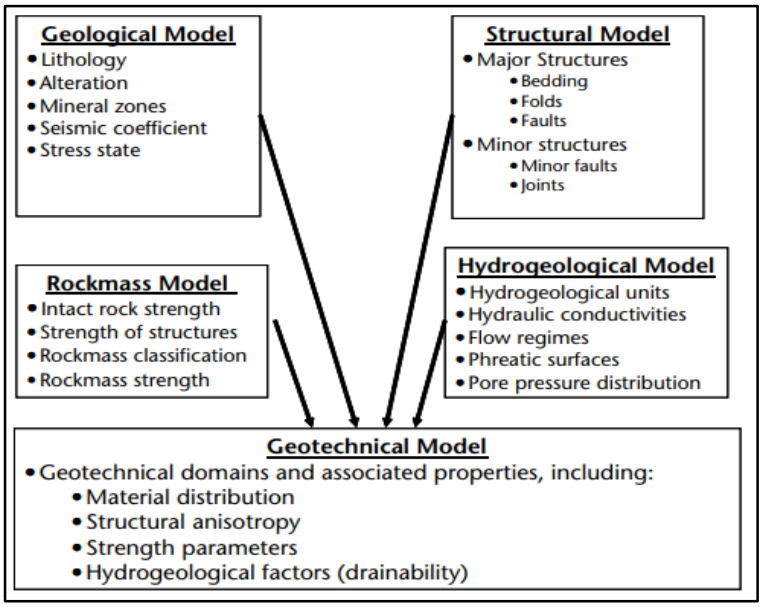


Figure 2.4. Component information and output from the geotechnical model (Read & Stacey, 2009)

2.4.1 Geological model

A geological model serves as a conceptual representation of the subsurface geology at a given site, typically constructed using a combination of geological data, expert interpretation and specialised computer software. These models are essential tools for geologists, engineers and earth science professionals seeking to better understand subsurface structures and compositions. Their applications span resource exploration, environmental management and the assessment of geological hazards (Wellmann & Caumon, 2018). The development of geological

models generally involves a systematic process of data acquisition, analysis and visualisation. This includes gathering information on lithology, stratigraphy and structural features from various sources such as geological maps, borehole logs, seismic data and other geophysical surveys. Once compiled, the data is used to construct a three-dimensional (3D) model that provides a visual and analytical representation of the subsurface conditions, often with the aid of advanced modelling software.

2.4.2 Structural model

In the context of open-pit mining, a structural model refers to a 3D representation of the geological framework within a mineral deposit. This model is a critical tool used by geologists and engineers to understand the spatial distribution, orientation and geometry of mineralisation and associated geological structures, thereby supporting exploration activities, mine design and operational planning (Read & Stacey, 2009). The construction of a structural model typically relies on data obtained from geological mapping, core drilling and geophysical surveys. These datasets are integrated to delineate the positions and orientations of structural features such as faults, joints and other discontinuities. The structural model often serves as a foundation for generating a block model of the deposit, which offers a detailed representation of mineral distribution and other key geological characteristics essential for informed decision-making in mining operations (Stacey & Hadjigeorgiou, 2021).

In recent years, remote face mapping using a variety of digital approaches has grown in popularity. This was formerly accomplished by making direct contact with the mapping face using methods such as line mapping or window mapping. A sampling technique called scanline mapping involves physically measuring each feature on an exposed face that crosses the sample line. These sampling lines are typically oriented nearly perpendicular to the dominant structural features to ensure accurate characterisation (Tuckey & Stead, 2016).

According to Read et al. (2009), an outcrop or face is separated into cells using the manual face mapping technique known as ‘cell’ or ‘window’ mapping. Each cell contains discontinuity sets, and measurements are made of the discontinuities'

orientation, spacing, persistence and other characteristics. Usually, 10 to 25% of the face's total visible area is made up of cells.

The use of 3D terrestrial laser scanning data for digital face mapping is a more recent method. Compared to photogrammetry, laser scanner mapping is quicker and more effective. In just a few minutes, a terrestrial laser scanner that can sample hundreds of thousands of points per second may produce a high-resolution point cloud that covers several hundred square metres. By using concurrent digital photography, the scan points can also provide real colours in addition to the usual X, Y, Z and intensity information. A rock face can be accurately represented in real 3D space by utilising a variety of georeferencing techniques in combination with concurrent digital imaging (Feng & Roshoff, 2006).

Using kinematic analysis, the toppling potential can be evaluated. This is typically observed when discontinuity sets are steep but dip away from the slope face, yet are intersected by a weak plane at the base (Figure 2.5). Planar failure occurs when a discontinuity plane dips towards the slope face and is steep enough for sliding to occur. Wedge failure results from the intersection of two discontinuity planes forming a wedge that can slide along the line of intersection (Figure 2.5).

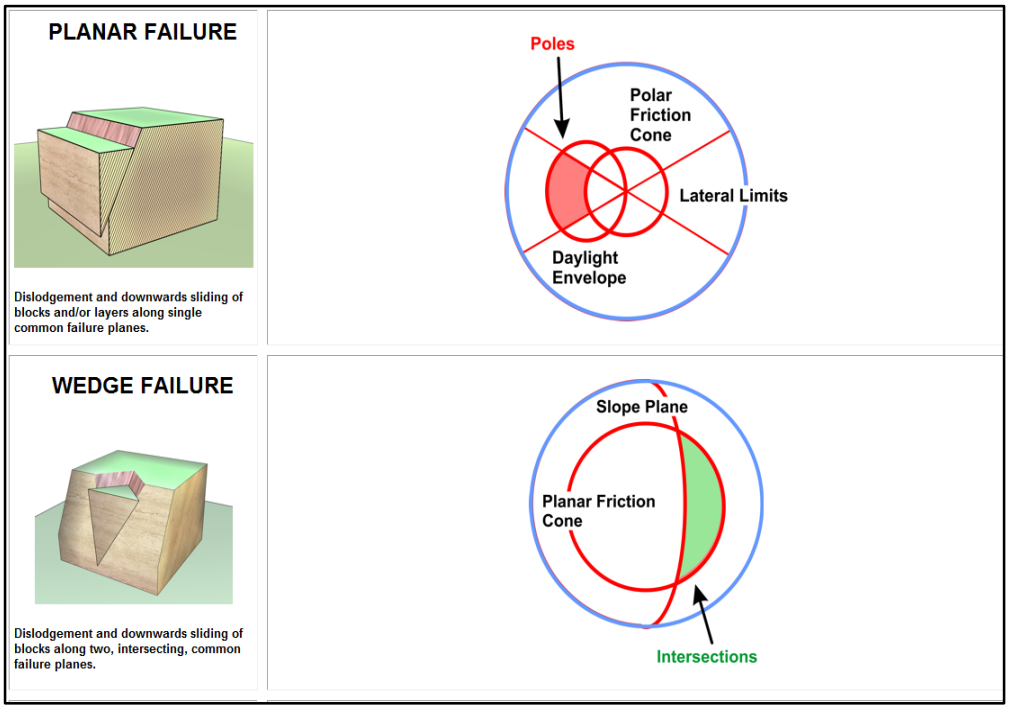


Figure 2.5. Kinematic analysis considerations (Rocscience, 2023)

Toppling failure occurs when the centre of mass of the blocks moves beyond their base of support. This failure is common in steep slopes with vertically or steeply inclined discontinuities, such as joints, bedding planes, or foliations. Refer to Figure 2.6.

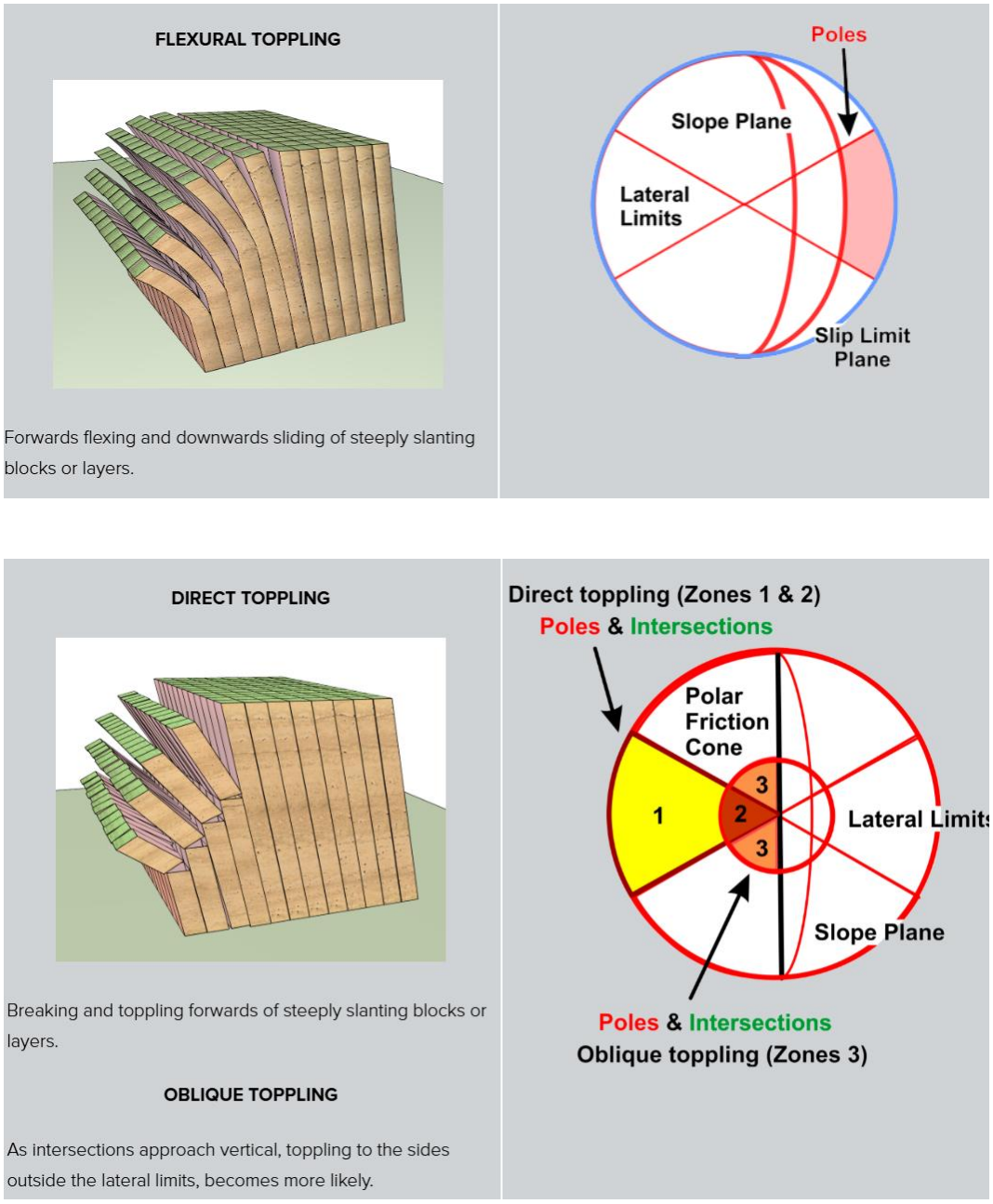


Figure 2.6. Kinematic analysis considerations for toppling (Rocscience, 2023)

2.4.3 Rock mass model

A rock mass model is a simplification of the geological and geomechanical characteristics of a rock mass. In geotechnical engineering and mining, it is commonly employed to predict the behaviour of the rock mass under applied stresses and loads (Read & Stacey, 2009).

Rock mass models incorporate various factors, including rock type, structural features and discontinuities, the presence of water or other fluids and the in-situ stress state. Generally, these characteristics are consolidated into a singular measure referred to as rock mass quality or strength, which is utilised to assess the stability of slopes, tunnels and underground excavations (Howard, 2003).

Diverse methodologies exist for constructing rock mass models, including empirical techniques grounded in statistical evaluations of field data and numerical approaches reliant on mathematical models that replicate the behaviour of the rock mass under different loading conditions. The accuracy of a rock mass model depends on the quality and quantity of the input data, together with the model's assumptions and simplifications. Employing appropriate approaches and tools is critical for the collection and comprehension of geological and geotechnical data, as well as for validating the model against field observations and measurements (Read & Stacey, 2009).

2.4.4 Hydrogeological model

A hydrogeological model is a mathematical representation designed to simulate the physical and chemical processes occurring within an aquifer system, including groundwater flow and solute transport. These models are instrumental in reproducing groundwater dynamics, which are essential for effective water resource assessment and management. The development of hydrogeological models is based on data gathered from geological surveys, hydrological investigations and groundwater monitoring wells. This information is used to formulate a conceptual model of the subsurface hydrological system, capturing key elements such as aquifer geometry, spatial variations in permeability and the locations of recharge and discharge zones (Read & Stacey, 2009). Once established, the model can be applied to predict the response of groundwater systems to various changes, including land use modifications, groundwater

abstraction and the effects of climate change. Hydrogeological models play a critical role in water resource management by enabling the evaluation of alternative management scenarios and supporting the development of sustainable groundwater use strategies (Mensah et al., 2022).

2.4.5 Data uncertainty

Sullivan (2013) asserts that data uncertainty can significantly impact slope stability studies. Slope stability analysis necessitates a comprehensive understanding of the geotechnical properties of soil and rock materials, groundwater conditions, slope geometry and slope orientation. The data must be precise and reliable for the analysis to yield meaningful results. Slope stability analysis often involves calculating safety factors to assess the balance between forces resisting slope failure and those promoting it. Fluctuations in safety factor estimations may be affected by errors in input data, such as rock mass characteristics or pore pressure, which can subsequently influence the precision of failure forecasts (Potvin, 2007).

The positioning and layout of key failure surfaces substantially influence slope stability analysis. Fluctuations in the identification of failure surfaces may arise from uncertainty in factors such as discontinuity orientations or layer boundaries, subsequently leading to modifications in the computed stability (Sullivan, 2013).

Diverse failure modes, such as sliding, toppling and rotational failure, may occur due to the intricate interactions among numerous pieces (Figure 2.7). Data ambiguity can adversely affect the precise identification of the dominant failure mechanism and the subsequent formulation and execution of effective mitigation strategies. Uncertainties in groundwater conditions, including the location and intensity of seepage forces, may lead to analytical errors and potentially unstable slopes (Soren et al., 2014). Consequently, it is imperative to assess the possible impact of data ambiguity on slope stability and to implement suitable safety measures to mitigate these uncertainties. Site inquiry and monitoring programmes can diminish data uncertainty and enhance the accuracy and reliability of slope stability calculations (Sullivan, 2013).

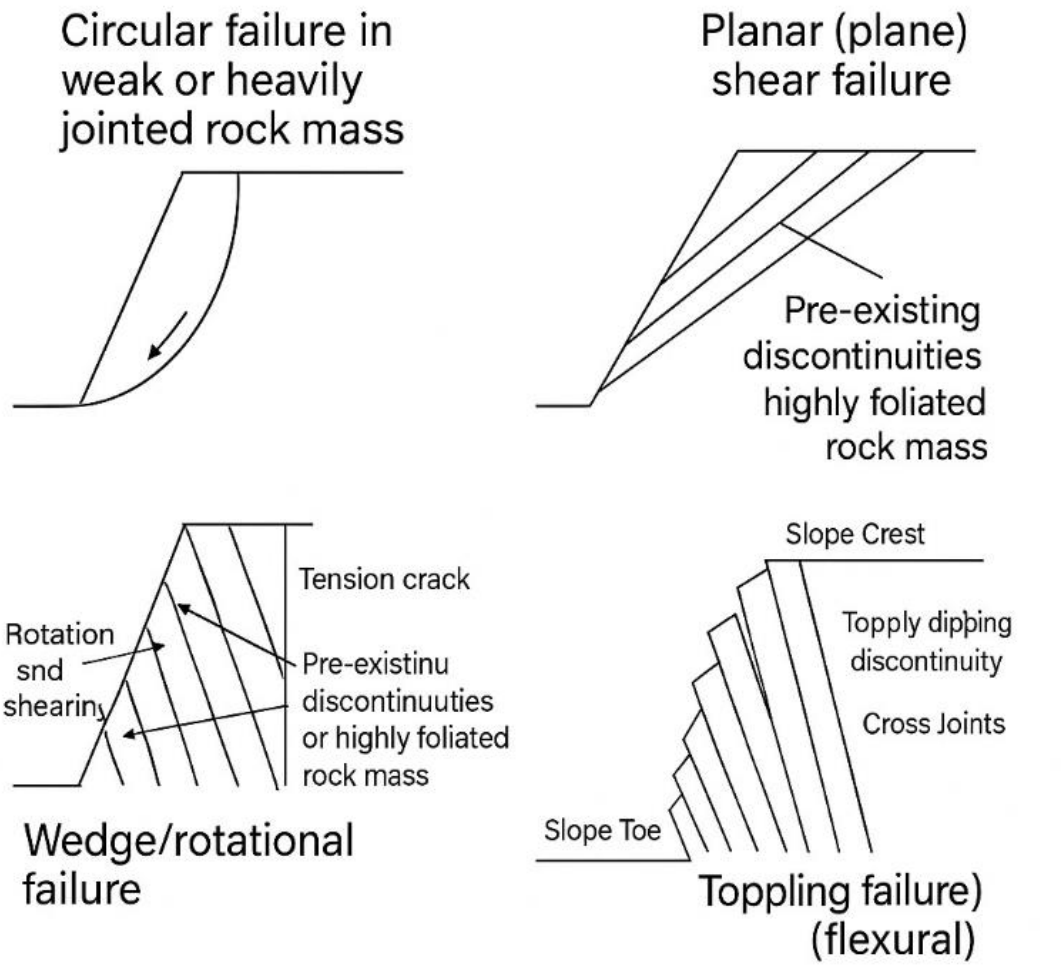


Figure 2.7. Modes of failure (Soren et al., 2014)

2.5 Slope Design

Slope design in open-pit mining involves the engineering and geological analysis of the rock slopes encircling an open pit to guarantee their stability and safety during the mining operation. Numerous slope design methods exist, which can be broadly categorised into deterministic and probabilistic approaches (Potvin, 2007). Deterministic methodologies rely on theoretical and empirical correlations, assuming that rock mass properties and stress conditions are clearly defined and foreseeable. The following outlines the most prevalent deterministic slope design methodologies utilised in open-pit mining.

2.5.1 Limit equilibrium analysis

The limit equilibrium concept is a foundational tool in geotechnical engineering, widely employed to assess the stability of earth structures such as slopes and retaining systems. At its core, the approach is grounded in the premise that failure occurs when the driving forces acting on a soil or rock mass exceed its shear strength along a potential failure surface. These driving forces are often gravitational in nature. As such, limit equilibrium analysis is applied to evaluate conditions approaching failure, assuming that movement will occur along a defined failure plane—typically inclined—representing the path of least resistance within the ground mass (Firincioglu & Ercanoglu, 2021).

A widely adopted form of this analysis involves the method of slices, in which the material above the assumed slip surface is divided into a series of vertical slices. These slices, often shaped as trapezoids or triangles, are aligned parallel to the suspected failure surface. The stability of each slice is evaluated based on static equilibrium conditions (Firincioglu & Ercanoglu, 2021). Figure 2.8 provides a schematic illustration of the forces acting on both the slope and a representative slice. Each slice is subjected to multiple forces, including self-weight, external loads such as surcharges, and any additional applied forces. The resisting forces mobilised along the base of each slice are then compared against the shear strength of the material to determine the potential for failure (Read & Stacey, 2009).

