Advancing geotechnical risk management in mining with spatially- enabled and process-driven information systems

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Most large open pit mines currently employ risk management concepts which are aimed at the anticipation of slope instability, provided that the risk of expected events is tolerable, adheres to industry and company geotechnical standards, as well as being controllable. In order to facilitate this outcome in an increasingly complex mining environment, geotechnical engineering aspects including slope design (stability analysis and geotechnical risk assessment), waste dump risk management, mine to design compliance and blasting performance, slope performance (bench, stack and overall), mine dewatering/depressurisation and slope monitoring need to be managed effectively. Therefore, the accurate measurement/verification and detailed analysis of the correct parameters and safety controls are essential. Information management systems play a key role in supporting decision-making in the geotechnical risk management process through the conversion of data into information, empowering specialists with knowledge to make informed decisions. The successful implementation of information management systems in Anglo American are discussed, focussing on processes, people, and technology. The integration of various data sources, geotechnical analysis and outputs on an information management system is critical to actively manage fall of ground hazards as they materialise in a dynamic rock mass and mining environment. The collaboration between geotechnical engineering, systems engineering and various other mining disciplines is key to facilitate the integration of technology and process-driven information management strategies. Ultimately it sets a robust foundation for sustainable and effective geotechnical risk management.

INTRODUCTION

Background

Most large open pit mines employ the concept of 'slope management,' which focuses on anticipating slope instability and ensuring that the associated risks are justifiable, controllable, and aligned with industry and company standards. Effective slope management requires the careful coordination of various operational geotechnical engineering aspects, including controlled limit blasting, mine dewatering and/or depressurisation, mine to design performance, slope performance verification at the bench, stack, and overall scale, as well as critical slope monitoring and fall of ground (FOG) hazard management to ensure safety of personnel.

Problem Statement

In increasingly complex mining environments, effective geotechnical risk management is critical to prevent uncontrolled slope instability and ensure operational safety. Current practices often struggle to integrate diverse data sources and analyses efficiently, making it difficult to manage dynamic geotechnical hazards in real-time. There is therefore a need for process-driven, spatially-enabled information systems to enhance decision-making and improve the proactive management of geotechnical risks.

Objective
This paper aims to demonstrate how process-driven and spatially-enabled information systems can enhance geotechnical risk management in the modern mining world.

GEOTECHNICAL RISK MANAGEMENT IN MINING

Risk Management Principles

The principles of safety process risk management are crucial for ensuring safe and sustainable operations in industries dealing with hazardous processes. The Centre for Chemical Process Safety (CCPS), in its widely recognised publication Guidelines for Risk-Based Process Safety (2007), provides a foundational framework for managing process safety risks. This comprehensive guide details the principles and practices necessary for organisations to effectively anticipate, manage, and mitigate process safety risks. The risk-based approach outlined by CCPS has been adopted across various industries, offering a structured methodology for maintaining safe operations.

Another key reference in the development of process safety management principles is the American Petroleum Institute's Recommended Practice 750: Management of Process Hazards (1990). This document lays the groundwork for managing process safety hazards, particularly within the oil and gas industry, and has influenced the development of subsequent safety management systems. Together, these references have become central to the understanding and implementation of process safety risk management and are extensively cited in both academic and industrial literature.

Elimination of Uncontrolled Falls of Ground

In the mining industry, particularly in geotechnical engineering, the principles of safety process risk management can be applied to ensure stable, safe, and sustainable operations in highly complex, dynamic and potentially hazardous environments. Drawing on methodologies from process safety frameworks discussed in the previous section, a structured approach to identifying, assessing, and mitigating geotechnical risks has been developed. Originally designed for the chemical and oil industries, these principles have been adapted to address the unique challenges of mining operations, particularly in relation to slope stability, ground control, and the prevention of uncontrolled FOG incidents. By applying a risk-based approach, the goal is not only to enhance operational safety but also to improve long-term financial sustainability and environmental responsibility.

The Risk-Based Safety Management System is built on four key pillars that provide a structured framework for maintaining safety and operational excellence in hazardous environments. These pillars are designed to help the organisation to anticipate, manage, and mitigate risks effectively, ensuring long-term stability, safety, and sustainability (refer to Figure 1).