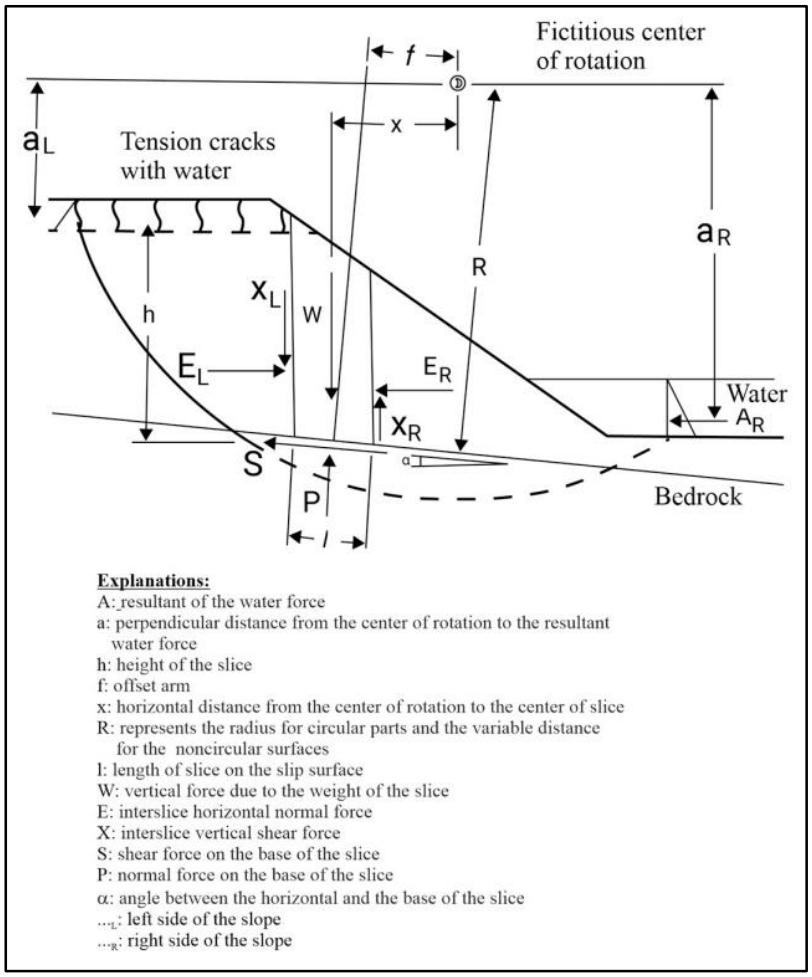


Figure 2.8. Forces acting on the slice and the slope (Firincioglu & Ercanglu, 2021)

Skempton (1985) asserts that the Mohr-Coulomb criterion can be employed to ascertain shear strength in soil slopes. The Mohr-Coulomb criterion is widely utilised in slope stability evaluations and numerous other geotechnical applications. This approach was developed by Coulomb in 1776, with later revisions by Mohr in 1882. This criterion assesses the mechanical qualities of materials employed in theoretical situations. The assessment of shear strength is essential in limit equilibrium analysis, as it relates to the resistance of soil or rock to shearing pressures along a failure plane. The components of this system are cohesiveness, relating to the material's inherent strength and friction, denoting the resistance experienced during sliding along a failure plane. Firincioglu and Ercanglu (2021) assert that the determination of shear strength in soil slopes is achieved through Skempton's (1985) approach or the Mohr-Coulomb criterion in rock slopes.

The safety factor is essential in evaluating the stability of slopes or structures. This notion relates to the ratio of forces resisting motion to those facilitating motion. A safety factor greater than 1 indicates stable conditions, while a safety factor less than 1 suggests a risk of failure. The essential safety factor, typically denoted as FoS signifies the minimum safety margin required to guarantee stability (Read & Stacey, 2009).

Slide2 (Rocscience, 2025) is a 2D limit equilibrium slope stability program for evaluating the safety factor or PoF of circular or noncircular failure surfaces in soil or rock slopes. Slide2 analyses the stability of slip surfaces using vertical slice or non-vertical slice limit equilibrium methods.

2.5.2 Numerical modelling

Slope stability analysis now depends critically on numerical modelling techniques, including finite element and finite difference methods. Although limit equilibrium techniques offer initial stability assessments, more advanced numerical approaches are needed to grasp complicated failure mechanisms and stress–strain relationships. Particularly helpful for analysing jointed rock mass problems, finite element modelling allows the integration of joint slip with failure through intact material, as shown by Hammah and Yacoub (2009). In situations such as Klipbankfontein, where several geological structures interact, finite difference methods – used through programs such as FLAC – offer extra capabilities in modelling progressive failure and complex geological conditions.

When geological structures and pit geometry produce intricate spatial relationships that cannot be sufficiently shown in two dimensions, 3D modelling becomes essential. Where structural elements such as faults and contacts intersect at oblique angles to the pit face, as seen at Klipbankfontein, 3D analysis is especially important, according to Chiwaye and Stacey (2010). As shown by Ali and Meysam (2022), the ability to replicate these 3D interactions helps to better grasp possible failure mechanisms and evaluate mitigating strategies with more accuracy. This is particularly pertinent in cases where 3D geological structures affect groundwater flow and pore pressure distribution, elements of which proved important in the failure of the Klipbankfontein slope.

Chiwaye and Stacey (2010) emphasise the critical role of numerical modelling in the development of mining practices that are both safe and economically viable. These models provide a range of advantages that contribute to enhanced safety, operational efficiency and financial performance in mining operations. By offering detailed insights into the geological and geotechnical characteristics of ore bodies and surrounding rock masses, numerical models support informed decision-making by geologists and mining engineers. They are particularly valuable for simulating complex geotechnical scenarios, including slope instability, ground deformation and rockfall risk, through accurate representations of deposit geometry, lithology and structural features. Such modelling techniques are essential for mitigating slope failures, which can result in significant safety hazards, operational interruptions and elevated costs (Coulthard & Little, 1999). The overarching aim of mine design optimisation is to maximise the economic recovery of ore while minimising waste handling, haulage costs and environmental impact through integrated planning that balances technical, financial and sustainability objectives (Read & Stacey, 2009).

The discrete element method and discontinuous deformation analysis are widely recognised as effective computational tools for analysing rock masses characterised by blocky structures and intricate joint networks. These methods are particularly suited to modelling the mechanical behaviour of discontinuous rock systems under various stress conditions. More recently, the finite element method (FEM) has also gained credibility as a reliable technique for explicitly incorporating discontinuities through the use of specialised joint elements (Soren et al., 2014). FEM enables the simulation and analysis of stress and strain distribution within rock masses and is particularly valuable in slope stability assessments. Compared to traditional limit equilibrium approaches, FEM offers a more detailed evaluation of material properties, boundary conditions and external loading (Etchells et al., 2013).

Additionally, particle-based approaches such as the distinct element method allow for the modelling of individual rock blocks as separate entities, facilitating the simulation of their dynamic interactions. This is particularly useful for investigating the mechanical behaviour of discontinuous rock masses and evaluating the influence of fractures and joints on overall slope stability (ITASCA, 2004). These

computational techniques continue to serve as important tools for both practical engineering applications and academic research in rock mechanics and slope stability. The implementation of the finite difference method (FDM) in jointed rock masses has become viable owing to the extensive availability of high-performance computers. This is mostly due to the modelling of joint behaviour within the FDM framework. The development of discrete fracture network generation techniques and the shear strength reduction (SSR) approach has significantly contributed to this improvement. The application of SSR analysis facilitates the calculation of safety factors for slopes by numerical methods (Hammah & Yacoub, 2009). FDM-based SSR analysis is a viable alternative to the traditional limit equilibrium method in numerous situations, with its primary advantage being the ability to effectively incorporate joint slip with failure through intact material, thus serving as a valuable tool for modelling jointed rock mass issues. A significant benefit of FDM-based SSR analysis is its capacity to independently detect various failure causes without preconceived notions regarding their nature, form, or position (Soren et al., 2014).

Slide2 is a two-dimensional limit equilibrium software application developed for the assessment of slope stability in both soil and rock environments. It is designed to compute the factor of safety (FoS) or the PoF associated with circular and non-circular slip surfaces. The program utilises a variety of limit equilibrium methods, incorporating both vertical and non-vertical slicing techniques to evaluate the stability of potential failure surfaces. Slide2 supports detailed modelling of slope geometries and material properties, offering a robust platform for geotechnical engineers to conduct comprehensive stability analyses.

2.5.3 Acceptance criteria

The acceptance criteria in slope stability analysis refer to the safety factors or margins of safety employed to evaluate slope stability. The safety factor is the quotient of the resisting forces to the driving forces. The acceptance criteria frequently employed in slope stability analysis (Kirsten, 1982) include the following:

- The FoS is the predominant acceptance criterion in slope stability analysis. The FoS is the ratio of resisting forces to driving forces. An FoS beyond 1 signifies slope stability, but an FoS below 1 denotes slope instability (Read & Stacey, 2009).

- Probability of failure (PoF) – The PoF denotes the likelihood of a slope's failure under specific conditions. This is a more sophisticated and probabilistic approach to evaluating slope stability. Table 2.1 presents the recommendations for PoF and FoS (Read & Stacey, 2009).

- The strength reduction approach entails diminishing the strength of the soil or rock mass until the slope reaches a state of instability. The safety factor is thereafter determined using the diminished strength criteria (Read & Stacey, 2009).

Table 2.1. Proposed guidelines for PoF and FoS (Read & Stacey, 2009)

		Acceptable values		
Consequence of failure	**Examples**	**Mean FoS**	**Minimum P[FoS < 1.0]**	**Maximum P[FoS < 1.5]**
Not serious	Individual benches; small (< 50 m), temporary slopes, not adjacent to haulage roads	1.3	10%	20%
Moderately serious	Any slope of a permanent or semi-permanent nature	1.6	1%	10%
Very serious	Medium-sized (50–100 m) and high slopes (<150 m) carrying major haulage roads or underlying permanent mine installations	2.0	0.30%	5%

The acceptance criteria for slope stability analysis are contingent upon the particular project requirements, the acceptable risk threshold, and the applicable legislation and standards governing the project. It is essential to meticulously assess and choose suitable acceptance criteria for each project to guarantee the safety and stability of the slope (Obregon & Mitri, 2019).

2.5.4 Design implementation

The implementation of suitable design measures for slope stability is essential in reducing the risks associated with rockfalls, landslides and slope failures. The execution of actions to improve slope stability is essential for safeguarding the safety and well-being of individuals involved in mining activities (Sjoberg, 1996).

Fleurisson (2012) asserts that design and implementation focus on establishing the geometry necessary for structural safety, while the whole project cost must remain within budgetary constraints. Alongside these economic issues, certain environmental considerations must be addressed regarding the protocols for

decommissioning mine sites, where challenges related to long-term slope stability may emerge.

Gunasekera et al. (1995) assert that regular evaluation is essential to verify compliance with the design. Systematic documentation and assessment of bench performance are essential for every slope evaluation program. Oversight of bench creation operations is essential for monitoring slope performance. A reconciliation mechanism is essential for ensuring effective implementation and optimal pit slope design. An emphasis on reconciliation throughout the mining value chain guarantees that the mining process unfolds with increasing predictability. Consequently, reconciling the geotechnical process is essential for achieving a progressive and predictable result.

A variety of monitoring instruments, such as radar, inclinometers and piezometers, are utilised to assess slope movements and groundwater levels. Regular maintenance and reassessment of the slope design are essential for ensuring the slope's enduring stability (Little, 2006). Monitoring slope performance is essential for open-pit mining operations, as it safeguards the safety of persons and equipment in the area. Slope failures can result in substantial injuries, fatalities and equipment damage, adversely affecting operational productivity and profitability. Therefore, it is imperative to continuously assess slope stability to detect and mitigate potential hazards (Braathen et al., 2004). A variety of methodologies exist for evaluating slope performance in open-pit mining, with several of the more notable being:

- Visual inspection
- Geotechnical instrumentation
- LiDAR (light detection and ranging)
- Satellite-based Interferometric Synthetic Aperture Radar (InSAR)
- UAV (unmanned aerial vehicle)-based photogrammetry

Visual inspection forms a critical component of slope stability assessment, involving systematic field evaluations by qualified geotechnical professionals. These inspections help identify surface indicators of instability such as tension cracks, bulging and displacement, which may warrant further geotechnical

investigation. Complementing visual assessments, slope monitoring systems—such as extensometers, inclinometers and piezometers—are deployed to measure displacement, strain and pore pressure. These instruments provide continuous data that support early detection of slope movement. Additionally, remote sensing technologies, including laser scanning and photogrammetry, are used to generate high-resolution 3D models of the slope surface, enhancing the understanding of slope behaviour and aiding in predictive stability analysis (Read & Stacey, 2009).

Geotechnical monitoring systems are fundamental in evaluating slope stability, particularly in environments where ground movement poses safety and operational risks. A range of instruments—including inclinometers, piezometers, extensometers and time domain reflectometry are employed to measure subsurface deformation, water pressure and displacement along structural discontinuities. These tools provide detailed insights into slope behaviour, enabling early detection of instability. For example, probe inclinometers are capable of identifying lateral shifts as small as 0.5 mm over a 10-metre depth, making them effective for detecting shear zones in deep-seated landslides (Mohammed, 2021). Surface displacement is often tracked using GPS and total station systems, which offer high spatial resolution across large areas (Thomas, 2011). Recent innovations in sensor design and telemetry have facilitated real-time data collection and remote access, enhancing the responsiveness of slope monitoring programs (Salvi & Khan, 2024). The integration of multiple instruments within a single monitoring framework allows for a more comprehensive understanding of slope dynamics and supports informed geotechnical decision-making.

LiDAR technology enables the detection of slope displacement and deformation over time by comparing successive high-resolution 3D terrain models. This method is particularly effective for identifying subtle changes in topography. In contrast, InSAR is a satellite-based remote sensing technique capable of monitoring ground movement across extensive areas with high spatial resolution and frequent revisit intervals. It is especially valuable for detecting slow, progressive deformations and complements ground-based monitoring systems in slope stability assessments (Watton & Fowler, 2020)

InSAR, utilising satellite-based systems, has emerged as a dependable method for tracking ground deformation over extensive and hard-to-reach areas. By comparing radar signal phases from multiple acquisition times, InSAR can detect minute surface movements with remarkable precision. This makes it especially valuable for identifying early indicators of slope instability in regions such as forests or mountainous terrain, where conventional monitoring techniques may be impractical. Advanced instruments such as PALSAR-2, onboard the ALOS-2 satellite, enhance image resolution and can penetrate vegetation, thereby improving data coherence and reliability in complex landscapes. Research by Nishiguchi et al. (2017) demonstrated that InSAR-derived displacement measurements closely align with global navigation satellite system field data, showing an average discrepancy of only 15.1 mm, underscoring its suitability for geotechnical monitoring.

UAV- or drone-based photogrammetry involves utilising drones fitted with cameras to capture high-resolution images of a slope. These photographs can be utilised to create 3D models of the slope, which can be analysed over time to detect any alterations in slope stability (Read & Stacey, 2009).

In open-pit mining, slope performance monitoring requires a synthesis of visual inspections and advanced monitoring technologies to guarantee the safety of persons and equipment in the area. A complete monitoring programme must be designed with appropriate technology and undergo continuous evaluation and updates to ensure its effectiveness (Little, 2006).

The training and education of mining personnel are crucial for the effective execution of the slope design. This involves instructing mining engineers, geologists and technicians on slope design principles, the importance of monitoring and the imperative of safety protocols (Read & Stacey, 2009).

2.5.5 Time to failure

Time to failure in the context of slope stability refers to the amount of time it takes for a slope to experience failure or collapse due to the gradual degradation of its strength, external forces, or environmental changes (Yang et al., 2023).

2.5.6 Slope reconciliation

Slope reconciliation is a technique used in geological and geotechnical engineering to evaluate the stability of slopes by comparing predicted performance with actual field behaviour. This process supports the refinement of design assumptions and contributes to safer engineering decisions for infrastructure located on or near slopes. It involves analysing discrepancies between expected slope stability and observed performance, such as deformation patterns or failure mechanisms. According to Sullivan (2013), the typical steps in slope reconciliation include.

- Formulating a conceptual model of the slope along with the relevant geological and geotechnical conditions;

- Employing numerical modelling or alternative analytical techniques to forecast the anticipated slope stability;

- Assessing the slope's performance over time to evaluate actual stability and any potential alterations that may arise;

- Assessing the variance between predicted and actual stability to detect differences or potential concerns; and

- Modifying the conceptual framework and analytical techniques as necessary to enhance the precision of subsequent predictions.

Slope reconciliation is an iterative process aimed at refining slope design and management strategies to achieve long-term stability. This process may be conducted repeatedly throughout the lifecycle of a project to account for evolving geological, operational, or environmental conditions. It plays a critical role in mitigating geotechnical risks associated with infrastructure development and is

essential for safeguarding human life and property in areas prone to slope instability (Sullivan, 2013).

A fundamental part of open-pit mining activities, slope optimisation calls for careful balance between safety, stability and economic extraction (Stacey, 2006; Read & Stacey, 2009). The basis of good slope optimisation consists of the following main components: geotechnical investigation, slope design, monitoring, risk assessment and maintenance.

Geotechnical investigation

Effective slope control relies heavily on comprehensive geotechnical investigations. This process involves characterising rock mass properties through various investigative methods. Stacey and Hadjigeorgiou (2021) suggest that this should include in-situ testing to determine rock strength parameters, geophysical surveys, core drilling and logging. All significant discontinuities – such as faults, joints and bedding planes that could influence slope stability – must be identified and documented through structural mapping. Equally critical is hydrogeological research that employs piezometer installation and monitoring, permeability testing and groundwater modelling to understand potential pore pressure effects on slope stability.

Slope design

The evolution of ideal slope designs calls for the advanced study of several elements. Read and Stacey (2009) show how a study of rock mass strength, structural controls and groundwater conditions assists with ascertaining slope angles. Careful optimisation of inter-ramp and general slope angles help to balance stability needs with financial goals. Bench geometry must consider operational needs and offer enough catchment capacity to prevent possible rockfalls. Different geotechnical conditions should guide the establishment of design sectors; specific design criteria should be developed for every sector. Sjoberg (1996) argues that the choice of a suitable FoS must consider the degree of uncertainty in design inputs as well as the consequences of failure.

Monitoring

Many technologies and methods are combined in a proper monitoring programme. Little (2006) explains how contemporary slope monitoring should combine innovative technologies with conventional approaches, including regular visual inspections, survey prism monitoring, ground-based radar, satellite InSAR and several geotechnical instruments, including extensometers and piezometers. The data from these systems must be combined and examined in real time to find possible failure points and movement trends. Programmes for monitoring should be dynamic and able to change frequency and coverage depending on risk level and observed circumstances.

Risk assessment

Over the lifetime of the mine, systematic risk assessment calls for a multifarious strategy. Wessels and Dixon (2020) underline the need for qualitative as well as quantitative risk evaluation techniques. This should cover an investigation of possible failure mechanisms, an assessment of trigger elements and an evaluation of possible consequences. Calculations of the PoF must take structural as well as stress-oriented failure modes into account. A comprehensive analysis of data trends and established warning thresholds should form the basis of the development of TARP. Changing pit conditions and operational requirements call for routinely reviewing and updating emergency response protocols.

Maintenance

Long-term slope stability depends on aggressive maintenance programmes. Regular maintenance should include inspection and clearing of drainage systems, scaling of loose rock, maintenance of access ramps and berms and the regular assessment of support system effectiveness (Sullivan, 2013). Clear responsibilities and schedules in maintenance programmes must be methodical and well-documented. Particular attention should be given to key areas found by monitoring projects and risk analysis. Frequent review and updating of maintenance practices ensure their stability as pit conditions change.

Successful application of these components calls for close cooperation among geotechnical engineers, mining engineers, operations staff and management (Read & Stacey, 2009). Frequent review and updating of all elements ensures the effectiveness of the optimisation programme throughout the lifetime of the mine. This methodical approach assists mining activities in maximising resource recovery while keeping reasonable safety criteria in place and properly controlling operational risks.

Risk management

Risk management is essential in slope stability assessment in open-pit mining. Slope stability denotes the ability of a rock slope to preserve its integrity against the effects of gravity and various external and internal factors (Chiwaye & Stacey, 2010). Risk management in slope stability analysis within open-pit mining is essential for the following reasons:

- To ensure the safety of personnel and equipment;
- To minimise economic losses;
- To protect the environment; and
- To ensure compliance with regulatory requirements.

Ensuring the safety of personnel and equipment

Ensuring the safety of personnel and equipment in open-pit mining operations requires a proactive and systematic approach to risk management. This involves identifying potential slope failure scenarios, assessing associated hazards, and implementing targeted control measures to mitigate risks (Wessels & Dixon, 2020). One such measure is the strategic use of buffer blocks during blasting activities. A buffer block refers to a section of rock deliberately left unblasted between the main blast zone and sensitive areas, such as pit boundaries or infrastructure zones. By acting as a physical barrier, the buffer block helps absorb shock waves, reduce vibration transmission and limit ground movement, thereby protecting nearby assets and reducing the likelihood of unintended damage. To further control the blast impact, buffer blocks are typically detonated last using smaller diameter blastholes, allowing for more precise energy distribution and minimising

disturbance to critical zones (Smith & Brown, 2020). This integration of blasting design with risk management principles enhances operational safety and supports the long-term stability of the pit environment.