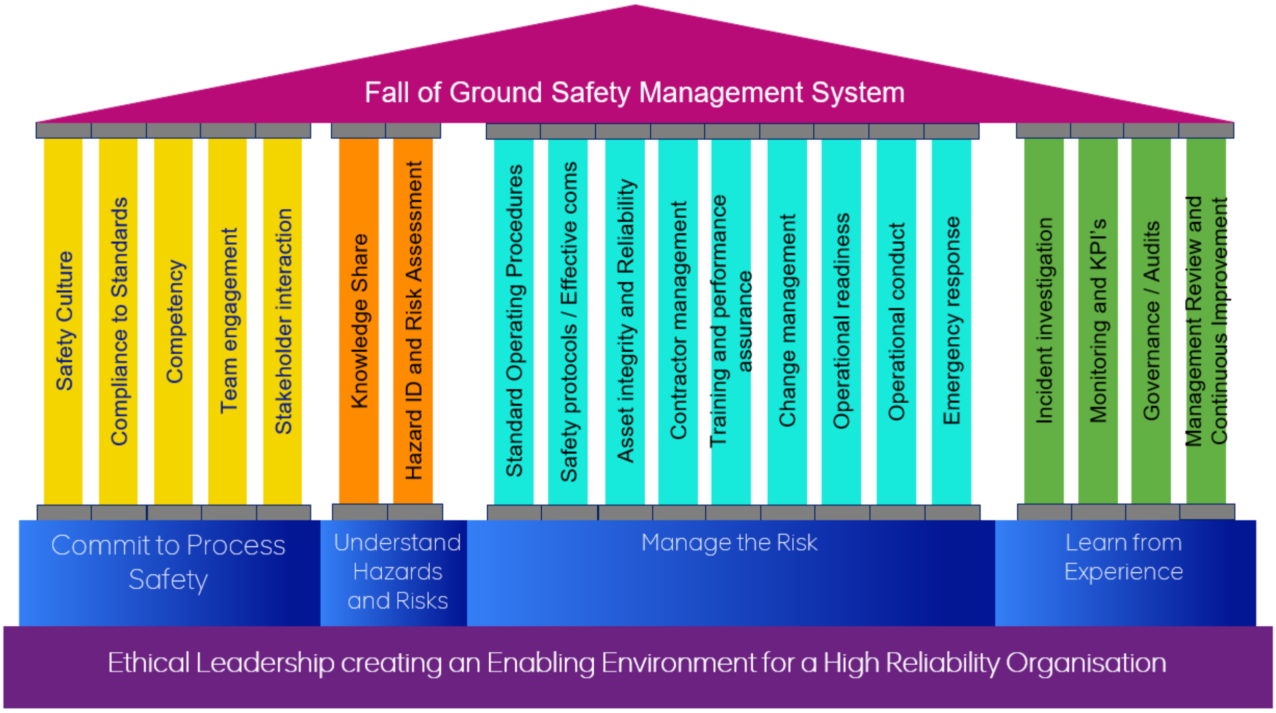


Figure 1. Adaptation of the risk-based process safety framework for fall-of-ground safety management in mining. (Modified after CCPS Guidelines for Risk Based Process Safety, 2007.)

Commitment to Safety
The cornerstone of process safety is an unwavering commitment to safety as a core organisational value in the company. The workforce is convinced the organisation fully supports safety as a core value and will tend to do the right things, in the right ways, at the right times — even when no one else is looking.

Anglo American has established a comprehensive but concise Geotechnical Standard for Mining applicable to both surface and underground operations. This standard defines the minimum requirements necessary to eliminate uncontrolled FOGs and reduces the risk of FOG incidents and fatalities. It is underpinned by a parent bowtie risk assessment which outlines the minimum mandatory critical controls that must be implemented across all Anglo American mining operations to ensure consistent adherence to safety protocols.

Understand Hazards and Risk
A deep understanding of hazards and risks forms the foundation of a risk-based approach. In the mining geotechnical engineering context, this includes detailed assessment of potential FOG risk. By accurately identifying all ground-related hazards and quantifying these risks, mining operations can allocate resources effectively to implement adequate and effective controls, such as real-time monitoring systems for early detection of slope failures or designing appropriate ground control measures to mitigate risks.