Minimising economic losses

Slope failures can result in economic losses for mining operations due to production interruptions, equipment damage and necessary repairs. By mitigating slope stability hazards, the mining sector can reduce losses and enhance the project's financial sustainability (McQuillan & Bar, 2020).

Protecting the environment

Slope collapses may lead to soil erosion, river sedimentation and the discharge of hazardous chemicals into the environment. Employing effective risk management strategies can mitigate environmental effects and decrease the carbon footprint of mining activities (Nikolaos & Chouliaras, 2018).

Compliance with regulatory requirements

Regulatory authorities mandate that mining corporations comply with safety, health and environmental regulations. Risk management strategies are essential to ensure adherence to these requirements and avert legal or regulatory sanctions. Effective risk management strategies are fundamental to any open-pit mining endeavour (International Labour Office, 1991).

TAMU-MineSlope database

The TAMU-MineSlope database (Timchenko & Briaud, 2023) is a global compilation of slope failure cases from open-pit mines, developed by researchers at Texas A&M University. It includes detailed records from 134 failures across 76 mining sites, offering insights into the geometry, runout behaviour, and setback distances associated with slope collapses.

2.5.7 Design methodology

Contreras (2015) asserts that a pit slope design approach must evaluate the safety and economic ramifications of potential slope failures, which should serve as the foundation for establishing design acceptance criteria (refer to Figure 2.9). The design methodology framework consists of the following key steps:

- Determine the cause of a hazard;
- Analyse the likelihood or probability that these events will occur;
- Evaluate the impact of the hazard;
- Integrate probability and impact to compute the risk;
- Compare the estimated risk to benchmark criteria to obtain an assessment of risk; and
- Use the assessment of risk as a decision-making aid.

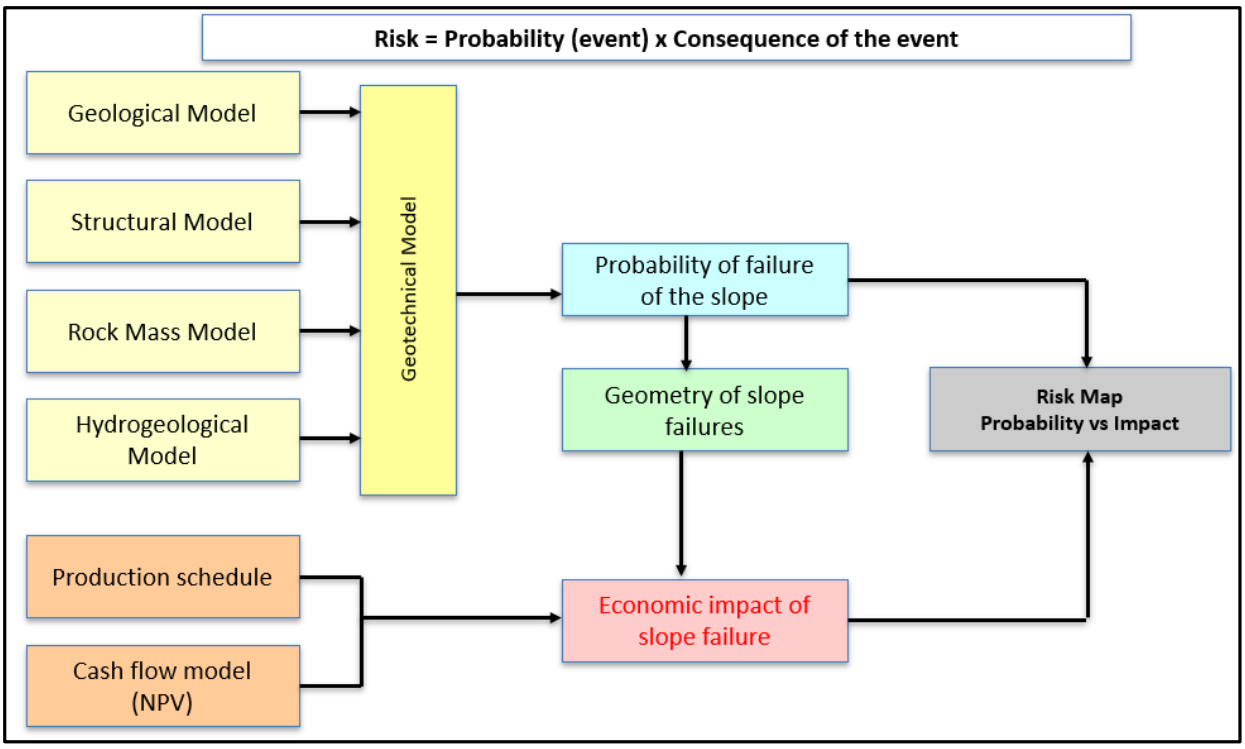


Figure 2.9. Illustration of risk management methodology (Contreras, 2015)

The results of the stability analysis include the FoS and the model PoF of the slope, which reflects the uncertainty due to the typical variability (under 'normal

conditions') of the rock strength. Probabilities of failure associated with atypical uncertain conditions leading to slope failure during the mine life and related to water, geology and mining aspects were defined and used for the calculation of the total PoF using the PoF and probability of occurrence (PoO) approach. The PoF for the normal operating condition is first determined, and the resulting probability distribution is calculated using a histogram for a given mean factor of safety (Figure 2.10). The calculated PoF is given by the ratio of the area under the distribution curve for F<1 divided by the total area under the distribution curve.

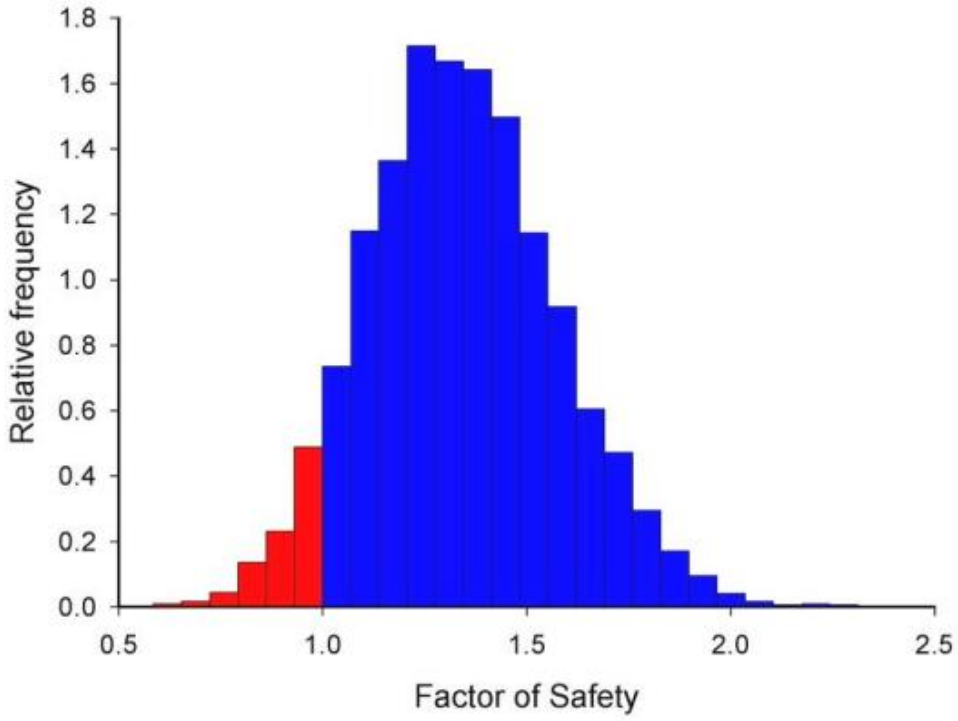


Figure 2.10 Distribution of the factor of safety (Rocscience, 2025)

This progressive approach to calculating the total PoF is visually represented in Figure 2.11, where each contributing factor—such as blasting, geological structures, water conditions and deviations from mine design—is assessed using its individual PoF and PoO values. These are then sequentially added to the initial PoF under normal conditions (0.01192), resulting in a cumulative PoF of 0.102 (10.2%). This method ensures that the compounded effect of multiple uncertainties is captured, offering a more realistic representation of slope failure risk. As

highlighted by Steffen et al. (2006), traditional models often overlook these layered uncertainties, and the single-pass PoF–PoO framework provides a structured way to incorporate them. The accompanying table (Table 2.2) further illustrates this process: starting with an initial condition PoF of 0.01490 and PoO of 0.80, a combined value of 0.01192 is generated. This is followed by geological boundary uncertainty and pore pressure variability, each with PoF and PoO values of 0.05000 and 0.90, respectively, contributing 0.04500 each to the cumulative PoF. The final cumulative PoF reaches 0.10192, corresponding to a reliability of 89.8%, referred to as the 'top fault' (Malesa et al., 2022), emphasising its significance in geotechnical risk management.

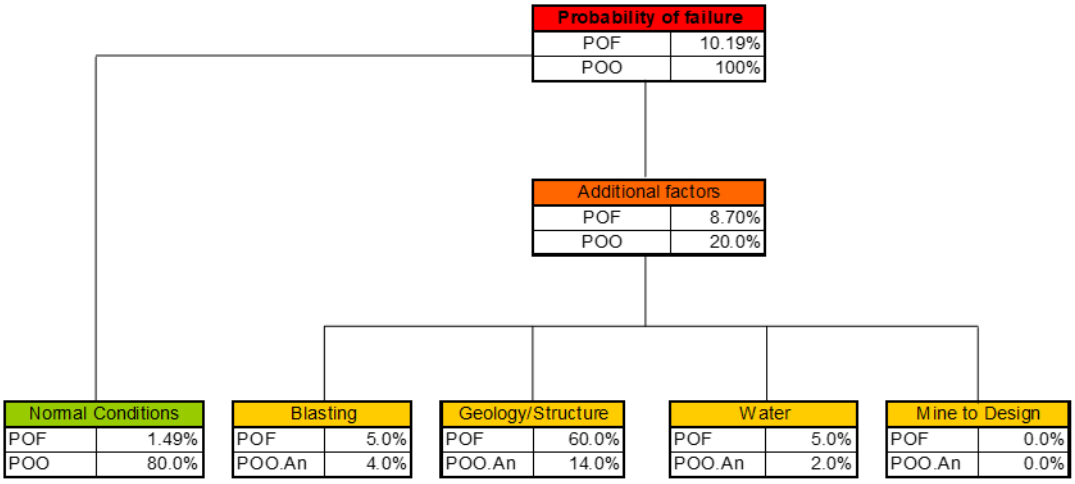


Figure 2.11. PoF–PoO fault tree analysis (Malesa et al., 2022)

Table 2.2. PoF–PoO fault tree analysis (Malesa et al., 2022)

Contributing Factor	PoF	PoO	Combined Value (PoF × PoO)
Initial Condition	0.01490	0.80	0.01192
Geological Boundary Uncertainty	0.05000	0.90	0.04500
Pore Pressure Variability	0.05000	0.90	0.04500
Final Cumulative PoF			0.10192

The second and major objective is to determine the risk of slope failure posed to personnel, utilising the fault/event tree process, which considers:

- PoF, slope instability history, data uncertainty and unknown factors;
- Exposure to personnel calculated based on mining activities, slope height and strike length;
- Slope stability monitoring system effectiveness for each area;
- Monitoring response effectiveness; and
- Evacuation effectiveness.

The accepted method of the fault and event tree analysis was incorporated into the Kumba Iron Ore HIRA criteria (Table 2.3) to enable the comparison of slope failure risks with other calculated risks in the mine (Malesa et al., 2022).

Table 2.3. HIRA acceptance criteria (Malesa et al., 2022)

HIRA VALUE	CATEGORY	ACTIONS
<20	Risk acceptable	No specific action
20 to 70	Possible risk	Attention required
70 to 200	Substantial risk	Action plan required
200 to 400	High risk	Immediate action required
>400	Very high risk	Consider suspension of the task

2.6 Chapter Summary

In open-pit mining, slope stability refers to the ability of a slope or wall to withstand movement and maintain its integrity. In open-pit mining, slope instability may arise from geological factors, the angle of the slope, moisture content and the load imposed by mining operations, among other causes. This chapter addressed strategies for preserving slope stability. Mining engineers and geologists are required to devise and execute strategies, including slope angle modifications, slope strengthening utilising materials such as rock bolts or mesh, drainage systems for water removal and slope movement surveillance employing technologies such as slope stability radar. The chapter emphasised the vital importance of slope stability analysis in enhancing worker safety, safeguarding equipment and improving operational efficiency in open-pit mining. These

discussions emphasise the essential need for continuous assessment and management of slope stability in open-pit mining operations.

3 RESEARCH APPROACH

3.1 Introduction

The research included kinematic analysis, slope stability analysis, runout distance and evaluation of the responses to the TARP system. The slope failure deformation profile and warning time were also evaluated (Figure 3.1).

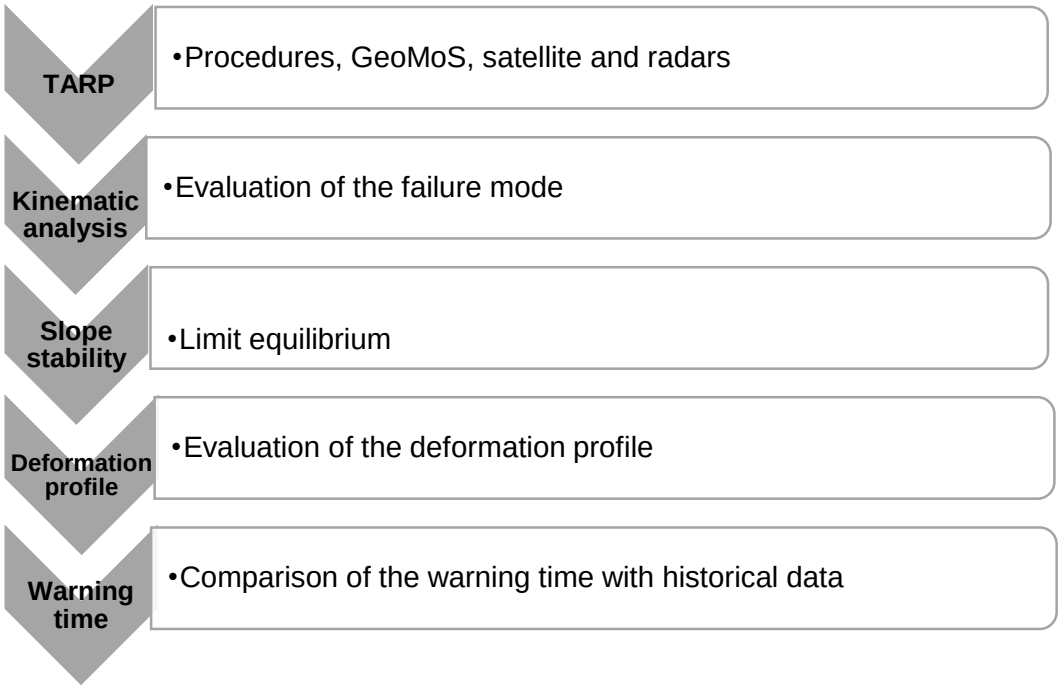


Figure 3.1. Summary of the analysis performed at Klipbankfontein pit

3.2 Research Design

The phenomenon of slope instability at the collapse site was examined by a thorough investigation of the key indicators (geotechnical, hydrogeological, operational, monitoring and early warning) related to the reported failure. The usefulness of several site inspection approaches, including visual inspections, photogrammetry and drone scans, was evaluated in discovering faults. A comprehensive study of the monitoring data was conducted, focusing on the interpretation of the information.

The investigation of the slope failure processes started with a detailed study of the drone footage and photogrammetric surveys gathered immediately after the incident (Appendix A). Combining structural mapping data with this visual evidence, it was clear that the failure happened along the haematite/BIF and gabbro contact, with lateral release given by the intersecting fault systems. This structurally controlled failure mechanism guided the choice of suitable analytical instruments.

A stability analysis was conducted applying both kinematic and limit equilibrium approaches following mechanism identification. The fault planes and the BIF–gabbro contacts were modelled with their material properties in the slide simulation. Rocscience Slide2 was used for analysing sections where the geological contacts and fault intersections produced possible sliding surfaces, and the Dips software was used to assess the possibility of structurally controlled failures. The study concentrated on the following in terms of their contributions to the instability during the third quarter of 2022:

- how groundwater conditions and blasting might have affected stability along specified structural paths;
- interaction between geological structures;
- increased pore pressures from rainfall; and
- mining activities.

The results were then applied to calibrate run-off distance calculations, which took structural control of the failure into account instead of depending on empirical techniques devised for circular failures.

3.3 Data Collection Process

The necessary data for an analysis of this structurally controlled failure were obtained from several sources. The main data consisted of detailed structural mapping of discontinuities, especially the orientation and properties of the haematite/BIF and gabbro contact and intersecting fault systems. Drill core logging and face mapping allowed for joint roughness coefficients, persistence and infill characteristics to be recorded. Rainfall records, among other hydrogeological data,

were gathered to better grasp the function of water pressure along these structural paths. Additional data sources included historical drone footage showing increasing development of the failure, and slope monitoring data from radar and prism measurements capturing displacement patterns along the controlling structures (Appendix B).

The data collection methods described above directly informed the analyses presented in Chapter 4. Specifically, face mapping data supported the structural interpretation of the failure mechanism, rainfall data contextualised pore pressure effects, and monitoring data validated the deformation trends and early warning system performance. Refer to Table 3.1 for the integration of data sources into analytical methodology.

Table 3.1 Linking data to methodology

Data Type	Purpose in Methodology	Analytical Tool Used
Face Mapping	Identify fault planes, discontinuities and lithological contacts for failure mechanism	Kinematic Analysis, Maptek Software
Rainfall Records	Assess pore pressure variability and correlate with slope movement	Correlation Analysis
GeoMoS & Radar	Monitor slope deformation trends and validate early warning system	Deformation Profile, TARP Evaluation
InSAR	Validate surface movement and detect early signs of instability	Comparative Analysis with GeoMoS
Limit Equilibrium	Evaluate slope stability under dry conditions using structural and geotechnical data	Slide2 Software, Monte Carlo Simulation

3.4 Data Validation Process

The information used from Anglo American went through rigorous review processes. Quality assurance and quality control processes included external

reviews, periodic geotechnical review boards and different levels of assurance audits.

3.5 Data Analysis Approach

The methods used to gather data for investigating slope instability at the Klipbankfontein site area are described in this section. Data was primarily collected using the slope monitoring system, as outlined in the slope monitoring strategy shown in Figure 3.2. The flowchart illustrates a comprehensive slope hazard monitoring and response framework designed for mining operations. It integrates multiple data sources such as digital mapping, visual inspections, blast and precipitation monitoring into laser scanning and radar slope monitoring systems. These technologies enable real-time detection of slope instability, triggering alarm thresholds linked to predefined first response and emergency plans. The process is structured into progressive stages, from initial hazard identification and stability trend analysis to safety-critical monitoring, operational response and mine evacuation. The final stage involves contingency planning for mine recovery, ensuring that both proactive and reactive measures are in place to manage slope failure risks effectively.

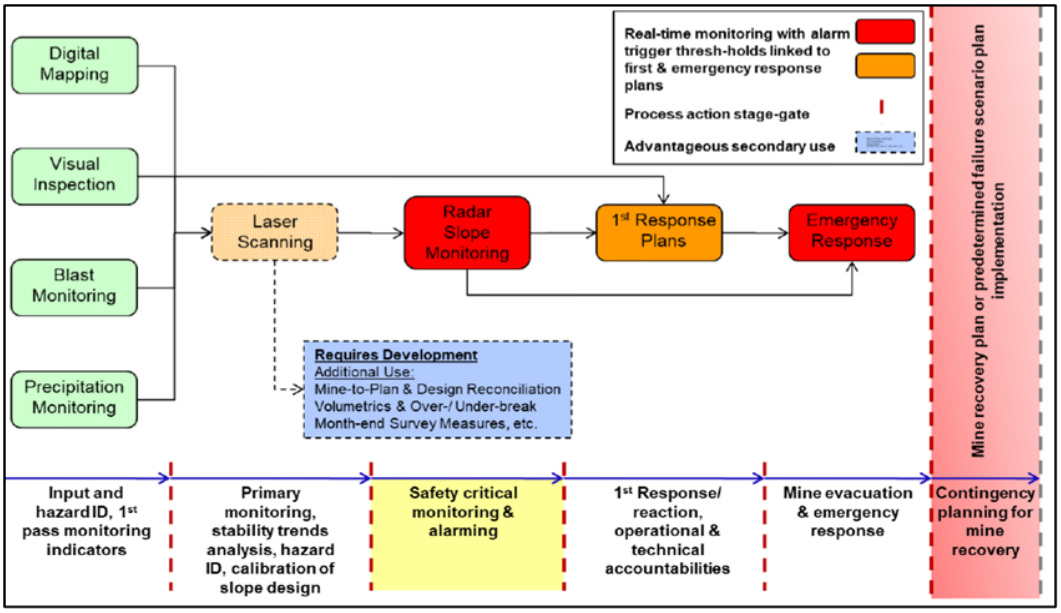


Figure 3.2. Generic slope monitoring strategy (Sekoere et al., 2014)

3.5.1 Procedures, GeoMoS, satellite and radars

The monitoring procedures implemented in the study were designed to capture both surface and subsurface deformation patterns with high precision and responsiveness. The GeoMoS system played a central role in this setup, providing real-time deformation data through a network of prisms installed on a staggered grid (50 m horizontal × 10 m vertical). This configuration allowed for targeted tracking of movement along structurally significant zones, particularly geological contacts and fault intersections. Complementing this, slope stability radar systems delivered continuous, millimetre-level precision coverage, enabling the detection of subtle acceleration trends and movement vectors. These radar systems were crucial for identifying early signs of instability and correlating deformation with triggering events such as rainfall and blasting. Together, these technologies formed the backbone of the site's hazard monitoring procedures, feeding into the TARP and supporting timely decision-making during critical movement phases.

3.5.2 Evaluation of the failure mode

The evaluation of the failure mode was conducted through detailed kinematic analysis, which aimed to characterise the structural mechanisms controlling slope instability. High-resolution scans of multiple benches were obtained using a Maptek laser scanner, and face mapping was performed using I-Site Studio software. This allowed for precise measurement of dip, dip direction and joint properties—including roughness, alteration, spacing and condition—for all structural features such as faults, joints and bedding planes. These data were used to identify the dominant failure mechanisms, including planar sliding, wedge failure and toppling, particularly along the gabbro contact zones and fault intersections. The analysis revealed progressive development of lateral release surfaces and movement along geological contacts, which were key indicators of structurally controlled failure. This structural understanding was essential for calibrating slope design parameters and informing the stability analysis and response planning.

To support the evaluation of the failure mode, detailed structural mapping was conducted using high-definition scans and I-Site Studio software, focusing on key geological zones such as the gabbro contact and haematite/BIF interfaces. This

mapping captured changes in joint conditions, fault intersections and the progressive development of tension cracks, which were critical in identifying structurally controlled failure mechanisms. The integration of deformation monitoring data from GeoMoS prisms and slope stability radar further refined the understanding of movement patterns, revealing acceleration trends and directional vectors aligned with geological structures. These insights enabled the identification of distinct failure phases, including initial movement along geological contacts, the formation of lateral release surfaces and eventual acceleration to failure. This multi-layered approach provided a robust foundation for characterising the failure mode and informed the calibration of slope design and response strategies.

3.5.3 Limit equilibrium analysis

The limit equilibrium method was employed to evaluate the stability of the slope using the Slide2 software by Rocscience (2025). This approach calculates the FoS by assessing the balance between driving and resisting forces along potential failure surfaces. In this study, representative slope sections were modelled based on detailed geological, structural and mining data, including fault planes and BIF–gabbro contacts. Material properties were assigned to each domain, and the Monte Carlo simulation tool within Slide2 was used to incorporate variability in rock strength parameters, allowing for the probabilistic estimation of the PoF. While the method provides valuable insights into slope stability under normal conditions, it does not account for 3D effects, which may lead to an overestimation of slope strength. However, due to the pit's configuration, a degree of confinement is expected, partially mitigating this limitation. The results from this analysis formed the basis for integrating atypical uncertainties—such as geological anomalies and pore pressure variability—into the total PoF using the PoF–PoO framework.

Limit equilibrium analysis was selected as the primary quantitative method to evaluate slope stability under varying geological and hydrological conditions. This method was used to simulate failure surfaces along the BIF–gabbro contact and fault intersections, incorporating material properties derived from face mapping and core logging.

3.5.4 Comparison of the warning time with historical data

The evaluation of warning time was conducted by comparing the real-time deformation data from radar and prism monitoring systems with historical records of slope movement and failure events. This comparison aimed to assess the responsiveness and reliability of the current monitoring setup in detecting early signs of instability. By analysing acceleration trends and movement vectors in relation to rainfall and blasting events, the study identified critical thresholds that preceded past failures. These thresholds were then matched against the alarm trigger levels embedded in the TARP. The effectiveness of the warning time was measured by how accurately and promptly these systems could forecast failure progression, allowing for timely evacuation and intervention. This analysis provided valuable insights into the adequacy of current alarm settings and informed adjustments to improve future response protocols. Furthermore, the study evaluated the implementation of response procedures, including evacuation protocols and decision-making processes during critical movement phases. This assessment focused on how well the alarm thresholds aligned with the actual failure mechanism and its progression rate, particularly in the context of structurally controlled collapses such as the Klipbankfontein slope failure. A qualitative methodology was applied, incorporating kinematic analysis, slope stability modelling, deformation profiling and warning time assessment to determine the overall effectiveness of the TARP and its alignment with site-specific failure behaviour.

3.6 Chapter Summary

This chapter presented an outline of the research methods utilised in the study, concentrating on slope stability analysis. The discussion encompassed the use of several methods, approaches and techniques, such as photogrammetry, drone scans, site inspections, visual inspections and limit equilibrium analysis. Photogrammetry and drone scans provide critical insights into terrain form and structural integrity, yielding high-resolution data for analysis. Site inspections constitute a crucial element, facilitating direct observation of geological characteristics and potential risks. Visual inspections augment site visits, enabling the detection of apparent indicators of instability and alterations in the terrain. The

limit equilibrium analysis offered an evaluation of slope stability by assessing the balance between resisting and driving forces. Furthermore, numerical modelling tools facilitate the simulation of intricate geological situations, providing predictive insights into slope behaviour under diverse loading conditions. By merging these techniques, the study attained a thorough comprehension of slope stability dynamics.

4 DATA FOR THE STUDY

4.1 Introduction

To achieve the objectives outlined in Chapter 1, it was necessary to gather and consolidate information, execute an analysis of the gathered data and validate the data obtained. The validation aims to adopt model parameters that are unbiased and objective, thereby producing the best representative outcomes of the available data. The collected data will be utilised to evaluate the atypical conditions that led to the instability, to ensure that similar conditions can be identified and their impact on safety and production minimised.

4.2 Slope Instability Sequence

The time from the first warning until the failure, as well as the various activities and warnings at the time, are shown in Figure 4.1. A total warning period of two months occurred before the failure took place. Before the first warning, the area had been mined for more than three years.

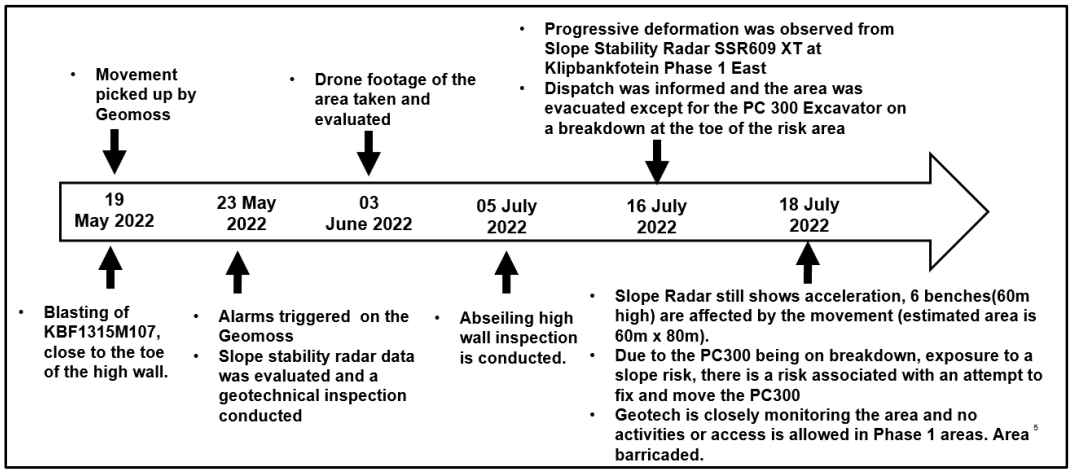


Figure 4.1. Slope instability timeline

4.2.1 Pre-failure stage

The GeoMoS system, InSAR and GroundProbe monitoring systems did not pick up any movement before the 19th of May 2022. There were no observations of minor ground movements, changes in seepage patterns, or small-scale cracks in the pit walls.

4.2.2 Failure initiation

A noticeable increase in movement or deformation in the pit walls was picked up by the GeoMoS system following the blasting of the buffer block at the toe of the slope. Movement was also picked up by the slope stability radar, which triggered an alarm; a drone was subsequently deployed to inspect the area for any signs of instability. The high-resolution imagery and detailed topographic data that were collected showed that the slope face remained intact, with no evidence of cracking, surface displacement, or rockfall activity. The inspection covered all critical areas of the slope, including benches, berms and highwall faces, providing a thorough visual assessment. Based on the drone's findings, the slope was considered stable.

4.2.3 Failure progression

The slope instability accelerated, leading to the triggering of an alarm on the 16th of July 2022, approximately two days before the failure. The area was evacuated, causing disruption to mine operations and resulting in equipment that was broken down being left behind at the toe of the slope during the evacuation.

A thorough investigation was conducted to determine the causes of the failure. This included analysing the failure data, reviewing the TAMU database (Timchenko & Briaud, 2023) of slope failures and identifying any procedural or design flaws. The pit layout design was re-evaluated to check the potential runout distance and potential mitigation measures.

The database was designed to support empirical analysis and improve predictive modelling in slope design. Using the collected data, researchers formulated equations to estimate how far failed material travels and how far operations should be set back from the pit crest for safety. One notable finding is that 3D slope stability models tend to produce higher safety factors than two-dimensional

models, highlighting the importance of spatial context in geotechnical assessments. This resource serves as a valuable tool for engineers and geoscientists aiming to enhance slope stability evaluations and risk management strategies in mining environments.

4.3 Fall-of-Ground Stats

The database of FoGs for Klipbankfontein Phase 1 (Malesa, 2022) was scrutinised to check for any events such as the instability under review. A total of 11 instabilities were recorded in the area from 2009 to 2023 (Figure 4.2).

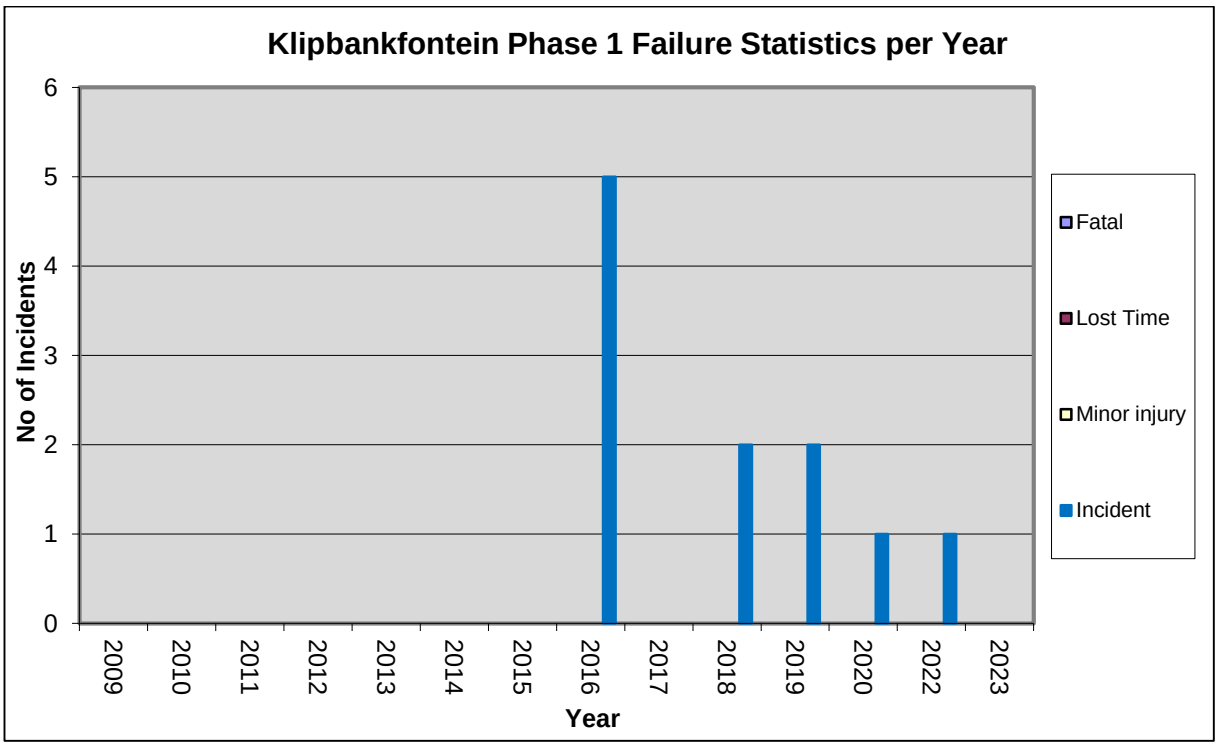


Figure 4.2. Fall-of-ground statistics for Klipbankfontein pit (Malesa, 2022)

The highest number of failures was in tillite, as it consists of a wide variety of particle sizes and rock fragments with weak bonding between the materials. This lack of uniformity can result in lower overall shear strength, making slopes prone to failure. Tillite often weathers into softer material, which reduces its stability over time. Weathered tillite can become prone to disintegration and slumping. Figure 4.3

shows the number of FoG incidents per ground control district in the Klipbankfontein pit.

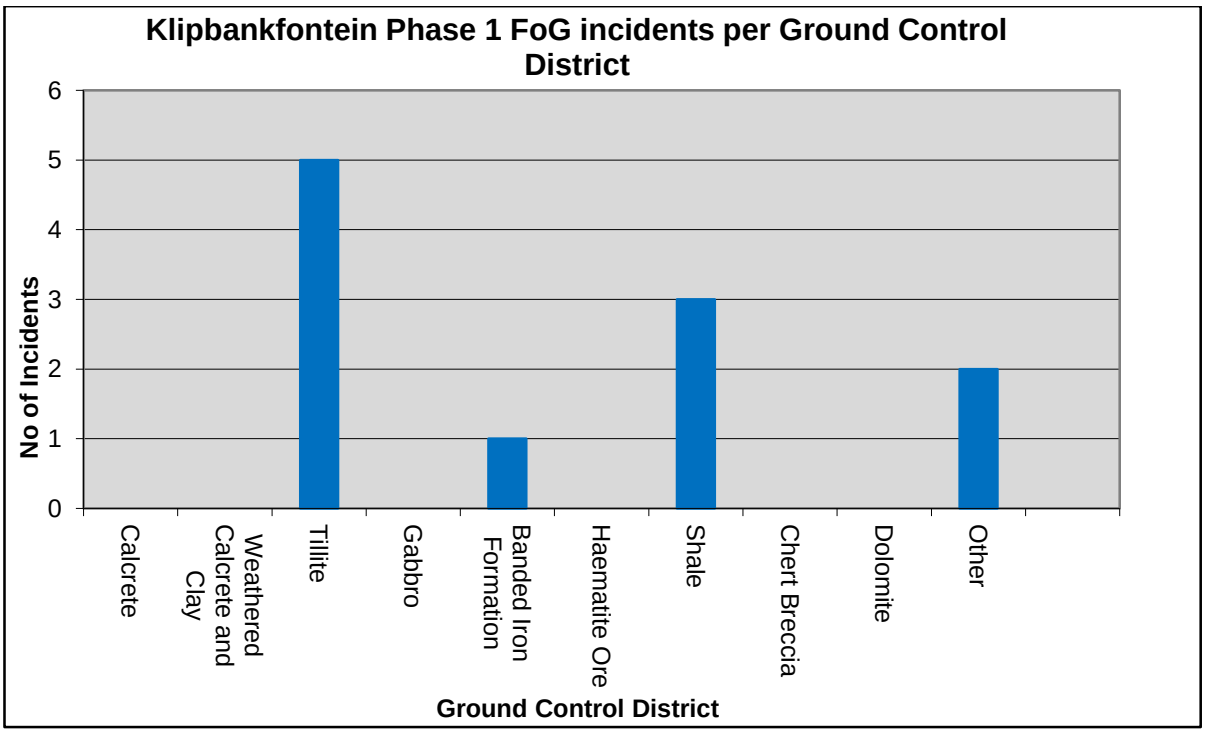


Figure 4.3. Fall of ground per ground control district (Malesa 2022)

Historical data show that geological structures and water are the leading drivers when it comes to failures at Klipbankfontein Phase 1 (Figure 4.4). This may be attributed to increased pore pressure, because when water infiltrates rock and soil, it can increase the pore water pressure, reducing the effective stress that holds rock particles or planes together. This weakens the material or reduces the normal stress on potential shear planes, making it more prone to sliding or collapsing. Water can seep into pre-existing cracks and joints within the rock mass, and the head will provide pressure, which serves to push the potential sliding planes apart. In addition, the water can act as a lubricant along these surfaces, reducing the friction angle. In some cases, water under pressure can create new fractures, further weakening the rock mass here.

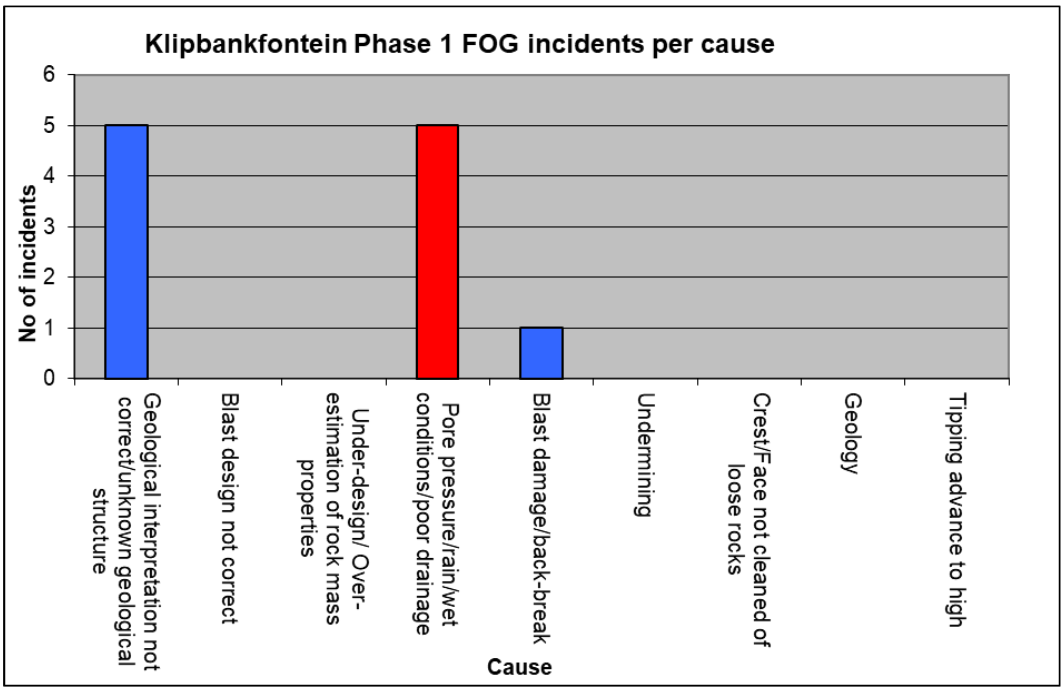


Figure 4.4. Fall of ground per cause (Malesa 2022)

Pre-existing faults and discontinuities in the rock mass provide natural weakness zones. These can act as potential failure planes along which rock masses can slide when stressed by mining activities or influenced by water infiltration. The overall strength of a rock mass is dependent on the type and condition of the rock as well as the intensity and orientation of joints and fractures. Weaker rock masses with more discontinuities are more susceptible to failure, especially when combined with water infiltration.

4.4 Face Mapping

Face mapping was performed using Maptek's I Site Studio software (2023), which enabled detailed structural and lithological characterisation of exposed pit walls. Stereonets were used to evaluate the stability of rock slopes or other geological structures. This was done by evaluating how planes, wedges and other features behave with respect to potential failure mechanisms. The major fault planes that were observed in the face are shown in Table 4.1. The fault planes are shown as poles in figures 4.5 to 4.7, and it was clear that planar, wedge and toppling failures were not expected.