Manage the Risk
Effective risk management requires continuous effort to control and mitigate identified risks, if it is not possible to eliminate the hazard. This includes maintaining ground control processes within defined risk tolerances, regularly updating procedures in response to changes in rock mass or mining conditions and being prepared to manage incidents when they occur. By leveraging a thorough understanding of risks, operations can better handle the resultant hazards and, in turn, sustain long-term, accident-free, and profitable operations.

Learn from Experience
The fourth pillar of the risk management system focuses on learning from experience, with a commitment to continuously improve by analysing past FOG incidents to enhance future safety performance. To facilitate this, a spatially-enabled database that captures comprehensive geotechnical data for each incident was developed. This system is further supported by a decision tree, aligned with the company FOG reporting framework, which classifies incidents based on criteria such as controlled, uncontrolled, significance, and reportability. This classification enables trend analysis to identify where controls may have failed. Notably, even if a preventative control fails, an incident can still be averted by mitigation controls—such as slope radar monitoring—which can remove personnel from hazardous areas in time. However, if any control fails, an internal investigation must be conducted to identify and close out any gaps.

Together, these pillars form a comprehensive and effective approach for not only safeguarding people and assets, but also enable maximum value from the operation.

INFORMATION MANAGEMENT SYSTEMS IN GEOTECHNICAL RISK MANAGEMENT

Role of information Management Systems
The accurate measurement and detailed analysis of the correct geotechnical and operational parameters are essential. Information management systems play a key role in supporting decision-making in the slope management process through the conversion of data into information, empowering specialists with knowledge to make informed decisions.

Data collection and integration
It is important that various data sources – for example geological, structural, rock mass and hydrogeological data, geotechnical analyses and risk assessment information, mine planning information, operational performance data and slope performance monitoring data – be integrated on an information management system to actively manage geotechnical hazards as they materialise in a dynamic rock mass and mining environment. The collaboration between geotechnical engineering, processes/systems engineering and various other mining disciplines; including new technologies and methodologies, is key to manage geotechnical risk effectively.

Transforming Data into Knowledge for Effective Communication
In the context of FOG risk management, effective communication is paramount. Clear, timely and accurate information sharing ensures that everyone involved—whether on-site or in support roles—understands the hazards, mitigation strategies, and safety protocols. This reduces the likelihood of accidents by promoting awareness and adherence to safety measures and controls, such as respecting 'No-Go Zones' and responding appropriately to changing hazard conditions. Without effective communication, even the best-designed safety systems can fail to protect workers, equipment, and operations. It is a critical element that bridges technical solutions with real-world application.

PEOPLE, PROCESSES, AND TECHNOLOGY: A COLLABORATIVE APPROACH

The Role of Geotechnical Engineering Teams
In the 1980s, the concept of high reliability organisations (HROs) was pioneered by researchers such as Karl E. Weick, Kathleen M. Sutcliffe, and David D. Woods. Their work focused on organisations that operate in complex, high-risk environments—such as nuclear power plants and air traffic control—yet manage to maintain remarkably low failure rates. The principles they developed emphasise the importance of organisational resilience, attention to failure, and a commitment to reliability, making them widely applicable across various sectors, including geotechnical engineering (Weick & Sutcliffe, 2001).

The framework of HROs in a geotechnical engineering context emphasises several key principles to ensure effective teamwork to achieve safety and reliability (Figure 2).