Table 4.1. Dip and dip direction of the discontinuities

Plane	Dip	Dip direction
A	86	263
B	41	269
C	86	125
D	89	340

The mechanism of planar failure requires a release mechanism to allow a block sliding on one plane to be removed from the slope. The crescent-shaped zone formed by the daylight envelope and the pole friction circle encloses the region of planar sliding, outside of the pole friction circle and inside the daylight envelope. Any poles in this region represent planes which may slide. Figure 4.5 shows that none of the faults plot in the critical zone of planar, highlighted in red.

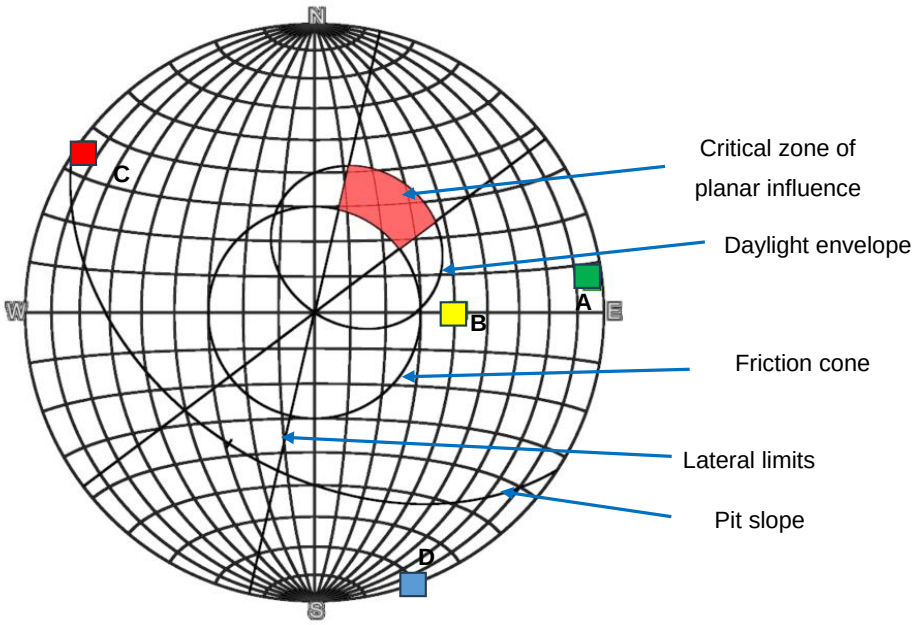


Figure 4.5. Plane failure stereonet (A, B, C and D are the poles of the planes described in Table 4.1)

The critical zone for wedge sliding is inside the plane friction cone and outside the slope plane (Figure 4.6). Intersections that plot in this zone represent wedges which satisfy frictional and kinematic conditions for sliding. None of the intersections of the discontinuities in Table 4.1 satisfied the conditions for wedge sliding.

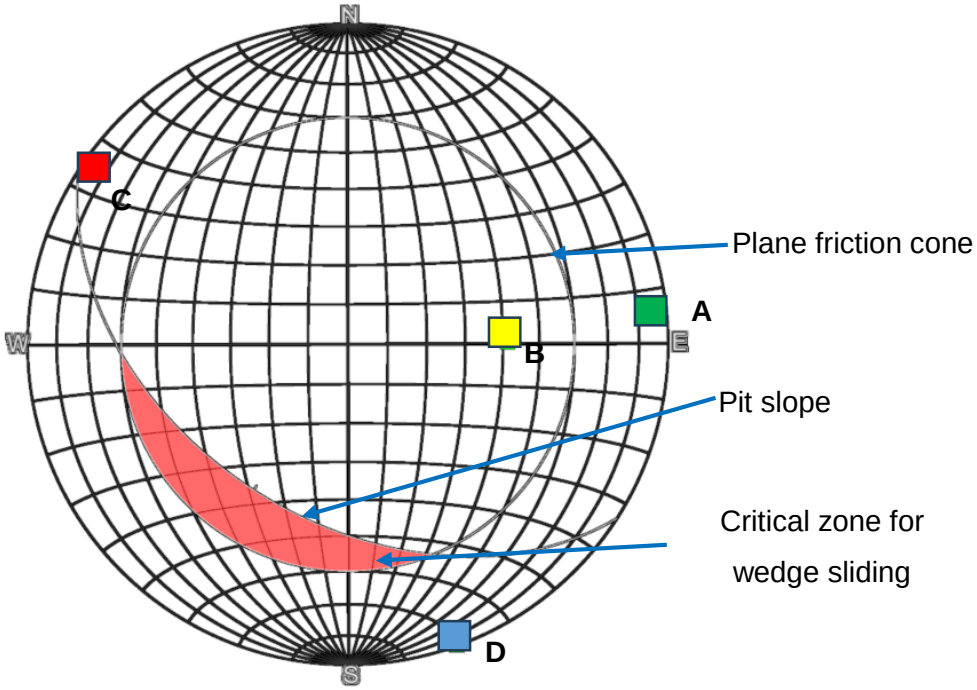


Figure 4.6. Wedge failure stereonet (A, B, C and D are the poles of the planes described in Table 4.1)

The critical zone for toppling is the area between the slip limit plane, lateral limits and the stereonet. None of the analysed discontinuities satisfy the conditions for toppling failure (Figure 4.7).

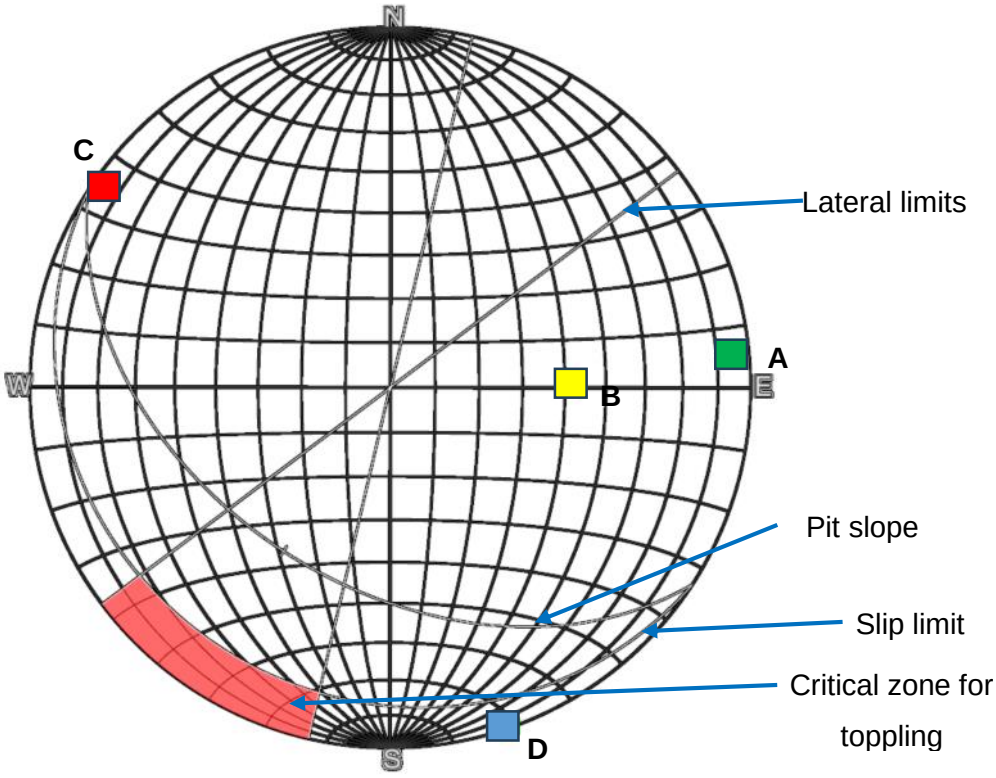


Figure 4.7. Toppling failure stereonet (A, B, C and D are the poles of the planes described in Table 4.1)

The components examined during the kinematic analysis include slope dip, slope dip direction, daylight envelope, slip limit, lateral limits, polar friction cone and planar friction cone. Figure 4.8 and Figure 4.9 illustrate the spatial relationship between the mapped fault planes and the eventual failure surface. They indicate that the failure mechanism was not confined to the BIF–gabbro contact but was influenced by intersecting fault orientations, suggesting a structurally controlled complex planar failure. Figure 4.10 shows a conceptual failure mechanism in the area. The failure surface in Figure 4.8 shows a complex planar failure mechanism as it involves more than one plane, and the contact along which the failure occurred bends towards the bottom of the slope. The failure surface was not mapped as it was behind the face, but was detected in boreholes and therefore plotted in Figure 4.8. The BIF contact was exposed in the sidewall (where it was mapped) and then curved sharply around the back of the area where the failure took place. The plane thus formed the planar surface as well as one of the side release surfaces. The

other side and top were bound by faults. The failure was therefore not purely planar; it occurred between fault planes and the BIF–gabbro contact.

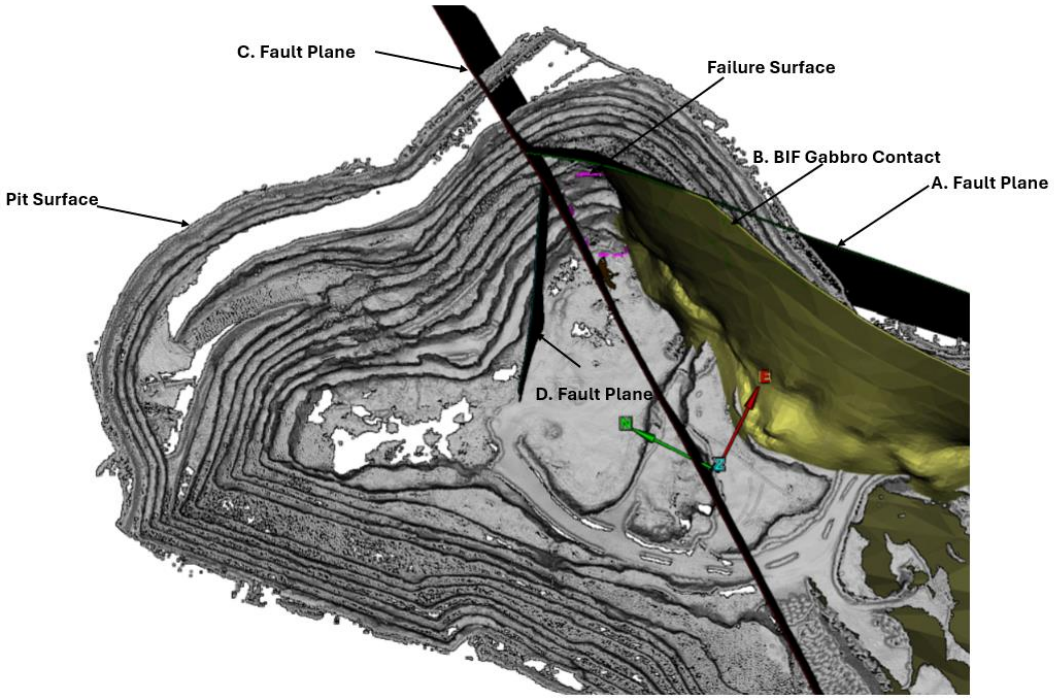


Figure 4.8. Detailed orientation of the fault planes

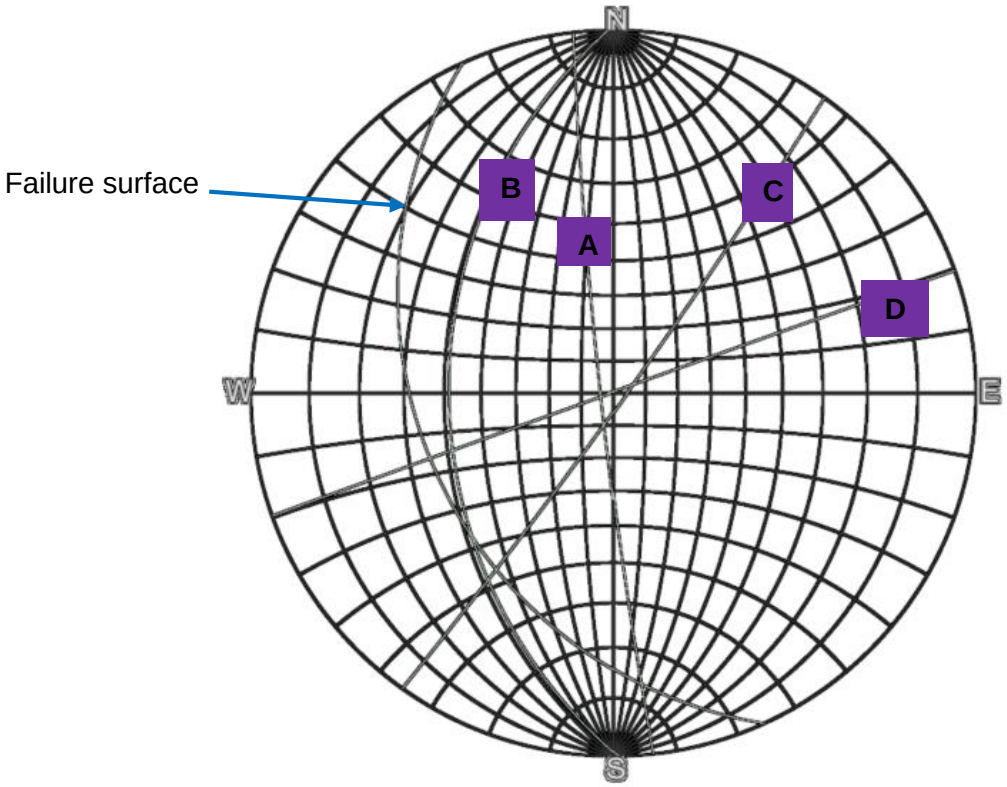


Figure 4.9. Detailed planes plot of the faults and the failure surface, as shown in Figure 4.8

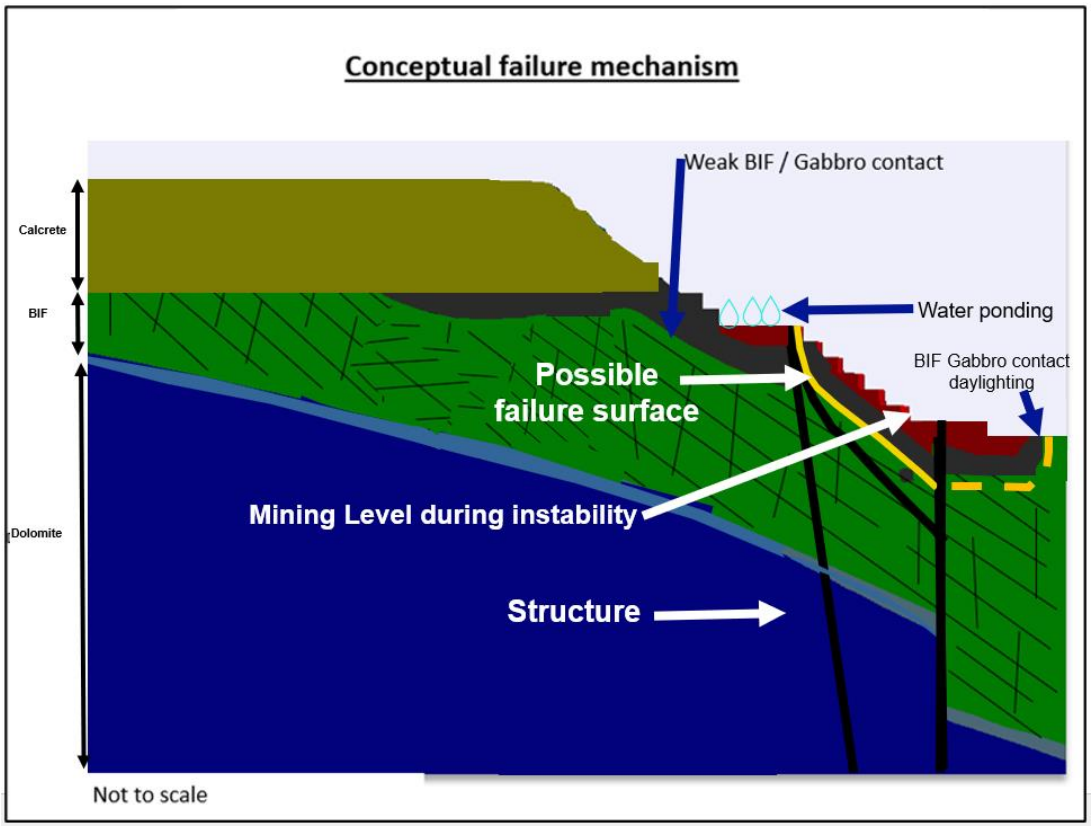


Figure 4.10. Conceptual failure model for Kolomela Mine

4.5 Limit Equilibrium Analysis

Slope stability analyses were carried out using the program Slide2 from Rocscience, which uses the limit equilibrium approach for the calculation of the FoS of the slope. The built-in Monte Carlo tool was used to calculate the PoF of the slopes, considering the variability of the strength properties. Representative sections of the slopes based on the pertinent geological, structural and mining data were considered (Table 4.2).

Table 4.2. Limit equilibrium analysis

Section	Klipbankfontein pit analysis					
	Global Analysis			Localised Analysis		
	Mean (FoS)	PoF (Model)	Remarks	Mean (FoS)	PoF (Model)	Remarks
KF2	1.88	0.00	Global/Overall Analysis	1.33	2.88	5 Benches, BIF, GAB, HEM & Faults
				1.98	2.38	5 Benches, BIF, GAB

4.6 Monitoring Data

4.6.1 Manual inspections

Inspections carried out by the geotechnical section dating back to January 2022 highlighted the area of concern. The material was observed to be composed predominantly of weak blocky gabbro intersected by a series of faults (Figure 4.11), with the weak gabbro material resulting in bench-scale instabilities.

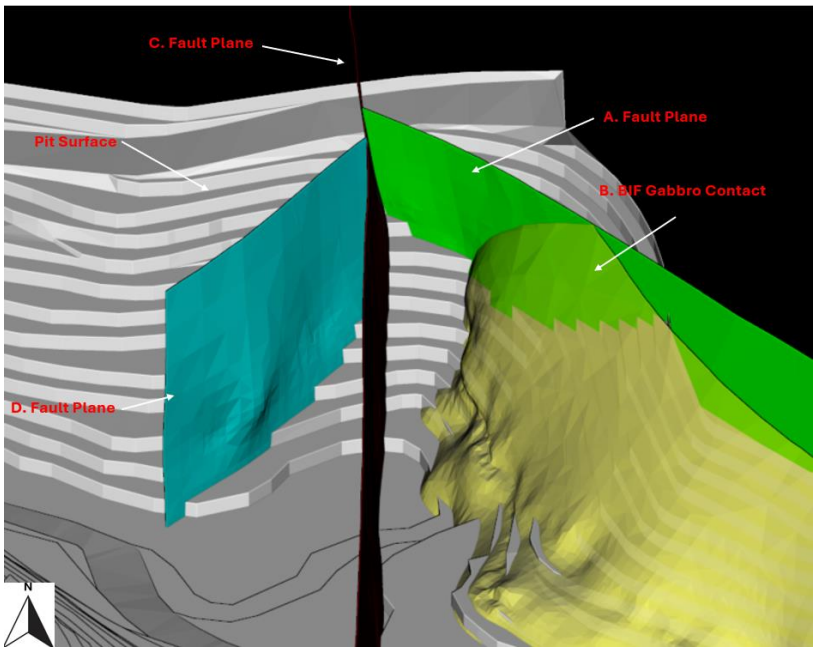


Figure 4.11. Graphical illustration of fault interaction in the area

At Klipbankfontein, pit wall control has been especially difficult, as the blast design was challenging and often interacted with unfavourable geological structures. Bench-scale failures have historically been common along the haematite/BIF and gabbro contact, particularly in areas intersected by NW–SE trending faults (Figure 4.12). Standard presplit blast designs did not consider the orientation of these geological structures. The loss of catchment capacity at the site is explained by two main causes. First, poor structural geology resulted in a back-break outside the intended pit limits, and second, through blasting damage on the pit slope. This set off a cycle whereby damaged crests lowered catchment capacity, hastening lower bench degradation and resulting in double benching. Face mapping data indicates that blast damage stretched far beyond the design limits, sometimes up to five metres behind the intended crest position, where pre-split holes intersected major discontinuities at acute angles. These results emphasise the need for structure-specific blast designs and stricter adherence to controlled blasting techniques for final pit walls.

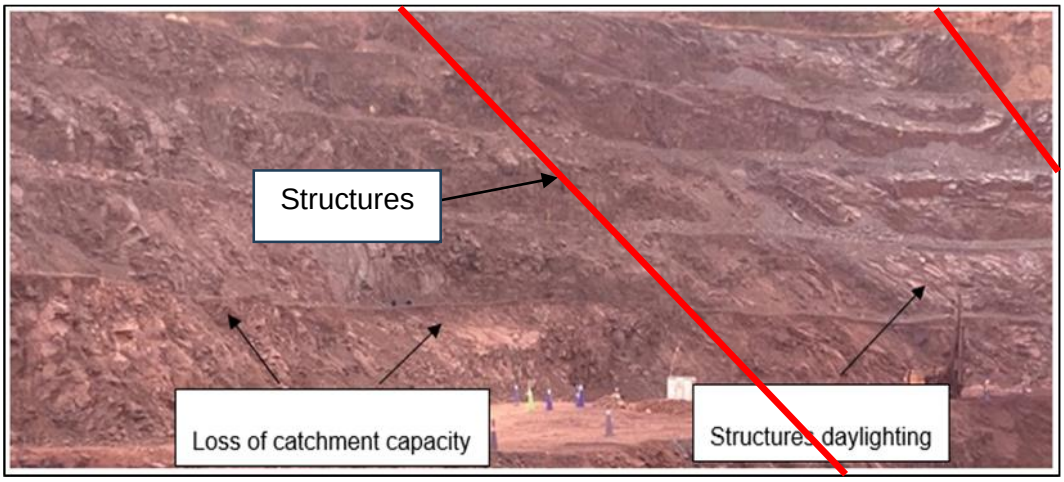


Figure 4.12. Loss of catchment at the site where slope instability occurred

The Klipbankfontein geological model included 29 major faults within the model boundary, of which 14 intersect the final pit design. Figure 4.11 shows that there are two major fault sets, the first striking NW–SE and the second striking NE–SW.

4.6.2 Routine inspections

Hazards were also identified from conducting routine inspections. The quarterly geotechnical report indicated that the area has been declared a special area due to geotechnical concerns (Figure 4.13).

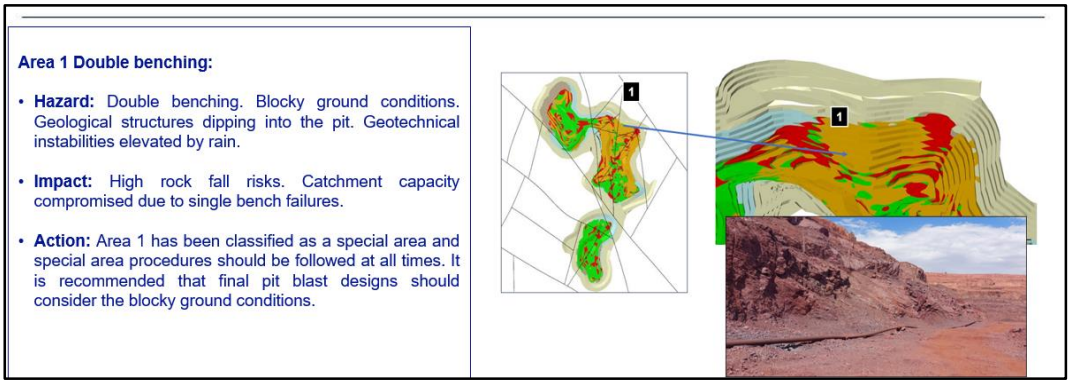


Figure 4.13. Extract from the geotechnical quarterly report (Malesa 2021)

Certain zones within an open-pit mining environment may exhibit higher susceptibility to rockfalls during standard mining activities. These zones typically arise due to unforeseen geological discontinuities, zones containing weaker rock materials, or ground disturbance within the excavation area. Upon identification, these zones can be designated as 'special areas', necessitating increased geotechnical vigilance. It becomes the responsibility of the geotechnical engineer to closely monitor these areas, thoroughly document their locations, classification methods, declaration processes and ongoing monitoring activities. These detailed records should be maintained transparently and made accessible for review purposes. According to the monthly report, the specific area discussed primarily consists of fragmented and structurally compromised gabbro intersected by multiple fault sets (refer to Table 4.3).

Table 4.3. Risk rating of the area of concern

Geotechnical Risk	Risk Rating	Required Actions
Slope Failure	19	Pro-actively manage
Bench Failure	18	Pro-actively manage
Rockfall	6	Actively manage
Crest Failure	N/A	
Subsidence	N/A	
Dump Failure	N/A	

Risk ratings are categorised into three management levels:

- High risk (15–25): Requires immediate proactive management and senior management attention.
- Medium risk (8–14): Requires active management with regular monitoring.
- Low risk (1–7): Requires routine monitoring and standard controls.

At Kolomela Mine, risk assessments are carried out using a methodical approach, compliant with international best standards in geotechnical risk control (Read & Stacey, 2009). The method combines probability and consequence ratings using a 5x5 risk matrix, as described by Contreras (2015) for open-pit slope design. Sullivan (2013) showed that this methodical rating system allows for consistent evaluation across several geotechnical zones, considering site-specific conditions. By combining probability with consequence scores, the final risk value is computed to produce a range from 1 to 25, whereby values above 15 indicate important hazards needing immediate management attention.

Bench-scale instabilities have been known to result from the gabbro material, which features weathered surfaces and closely spaced joints. Post-blast inspections and blast record analysis indicated that final wall blasting damage was significant. Charge weights often exceeded design criteria, and presplit hole spacing of 1.2 m proved too wide for the weak rock mass conditions.

The compromised bench geometry in the area of concern was aggravated by excessive water ponding on the slope. After heavy rainstorms, standing water was often observed in tension cracks. Insufficient pump capacity caused water to build up on damaged catch benches for protracted lengths of time. The bi-weekly geotechnical reports repeatedly highlighted these problems. Figure 4.14 shows how challenged blast control and insufficient drainage caused degradation of bench conditions, and consequently higher geotechnical risk in the vicinity.

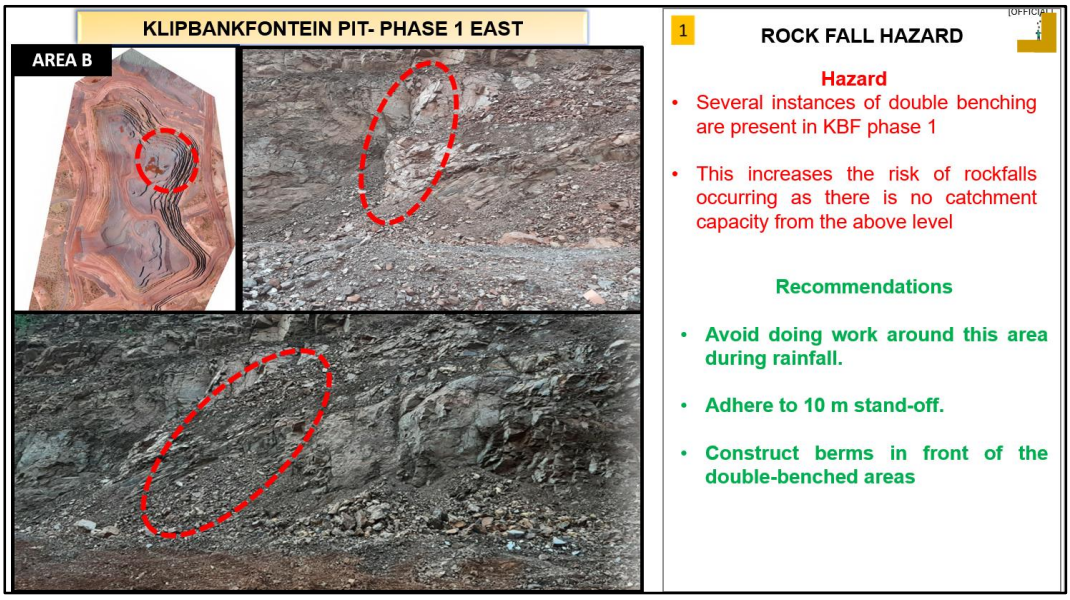


Figure 4.14. Extract from the geotechnical bi-weekly report (Clinton, 2022)

4.7 Rainfall Data

For purposes of aiding the slope performance analysis of this study, rainfall data was gathered for a period spanning 2011 to 2022 (Figure 4.15). The rainfall analysis of the third quarter of 2022 concentrated on the time preceding the slope failure. Historical averages were compared with monthly rainfall data from January 2022 through August 2022 to spot notable deviations. With a cumulative total of 642 mm by August already surpassing full-year totals for every year since 2011, the data shows that 2022 experienced extraordinary rainfall. The second quarter (April to June 2022) experienced an extremely high 285 mm of rainfall, 173% above the historical quarterly average of 165 mm for this period.

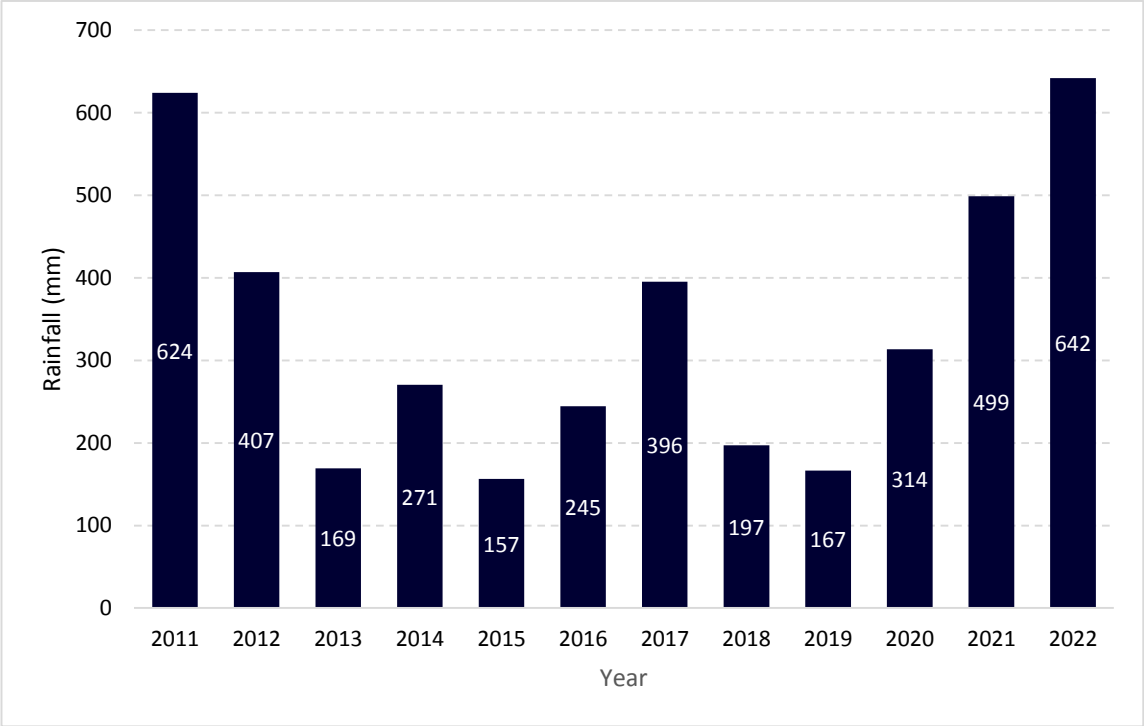


Figure 4.15. Historic rainfall information

Three notable rainfall events occurred in the period from May to June, corresponding with the start of slope movements. The deformation rate exceeded 50 mm/day, which marked a significant departure from past trends. A detailed historical rainfall record (2011–2022) is provided in Appendix C. It appears that water pore pressures were raised along the important haematite/BIF and gabbro contact, resulting from the abnormal rainfall. However, piezometers were not installed in the vicinity to be able to capture the exact magnitude of the pre-pressure increase.

4.8 GeoMoS Monitoring

A ground probe series slope monitoring radar was deployed to monitor the area as part of the slope monitoring strategy. GeoMoS is a primary monitoring tool for slope failure and was used for primary monitoring at Klipbankfontein Phase 1. The implication of the GeoMoS data relates to the premise that a diversion from a normal deformation trend signals the possibility of slope failure occurring.

GeoMoS movements were then broken down into components—longitudinal (along the length of the slope or pit), transverse (perpendicular to the slope) and vertical. The longitudinal component specifically highlights movement that could be a precursor to slope failure or ground instability in the direction of mining progress or geological structures. Transverse deformation informs if the slope is deforming outwards or inwards, such as bulging or arching across the face. In many open-pit mines, slope failures tend to happen in the direction of the slope face, which is usually aligned along the pit wall or bench. This makes longitudinal deformation a strong indicator of potential large-scale movement (Leica Geosystems, 2023).

Figure 4.16 shows the longitudinal deformation from the GeoMoS in the instability area. More detailed graphs are presented in Appendix D. As demonstrated in Figure 4.16, GeoMoS was able to detect the movement early; however, the prisms became damaged as the failure progressed.

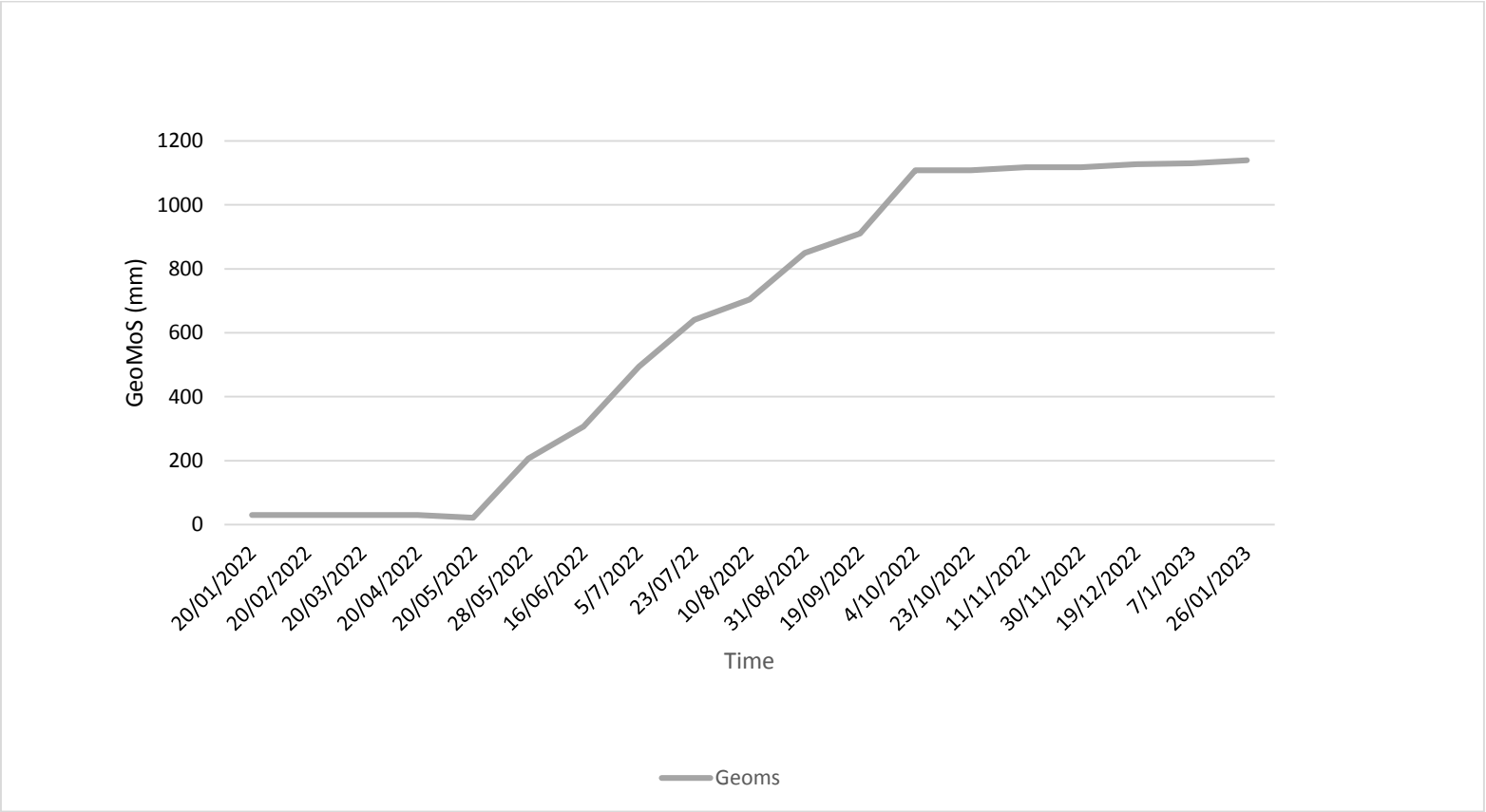


Figure 4.16. Illustration of the average movement GeoMoS graph

4.9 Slope Stability Radar

Figure 4.17 indicates that the site of slope failure showed a regressive deformation, underscoring the importance of having both primary and critical monitoring equipment in place. If the slope is decreasing or stabilising, this movement is referred to as the regressive displacement curve or stable movement. It has been shown that a regressive trend typically occurs as a reaction to nearby mining activities. Refer to Appendix B for a more detailed graph. Enhanced deformation refers to the increased or accelerated ground movement detected by radar monitoring systems in a slope, typically indicating potential instability or failure. Slope stability radar is commonly used in mining, construction and geotechnical engineering to monitor slope deformations in real time.

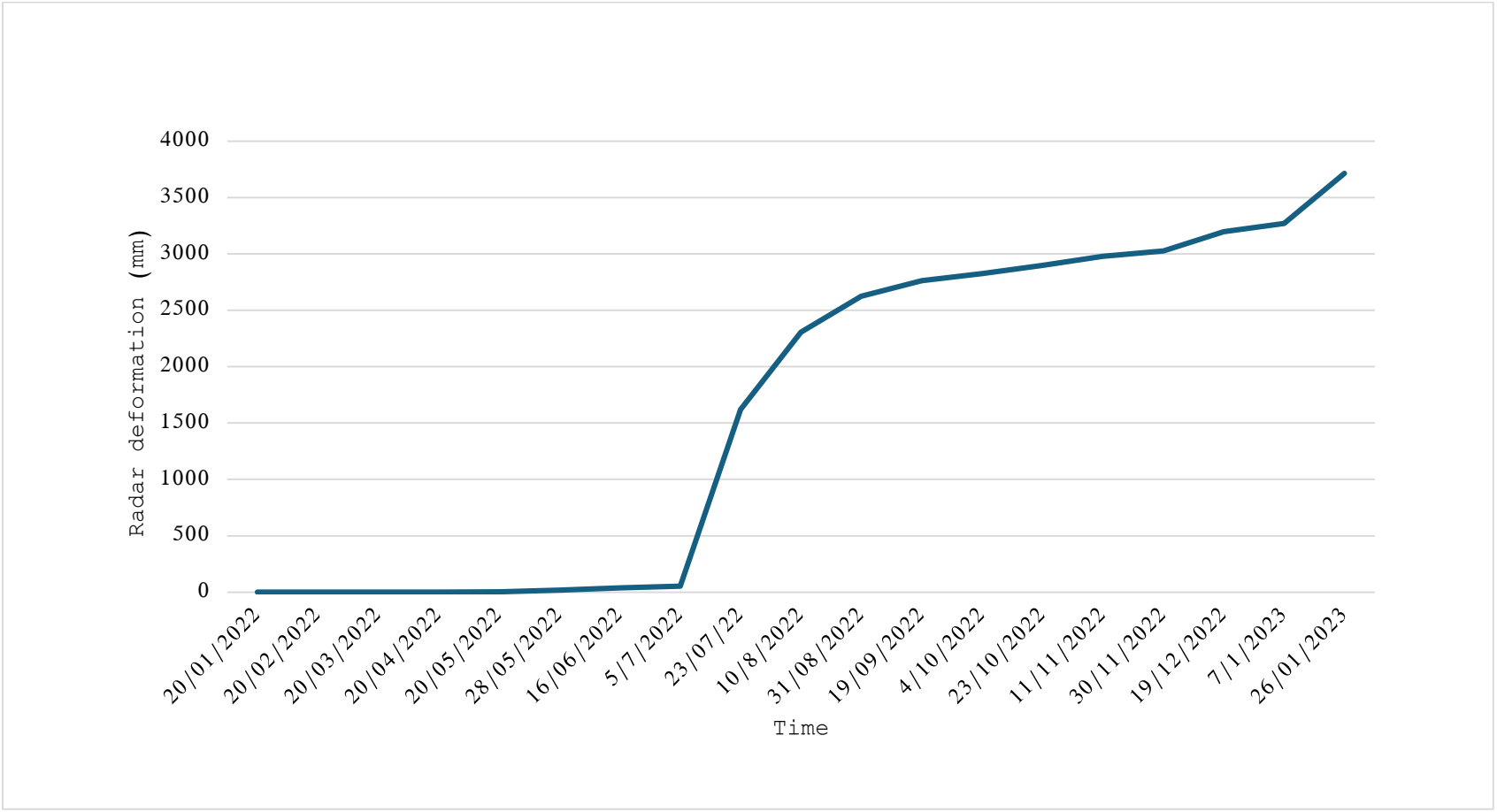


Figure 4.17. Deformation at the site of slope failure recorded by the radar system

4.10 Emergency Response

The emergency response TARP was well executed. Appendix D presents the TARP that was implemented in response to the instability. Following this, geotechnical assessments were conducted, including slope deformation monitoring, structural analysis and rock mass characterisation. As a slope stabilisation measure, it was determined that a strategic volume of ore needed to be left in place. This decision was based on geotechnical modelling and stability analyses, which indicated that the removal of this material would likely trigger further movement along existing failure planes.