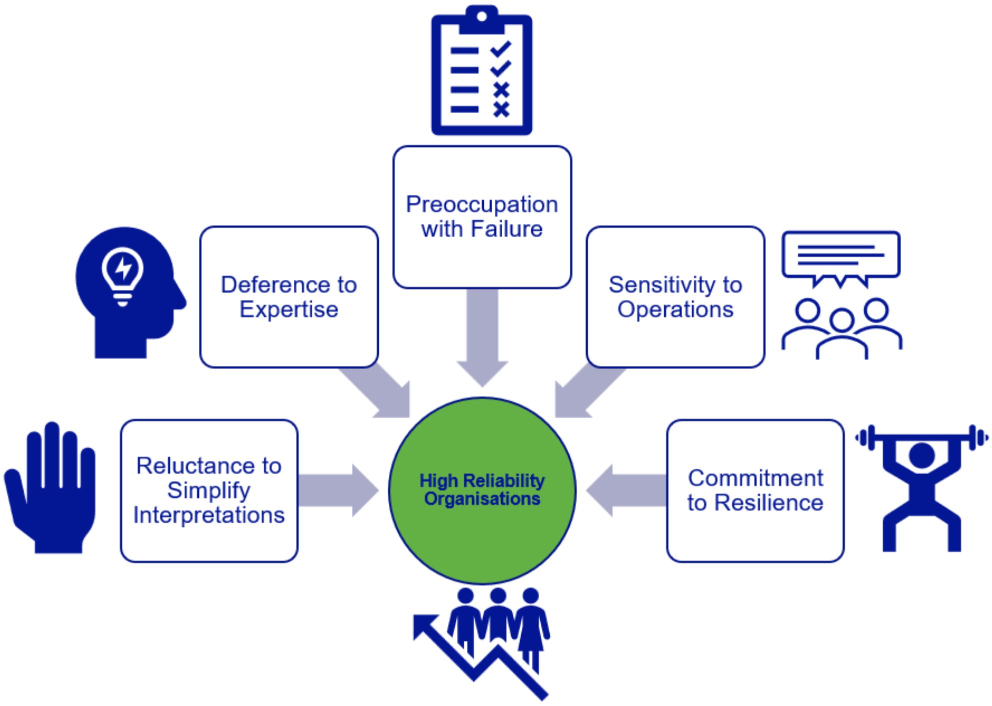


Figure 2. The five key principles of high reliability organisations (after Weick & Sutcliffe, 2001).

- **Preoccupation with Failure**
  The team maintains a mindset of chronic unease, constantly thinking about what could go wrong. Every new bench or exposed development is carefully mapped and assessed to verify that the design remains valid, for all four aspects of the geotechnical model on which the design is based. Critical controls are continuously monitored to ensure their effectiveness, and geotechnical engineers embrace the idea that 'all models are wrong, some are just more useful,' highlighting the importance of constant vigilance.

- **Deference to Expertise**
  Decisions are deferred to individuals with the most relevant experience and expertise, particularly those who are closest to the problem. Frontline personnel are actively engaged, and their inputs are sought to inform decisions. Hierarchies do not interfere with trusting the expertise of those who know the rock mass and operations best.

- **Sensitivity to Operations**
  Awareness of the specific challenges at a particular operation is essential to recognising and addressing anomalies and/or deviations. The team fosters a genuine interest in understanding the unique context of each operation in terms of setting, size, complexity, and culture. Actively engaging operational teams helps mitigate potential constraints that could affect the accurate execution of geotechnical designs.

- **Reluctance to Simplify Interpretations**
  While simplicity has its elegance, the team avoids oversimplifying models and designs. Critical parameters and the variability inherent in them are carefully considered to justify engineering judgements. The illusion of control (wanting to believe we are in control) is scrutinised, acknowledging that uncertainty is a constant factor in mining geotechnical engineering, and care is taken not to assume control when it may not exist, because the illusion of control is more persuasive than the reality of uncertainty.

- **Commitment to Resilience**
  The team is committed to understanding, recovering, and learning from errors and incidents. Personnel are encouraged to swiftly learn from events, anticipate variability, and remain adaptive to change. Lessons learned are openly shared, and while data is protected, it is made accessible for broader learning. This commitment helps the team continuously improve and become more resilient to future challenges.

Systems Engineering and Process Integration
Effective systems engineering focuses on creating an integrated approach that ensures all parts of a system work seamlessly together, reducing inefficiencies and communication gaps across departments (Blanchard & Fabrycky, 2010). In the context of mining, integrating geotechnical data into mine planning and operations is critical for ensuring stability, safety, and operational efficiency.

PROCESSES

When developing an information system, it is crucial to adopt certain principles and frameworks that ensure the system aligns with organisational goals and promotes efficiency. These approaches not only improve functionality but also ensure the system evolves effectively with user needs and operational demands. They are:

1. **Ensure alignment of Process to Standards:**
   It is crucial to align each process or workflow with company and industry standards, ensuring that no incorrect or immature processes are captured or systemised. This helps maintain consistency and the required standard.

2. **Build Measure Learn Cycle:**
   Following the iterative Build → Measure → Learn cycle is a powerful tool for improving the system (Ries, 2011). This approach involves:

   - Building systems that can integrate geotechnical data into mine planning and operations.