The execution of the TARP resulted in some ore being left at the toe of the slope. Mining of the ore bench was from SE to NW, towards the failure to ensure as much confinement as possible during the mining process (Appendix D).

Evacuation drills were conducted once every six months in the Klipbankfontein pit during Phase 1. Table 4.4 below indicates the evacuation time from the drills. The Klipbankfontein instability was evacuated within the evacuation drill time, which is an indication of effectiveness.

Table 4.4 Evacuation drill time

Year	Time to evacuate mining area (minutes)
2020	18
2021	18
2022	14

4.12 Chapter Summary

Several important features of the slope failure of the Klipbankfontein pit were exposed by data collection and analysis. Comprehensive structural mapping of the pit wall revealed the critical interaction between the haematite/BIF and gabbro contact and intersecting fault systems, finally regulating the failure mechanism. Face mapping data recorded progressive degradation of bench conditions, especially where poor blast control and insufficient drainage compromised design geometries. In particular, where intersected by NW–SE trending faults, the mapping revealed that bench-scale instabilities regularly occurred along these geological contacts.

The historical FoG statistics showed a trend of past failures in similar geological conditions. At the FoG site, the movement from initial displacement to final failure was monitored using prisms, radar and visual inspections. The evaluation of rainfall data showed three major events exceeding 50 mm/day in May to June, corresponding with the start of slope movements. This extraordinary rainfall undoubtedly played a role in raising pore water pressures in key discontinuities.

The gradual loss of catch-bench capacity increased the geotechnical risk. Inadequate blast control combined with unfavourable structural conditions and extreme rainfall produced conditions conducive to failure. The analysis provided vital insights into the underlying causes and triggers of slope failure and showed that future slope management techniques can be improved.

5 ANALYSIS AND FINDINGS

5.1 Introduction

In this chapter, a technical analysis is presented, integrating visual inspections, historical FoGs and data from the GeoMoS and InSAR instruments. The Klipbankfontein pit was built over several mining phases. Phase 1 included the first pushback of the pit to the east. This step-by-step plan was made to optimise ore extraction while keeping slopes stable. In Phase 1, the slope failed in the third quarter of 2022, mainly on the eastern highwall, where the haematite/BIF and gabbro contact was visible. This failure location and its timing are especially important, as other phases were set to start later that same year. Understanding the mechanisms and factors that led to the failure of Phase 1 was necessary for redesigning later mining phases to avoid similar problems.

5.2 Time-to-Failure and Failure Mechanism

The time-to-failure data from Klipbankfontein represents a combination of different types of failures, rather than a single failure mechanism. These include both single-bench failures and more complex slope instabilities. As such, the average time of 11.7 hours reflects a blended metric across these varying failure types. It is important to acknowledge that different failure mechanisms can exhibit significantly different time-to-failure behaviours. Further categorisation of the dataset by failure type would enhance the accuracy of future analyses and support the development of more targeted geotechnical monitoring and response strategies.

The current FoG took more than 72 hours from the start of an increased velocity, as shown by the radar, until the initiation of visibly unstable conditions (Figure 5.1). The highest evacuation time record is under 20 minutes, which indicates that safe evacuation was never compromised. The failure surface shown in Figure 4.8 suggests a complex planar failure mechanism as it involves more than one plane. The contact along which the failure occurred bends towards the bottom of the slope. The failure surface is not purely planar; it transitions between fault planes and the BIF–gabbro contact.

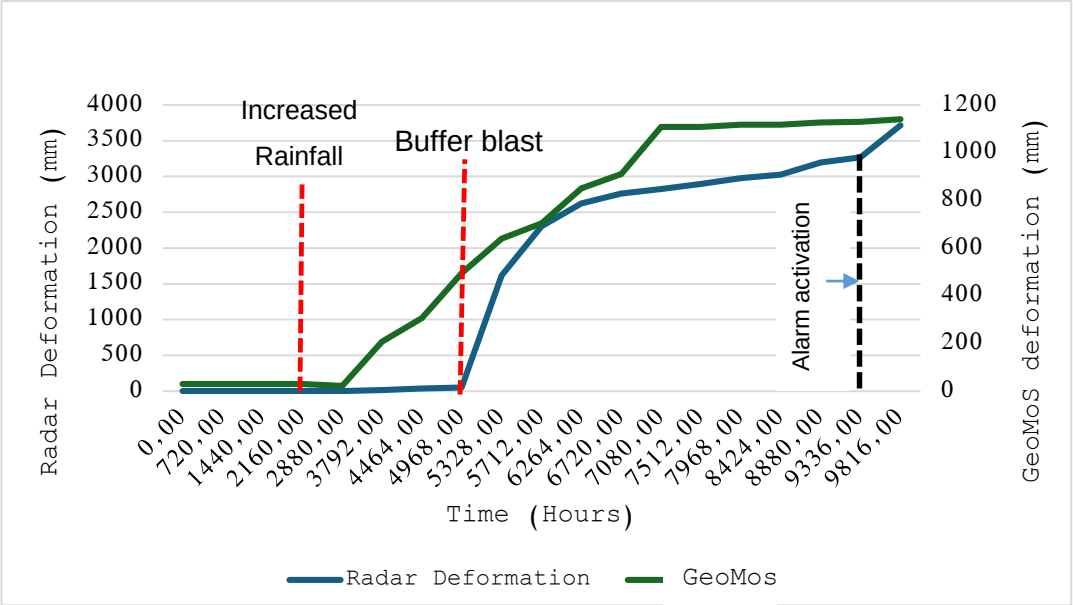


Figure 5.1. Radar vs GeoMoS deformation

5.3 Trigger Factor

Rainfall data indicates that the instability occurred following a period of high precipitation (Figure 5.1), suggesting that rainfall may have contributed to the event. However, geological factors also appear to play a significant role. According to Timchenko and Briaud (2023), rainfall-induced events account for approximately 40% of slope failure triggers globally (Figure 5.2). A comparison between the Klipbankfontein database and the TAMU database (Timchenko & Briaud, 2023) shows that at Klipbankfontein, the leading triggers are unknown geology and precipitation, while in the TAMU database, precipitation and daylighting structures dominate. The presence of geological triggers alongside precipitation in both datasets highlights the complex interplay of factors influencing slope stability in open-pit mining.

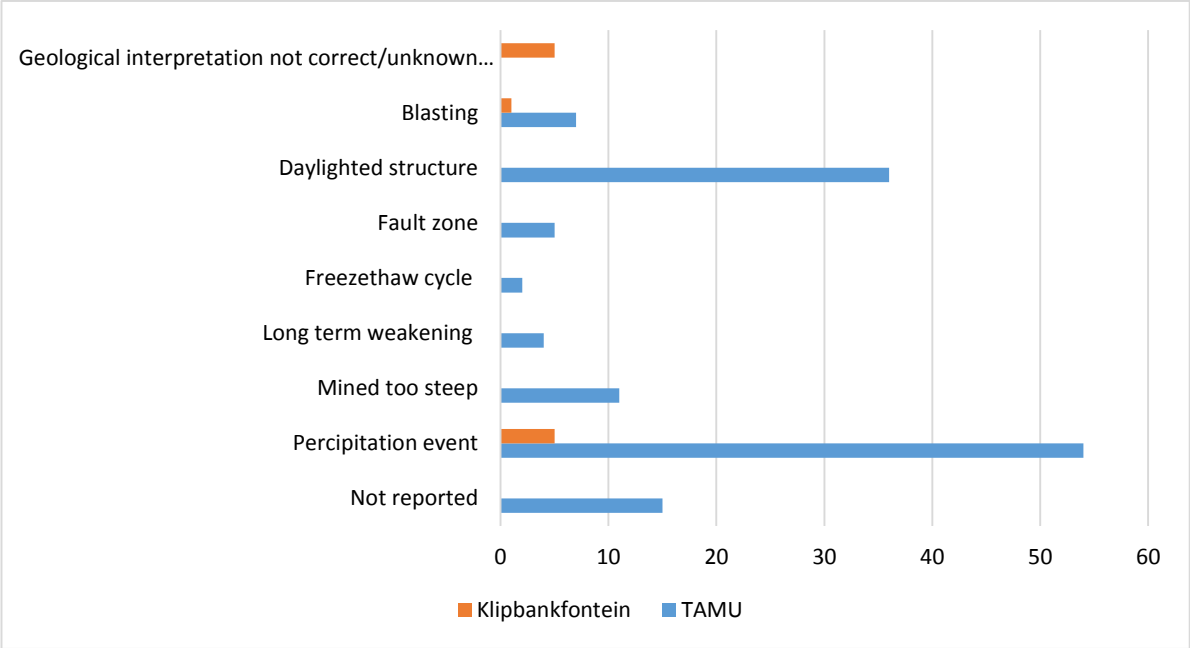


Figure 5.2. Reported triggering events from the TAMU-MineSlope database (Timchenko & Briaud, 2023)

As discussed in Chapter 4.7, heavy rainfall began around mid-March and peaked in April, as shown in Figure 5.3 (an expanded version of Figure 5.3 is provided in Appendix E). Although rainfall decreased in June, slope movements became evident around 16 June, with deformation rates exceeding 50 mm/day—a marked departure from previous trends. Figure 5.3 shows a clear temporal correlation between rainfall spikes and the onset of deformation. A detailed historical rainfall record (2011–2022) is provided in Appendix C. The abnormal rainfall likely elevated water pore pressures along the critical haematite/BIF and gabbro contact, contributing to slope instability.

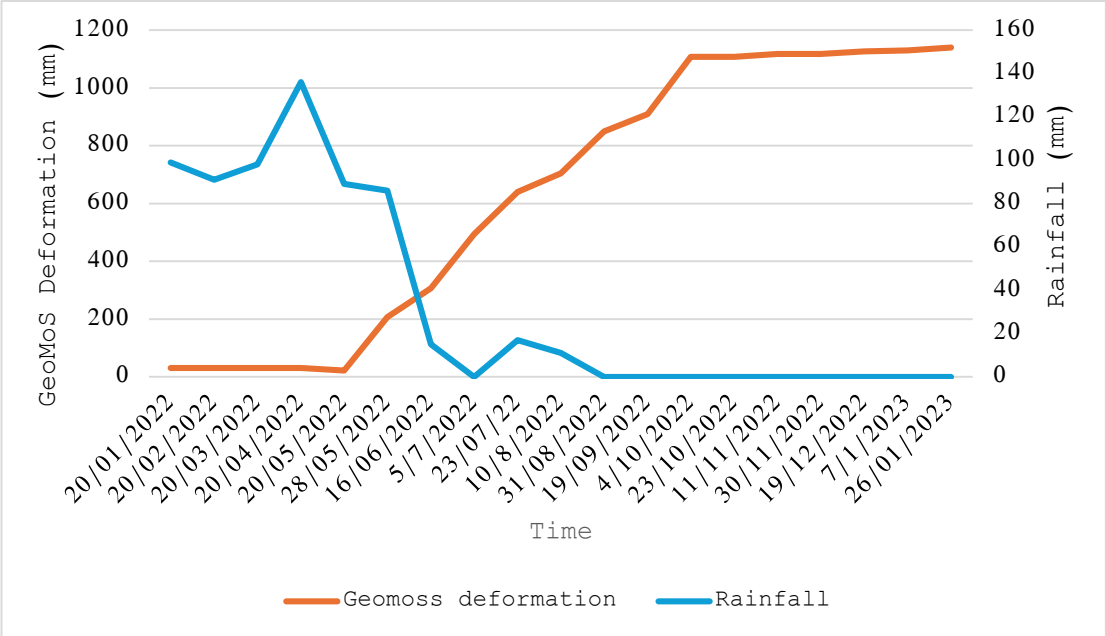


Figure 5.3. Rainfall vs GeoMos (longitudinal) deformation

5.4 Slope Stability Analysis

An important element in any stability analysis at Kolomela Mine is the anisotropic behaviour of some of the lithologies (BIF and Shale). To simulate this behaviour, the discrete fracture network and synthetic rock mass approach were applied. Another important element in stability analyses is the potentially weak lithological contact between BIF (or haematite) and gabbro materials.

Table 2.2 illustrates the slope stability analysis results. Based on this information and the geotechnical risk assessment (note that the slope in question does not carry a ramp, so a higher risk was deemed acceptable), the operational controls in effect were deemed adequate to manage potential instability. These controls included surface and groundwater management, an effective slope monitoring strategy, limited blasting and various operational controls.

5.5 Contributing Elements

The Klipbankfontein pit was supposed to be developed in several stages. The first stage was supposed to focus on the eastern part, which is where the failure took

place. A study of events that led to the failure showed high rainfall between January and June 2022 (Figure 5.3). During this time of heavier rain, a significant volume of mining took place on the slope near the haematite/BIF and gabbro contact. Figure 5.4 shows the location of the failure.

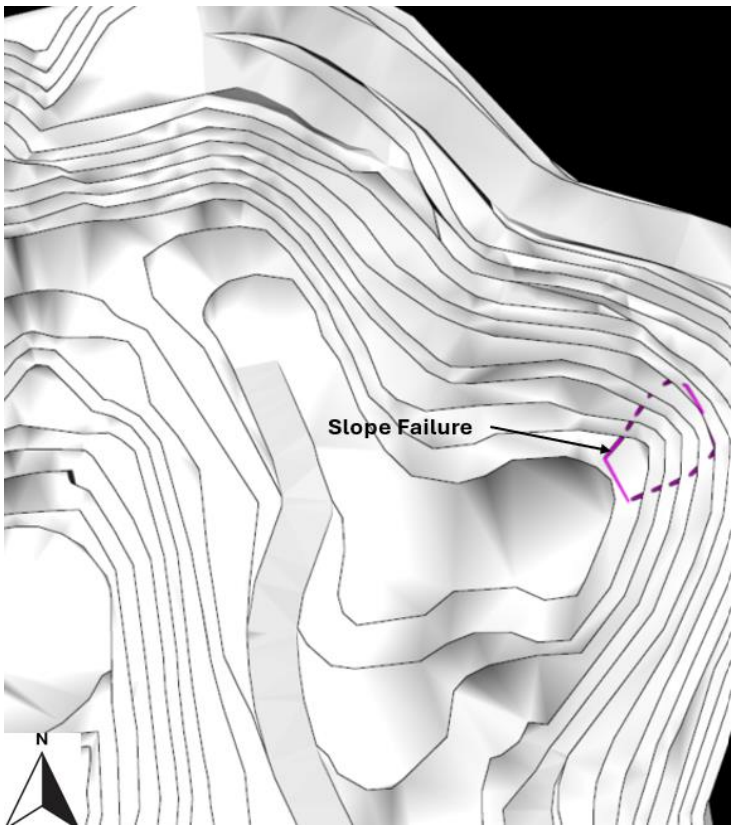


Figure 5.4. Plan view showing the position of the failure

High rainfall and the associated groundwater pressure along this geological contact, combined with the near-vertical fault systems crossing perpendicular to the plane, contributed to the fall of ground. Monitoring data shows that slope movements increase after heavy rains, especially where water could enter along the fault and contact surfaces (Figure 5.5).

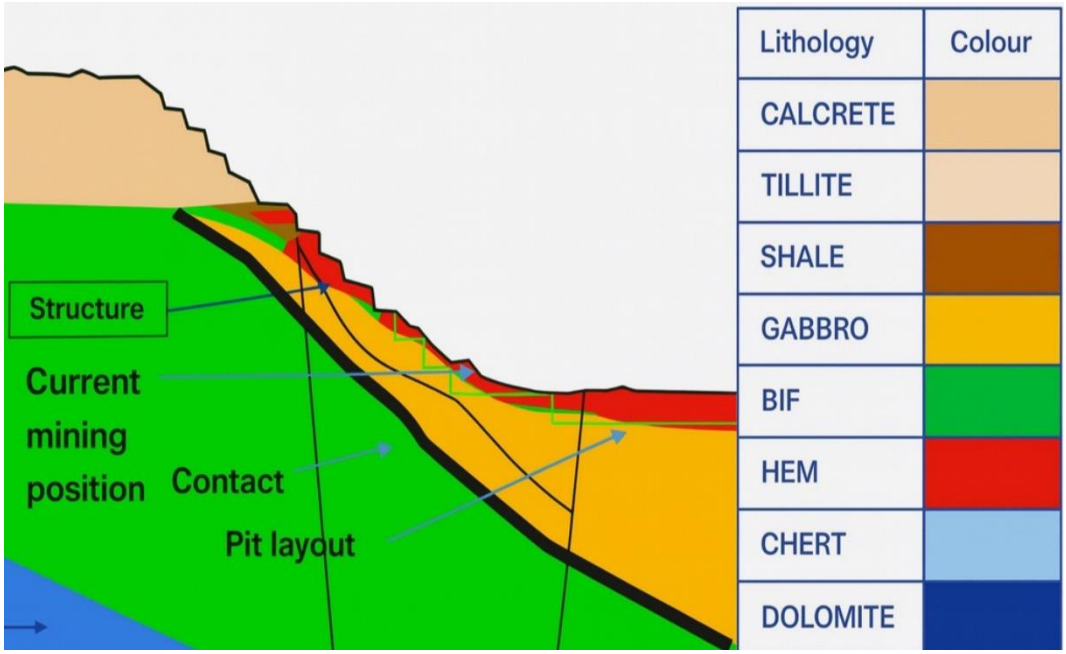


Figure 5.5. Section showing the BIF–gabbro contact

According to Morton et al. (2006), the Mohr-Coulomb equation is derived from the Coulomb-Terzaghi equation, which states:

$$\tau = (\sigma - \rho)tan\phi \qquad \textit{Equation 5.1}$$

Where: τ=shear strength; σ=stress normal to the plane; ρ=pore pressure; and Φ=friction angle.

Strength comes from the cohesion and the weight of the formations, and weakness comes from the pore water pressures and the internal angle of friction. A reduction in the effective stress (σ = σ–p) will reduce the shear strength of the rock mass. Therefore, due to the amount of rain, it is assumed that the pore pressure was increased. Consequently, the strength of the slope was decreased.

Records from site inspections show that flooding from stormwater occurred during three major rainstorms between 15 and 19 May 2022, resulting in standing water along the haematite/BIF contact. The gabbro in the failure zone had joints that were very closely spaced (about 0.3 m apart on average), and the rock mass rating was between 35 and 45 using the RMR rating system (Bieniawski 1989), which means

that the rock mass quality was poor to fair. This pattern of joints allowed for water percolation.

Several monitoring systems presented different information about how the slope was moving. From January to April 2022, InSAR data showed little deformation, while GeoMoS prism monitoring indicated an increased rate of 0.2 mm per day after the May rains (Figure 5.3). The failure mechanism showed a non-circular, structurally controlled failure. Sub-vertical faults provided lateral release surfaces. After the buffer blast on May 19, 2022, this movement increased, and radar tracking showed that the rates of displacement rose to over 2 mm/day.

The failure mechanism was a complex planar failure due to the sharp, concave failure surface and warning. According to Thikusho (2023), highwall strain criteria indicate that strain values above 1% could have abrupt failure. Relatively high strains are expected for toppling failures in a relatively deformable rock mass, whereas relatively low strains can be tolerated before a planar failure in a brittle rock mass becomes unstable. However, the amount of strain that can initiate failure in planar and wedge instability is relatively low compared to toppling failure.

Brox and Newcomen (2004) showed that the amount of movement within a highwall can be significantly influenced by the blasting practices at an open-pit mine. Figure 5.1 suggests that blasting had an impact on the integrity of the slope. This blasting is believed to have impacted the structures in the FoG area. At the time shown in Figure 5.1, the buffer block was being blasted at the toe of the slope. It appears that the ultimate triggers that initiated failure were the vibrations and removal of confinement at the slope toe.

5.6 Evaluation of the Effectiveness of the Slope TARP System

The TARP system should be judged by how well it works in terms of both its short-term safety measures and its longer-term stabilisation steps. To prevent a potentially larger slope failure, approximately 400,000 tonnes of ore was deliberately left in place to provide additional confinement to the slope. While this decision significantly impacted the mine's economic returns, effectively sterilising a substantial portion of valuable ore, it played a critical role in ensuring short-term safety. However, although leaving the ore behind was effective in the short term, it is not a substitute for proactive stability management.

On the positive side, stability analyses suggest that this action likely averted a more severe failure. This could have resulted in greater ore loss, infrastructure damage, or even safety risks to personnel. However, the downside lies in the conservative nature of the design. The original limit equilibrium analysis assumed dry mining conditions, which did not account for pore pressure effects. It is assumed that with proper drainage measures incorporated, a more efficient design could have achieved the same stability outcomes while leaving more ore recoverable. This highlights the importance of integrating both geotechnical and economic considerations in future slope management strategies.

The evacuation time at the onset of the failure was within the 13-minute evacuation time, albeit having to leave an excavator behind that was on breakdown at the time. This is also well below the minimum time to failure of 39 minutes for the fastest failure, according to Klipbankfontein historical data. These results show that the TARP system met its main safety goal.

Utilising unmined ore as confinement represents a reactive rather than proactive method for managing slope stability, although it can offer short-term effectiveness. While this approach may temporarily secure the unstable slope area, it does not tackle the fundamental reasons behind the slope instability, nor does it mitigate the risk of similar occurrences in the future. Additionally, dependence solely on retaining ore for confinement purposes may not guarantee adequate stability in the long term and could potentially trigger additional instability or future slope failures. Thus, enhancing the effectiveness of the TARP system requires proactive interventions, including comprehensive instrumentation to monitor pore water

pressures, blast-induced vibrations and optimal drilling patterns. Furthermore, incorporating consistent monitoring practices, detailed geotechnical evaluations and timely engineering solutions could proactively address slope stability concerns, preventing escalation.

A multifaceted approach based on the lessons learnt from the Klipbankfontein Phase 1 failure is needed to prevent future structurally controlled failures. Improving structural mapping and keeping the 3D geological model up to date in real time should be the first step in primary prevention. This should focus on finding and describing important contacts such as the haematite/BIF and gabbro interface. Setting up a regular joint orientation survey programme and updating structural models regularly would assist in finding potentially dangerous structural interactions at an early stage. Multiple data streams and automated analysis systems should be built into a new monitoring strategy. This could include using InSAR to continually check for large-scale deformation patterns. High-precision prism monitoring on a grid of 25 m horizontally and 5 m vertically spaced points in key areas. Placing multiple radar units to cover important structural features in overlapping ways is also recommended. Rain data should be correlated in real time with piezometer readings and measurements of displacement. The monitoring system should have automated alarms that go off at certain speeds and accelerations for structurally controlled failures, which tend to accelerate quicker than circular failures.

Operational controls need to be improved, especially when it comes to monitoring blasts and managing water. Precision presplit blasting with smaller hole spacing in areas with weak rock mass conditions, along with strict adherence to charge weight specifications, would help to maintain the integrity of the bench. A full drainage system with horizontal drains at important geological points and better surface water management is required. Right-sized sumps and pumping power would reduce the pore pressure conditions in planned levels. These steps should be backed up by regular checks using a piezometer and making any necessary changes to the drainage systems.

5.7 Chapter Summary

This research report combined structural mapping data, monitoring results and operational records to ascertain how the Klipbankfontein Phase 1 failure occurred. A close study of the haematite/BIF and gabbro contact showed that its orientation with the associated faults made it a high-risk area. The introduction of water pressure was not considered in the original planning.

The failure sequence began with heavy rain and blasting in the buffer zone in May 2022. These influences were clearly shown by the correlation of rainfall, blasting damage and displacement measurements. The tracking information showed a typical pattern of acceleration, with movement rates going from 0.2 mm/day to over 2 mm/day after the May 19 buffer blast.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This research investigated critical aspects related to the slope failure that occurred at Klipbankfontein Phase 1. Specifically, it examined factors contributing to the failure, assessed how effectively the slope stability TARP functioned, and evaluated insights gained from limit equilibrium analyses to identify probable causes of instability. The study also considered viable mining methods for dealing with challenging geological conditions and highlighted important lessons aimed at preventing similar incidents. Ultimately, the report sought to deliver an in-depth understanding of the failure, providing practical recommendations for improved slope stability management and risk mitigation in comparable situations.

6.2 Summary of Chapters

This report has presented six chapters that cover the following:

- The introduction chapter provided contextual background information on the site and offered a comprehensive overview of the history leading up to the slope failure.

- Chapter 2 offered a comprehensive review of the literature on slope stability, supplemented by case studies detailing similar failures observed in other mining operations.

- Chapter 3 described the data collection process and discussed the methods for subsequent analysis.

- Chapter 4 provided a comprehensive overview of the gathered information.

- Chapter 5 described the analysis of the data and the research findings.

- Chapter 6 provides the conclusions and recommendations.

6.3 Research Observations

6.3.1 Initial and complementary studies

The questions that this research aimed to answer were as follows:

- What were the contributing elements to the Klipbankfontein Phase 1 failure?
- Was the slope stability TARP programme effective?
- What results were provided by the linear equilibrium modelling of the area in question?
- How could the unfavourable area have been mined successfully?
- What can be learned from the incident to prevent similar occurrences?

6.3.2 Key findings and observations

Root Causes of the Slope Failure

The investigation revealed that the slope failure at Klipbankfontein Phase 1 was primarily structurally controlled, occurring along the haematite/BIF and gabbro contact, with lateral release facilitated by intersecting fault systems. The following factors were identified as key contributors:

- Unprecedented rainfall in Q2 2022 raised pore pressures along critical geological contacts.
- Blasting activities, particularly the buffer blast at the slope toe, likely triggered movement by removing confinement.
- Poor bench geometry and drainage, exacerbated by blast damage and water ponding, reduced catchment capacity.
- Closely spaced joints in gabbro, with low RMR values (35–45), allowed water infiltration and reduced rock mass strength.

Systematic Hazard Identification

Hazard identification was conducted through:

- Face mapping using Maptek I-Site Studio to characterise fault orientations and discontinuities.
- Kinematic analysis to rule out planar, wedge and toppling failures, confirming a complex planar mechanism.
- Limit equilibrium analysis using Slide2 software, which showed acceptable FoS under dry conditions but underestimated risk under wet conditions.
- Monitoring data from GeoMoS, radar and InSAR, which detected progressive deformation trends.

Trigger Action Response Plan (TARP)

The TARP system was evaluated and found to be effective in ensuring personnel safety:

- Evacuation occurred within 13 minutes, well below the minimum time-to-failure threshold.
- The system integrated radar alarms, GeoMoS prism data and routine inspections.
- However, the reliance on leaving ore in place for confinement was reactive and economically costly.

Measures to Reduce Future Risk

The study recommends the following proactive strategies:

- Install piezometers along critical geological contacts to monitor pore pressure.
- Improve drainage systems with horizontal drains and adequate sump capacity.
- Enhance blast control using structure-specific designs and near-field vibration monitoring.
- Update 3D geological models in real time and conduct regular joint orientation surveys.

- Automate data correlation between rainfall, pore pressure and deformation to improve early warning triggers.

6.3.3 Results from the linear equilibrium analysis

The limit equilibrium analysis showed that under dry conditions, the BIF–gabbro contact had an FoS of 1.95 with a PoF of less than 5%. The sudden increase in rainfall was unexpected, and the pumping and water-level equipment were unable to cope with the increased water. What was shown to be stable through limit equilibrium analysis (Table 4.2), using historical information, became unstable due to the increased head of water. Blasting of the buffer block appears to have influenced the instability; however, there was not enough data to quantify this impact. It is recommended that operational controls, such as near-field vibration monitoring, be used to quantify the amount of damage to the wall. Such monitoring would be especially useful in highly structured areas.

6.3.4 Hindsight strategy for mitigating the risk of failure

Near-field variation monitoring and other blasting monitoring techniques could have allowed for better quantification of the impact of blasting on the highwall. Piezometers should have been installed along the contact to better quantify the pore pressure. Finally, the limit equilibrium analysis carried out during planning should have included the sensitivity to water.

6.4 Research Contributions

This research enhances slope stability analysis by identifying practical strategies to mitigate slope failure risk. The report, via comprehensive investigation and analysis, identified the variables contributing to slope instability and proposed solutions that may have been implemented to avert the disaster. These findings provide essential insights for engineers, geologists and others engaged in slope management. This research has enhanced slope monitoring procedures in open-pit mines by providing comprehensive instructions and essential insights. These guidelines and insights were established to standardise monitoring protocols, promote uniformity in data collection and analysis, and advocate for the integration of advanced technology and methodology in slope monitoring.

6.5 Research Limitations

One limitation of this research relates to the scarcity of published failure information from other mining operations. In addition, the effects of blasting on stability require further research.

6.6 Recommendations for Future Research Work

Based on the findings of this study, the following recommendations are suggested:

- While it is commendable that the failure at Klipbankfontein Phase 1 did not result in loss of life, there is always room for improvement to ensure that the execution of TARP in the future assists in mitigating all forms of risks, including safety.

- The decision to leave ore behind was a passive geotechnical support that highlights the critical balance between resource recovery and slope stability in open-pit mining. It reflects an adaptive management approach grounded in real-time data and geotechnical best practices.

- The current stormwater management plan needs to be reviewed to ensure that there are adequate sumps and pumps to avoid water ponding over structurally complex areas.

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APPENDICES

Appendix A: Drone Images and Face Mapping Scans



Figure A1: Drone footage of the FoG

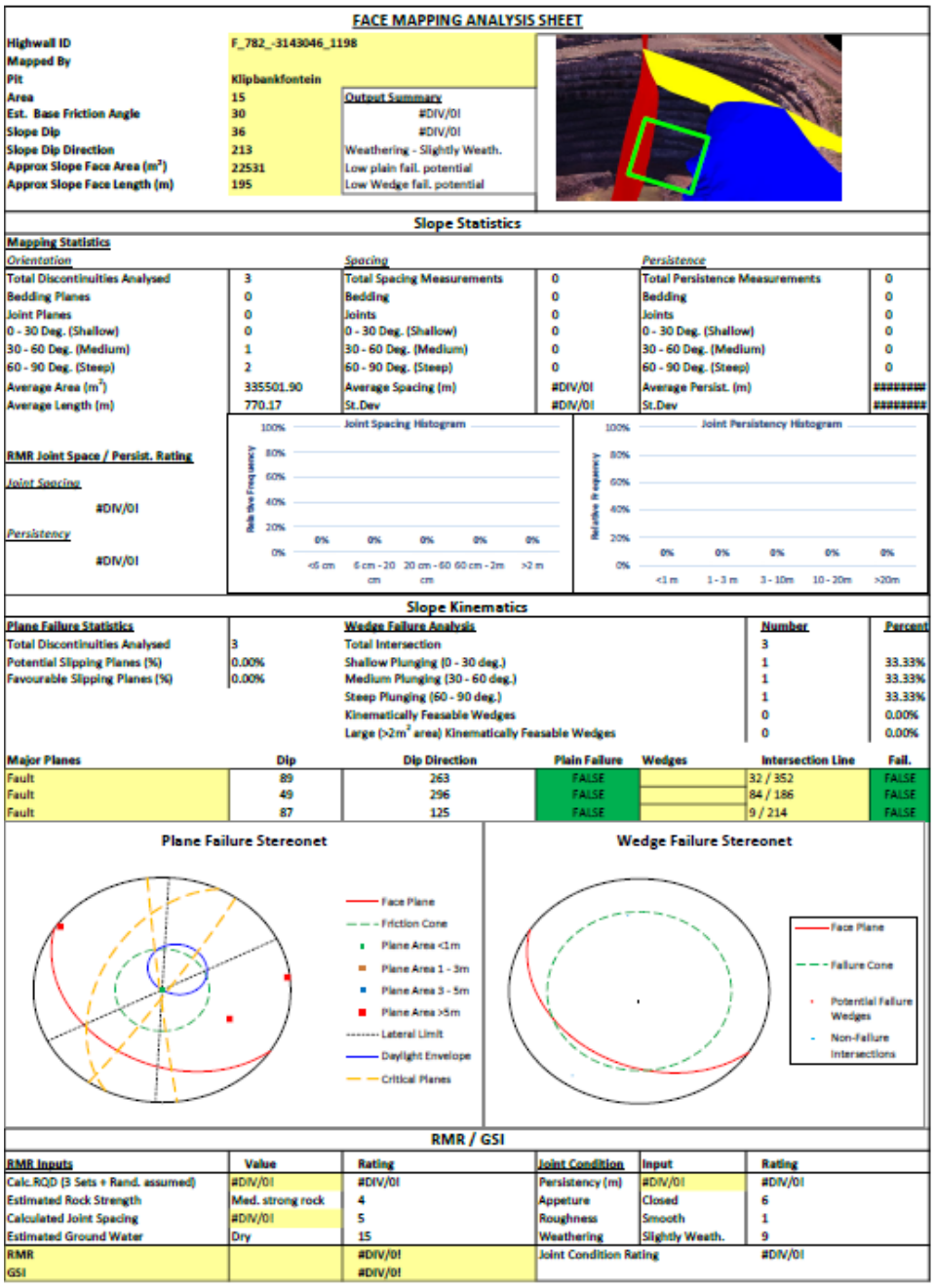


Figure A2: Face mapping analysis sheet

APPENDIX B: Slope Failure Data

Table B1: Radar deformation measurements

Date	Radar deformation (mm)
20/01/2022	0.677
20/02/2022	0.677
20/03/2022	0.677
20/04/2022	0.677
20/05/2022	2.985
28/05/2022	17.677
16/06/2022	38.086
05/07/2022	53.06
23/07/2022	1619.24
10/08/2022	2304.62
31/08/2022	2625.72
19/09/2022	2763.432
04/10/2022	2826.209
23/10/2022	2898.949
11/11/2022	2978.876
30/11/2022	3027
19/12/2022	3195.86
07/01/2023	3269.076
26/01/2023	3715.5

Table B2: GeoMoS deformation data

Date	GeoMoS (mm)
20/04/2022	160
09/05/2022	216
28/05/2022	207
16/06/2022	307
05/07/2022	494
23/07/2022	640
10/08/2022	704
31/08/2022	850
19/09/2022	910
04/10/2022	1108
23/10/2022	1108
11/11/2022	1118
30/11/2022	1118
19/12/2022	1127
07/01/2023	1130
26/01/2023	1140

APPENDIX C: Rainfall Data

Table C1: Monthly rainfall

Date	Rainfall (mm)
20/01/2022	99
20/02/2022	91
20/03/2022	98
20/04/2022	136
20/05/2022	89
28/05/2022	86
16/06/2022	15
05/07/2022	0
23/07/2022	17
10/08/2022	11
31/08/2022	0
19/09/2022	0
04/10/2022	0
23/10/2022	0
11/11/2022	0
30/11/2022	0
19/12/2022	0
07/01/2023	0
26/01/2023	0

APPENDIX D: TARP

RADAR MONITORING TRIGGER ACTION RESPONSE PLAN (TARP 2 – NIGHTSHIFT AND WEEKENDS) – KOLOMELA MINE During weekdays between 18:00 and 06:00				
	LEVEL 1: LOW RISK	**LEVEL 2: GREY ALARM/MEDIUM RISK**	**LEVEL 2: ORANGE ALARM/HIGH RISK**	**LEVEL 3: RED ALARM/EXTREME RISK**
TRIGGER				
	No triggered alarm	Grey alarm triggered	Orange alarm triggered	Red alarm triggered
ACTION				
Critical Control Monitoring Officer (CCMO)		Contact the GroundProbe Support Services (GSS) and notify them of the triggered grey alarm.	Contact the Geotechnical Support Services (GSS) and notify them of the triggered orange alarm	Contact the Geotechnical Support Services (GSS) and notify them of the triggered orange alarm
Geotechnical Support Services (GSS)		Contact the Geotechnical Technician on duty and notify them of the triggered grey alarm.	Validate the orange alarm **If the orange alarm is invalid:** Send out an email to the Geotechnical Engineering personnel notifying them of the invalid orange alarm triggered. **If the orange alarm is valid:** Contact the Geotechnical Engineering standby personnel to notify them of the valid orange alarm and send out an email to the Geotechnical Engineering personnel notifying them of the valid orange alarm triggered.	Validate red alarm **If the red alarm is invalid:** Send out an email to the Geotechnical Engineering personnel notifying them of the invalid orange alarm triggered. **If the red alarm is valid:** Contact the Geotechnical Engineering standby personnel to notify them of the valid orange alarm and send out an email to the Geotechnical Engineering personnel notifying them of the valid orange alarm triggered.
GroundProbe Technician on duty (2.9.2)		Determine if the grey alarm can be cleared remotely **If the grey alarm can be cleared remotely:** Reset and continue to monitor **If the grey alarm cannot be cleared remotely:** Determine if the grey alarm is due to 1- Network issue due to ScanRF or 2- Failure to connect to virtual servers. - If the grey alarm is due to ScanRF: Contact the Scan RF Technician on duty and notify them of the triggered grey alarm - If the grey alarm is due to failure to connect to virtual servers: Log a call via email to OT Service Desk. Once the root cause is determined, contact the Geotechnical Engineering personnel on standby and notify them of the triggered grey alarm and the root cause.		

	LEVEL 1: LOW RISK	LEVEL 2: GREY ALARM/MEDIUM RISK	LEVEL 2: ORANGE ALARM/HIGH RISK	LEVEL 3: RED ALARM/EXTREME RISK
	No triggered alarm	**Grey alarm triggered**	**Orange alarm triggered**	**Red alarm triggered**
Geotechnical Engineering personnel on standby		Refer to the Geotechnical Risk Plan for the affected pit. Allow mining operations within the 'Green Zone' of the Geotechnical Risk Plan to continue. Assess the level of the geotechnical risk in 'Amber Zone' based on: 1. Review available radar data 2. Recent geotechnical update 3. Operational controls (e.g., stand-off rule, safety berms and other mitigation measures) Allow mining operations in 'Yellow Zone' to continue if the geotechnical risk is managed. Evacuate mining operations in 'Yellow Zone' if personnel and assets are exposed and make safe prior to allowing resumption of mining operations. Ensure evacuation and access control in 'Red Zone'.	**Determine if the deformation is progressive or failure is imminent:** - If no: Continue critical monitoring for stabilisation or red alarm (progressive). - If yes: Activate the emergency evacuation process. Also, contact the Geotechnical representative the Section Manager Geotechnical and Hydrogeology (14.1(8)) to escalate.	**Determine if the deformation is progressive or failure is imminent:** - If no: Continue critical monitoring with reviewed threshold alarms. - If yes: Contact the CCMO and activate the emergency evacuation process. Also, contact the Geotechnical representative and the Section Manager Geotechnical and Hydrogeology (14.1(8)) to escalate.
Shift Supervisor (2.15.1)		Consult the Geotechnical Risk Plan. Allow work to take place in the 'Green Zone'. Consult geotechnical personnel on standby (083 764 8781) regarding continuation of mining operations in 'Yellow Zone' and maintain evacuation and access control in 'Red Zone'.	**Assist in the emergency pit evacuation process if deformation is progressive or failure is imminent:** - Manage traffic during evacuation. - Ensure work in the restricted areas is stopped and the areas are barricaded until further instruction from the Geotechnical Engineering personnel.	**Assist in the emergency pit evacuation process:** - Manage traffic during evacuation. - Ensure work in the restricted areas is stopped and the areas are barricaded until further instruction from the Geotechnical Engineering personnel.

APPENDIX E: Expanded Rainfall Data