   - Measuring outcomes such as safety performance, operational efficiency, and system robustness.

   - Learning from these results to make data-driven decisions and refine the processes continuously.

3. **SCRUM Methodology:**
   Using SCRUM principles, small, cross-functional teams can focus on incremental improvements, adapting as new data is gathered. This agile approach allows for quicker response times and improved coordination across departments (Schwaber & Sutherland, 2020).

Systems Engineering and Geotechnical Data Integration

Systems engineering plays a vital role in facilitating the integration of geotechnical data into mine planning and operational processes by:

- Establishing a framework that ensures different departments (geotechnical, survey, operational, planning) can share data and communicate effectively.

- Creating data-driven decision-making workflows that leverage the latest geotechnical information.

- Enabling automated or semi-automated processes that adapt based on real-time geotechnical conditions, enhancing mine planning flexibility and operational safety.

Through these integrated processes, mining operations can significantly reduce risk, improve decision-making, and ensure that all departments are aligned with both operational goals and safety standards.

Technological Advancements
The integration of modern information systems, along with the use of drone and satellite imagery provided by Survey, has revolutionised remote geotechnical inspections and risk control assessments. Geotechnical engineers and strata control officers can now conduct more efficient inspections remotely, significantly reducing the need for frequent pit visits (Figure 3). This not only enhances safety by minimising exposure to hazardous environments but also allows teams to focus their on-site efforts on high-risk areas. Moreover, the development of digital polygons for FOG zones of influence, for example, is paving the way for advanced geofencing capabilities. When integrated with existing vehicle management systems, this technology can soon provide real-time warnings to personnel, instructing them to vacate 'No Go' zones as defined, further bolstering safety and risk management in mining operations.

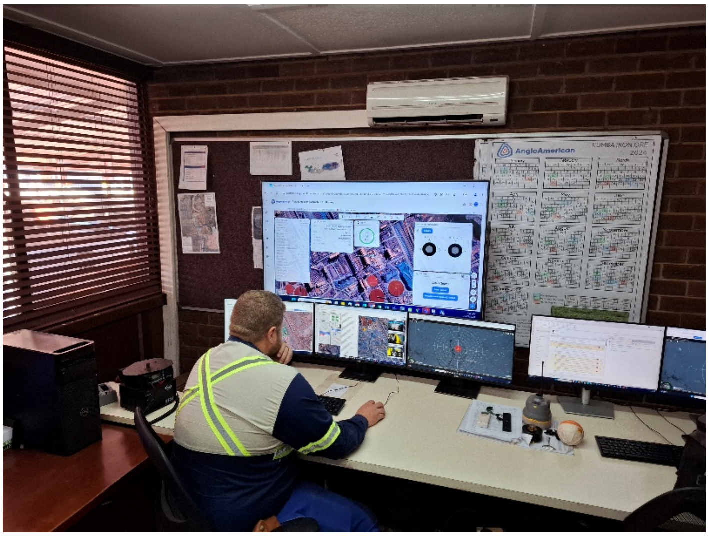


Figure 3. Drone flight control from the Sishen survey office.

CASE STUDY: IMPLEMENTATION OF GEOTECHNICAL ENGINEERING INFORMATION MANAGEMENT SYSTEMS

Overview of Implementation
The successful implementation of a global information management system supporting mine waste dump and stockpile management is discussed by Bester, *et al.*, (2022), focussing on processes, people, and technology. As waste dump and stockpile risk management data is published on the internet by ArcGIS enterprise as a feature service, the data is accessible to any authorised application capable of harvesting web-based feature services. ArcGIS Server supports all the open data sharing standards, allowing other supporting applications to share information.

The objective of the system is to make it as easy as possible for operational personnel to capture all relevant waste dump and stockpile information, following international guidelines by Hawley (2017). For this reason, using the ArcGIS Enterprise licence agreements in Anglo, all a user requires is a web browser with access to the Anglo American server (domain). Using the mine waste dump and stockpile template in Smart Editor, it is very quick and easy for site teams to create/digitise new features in the system. All relevant information required is assisted with full description domain lists (lookups), where possible, to enable easy data capture. Where required, factors are automatically calculated by attribute rules which have been added to the database structure.

The system, which can be accessed from anywhere, has been designed with four levels of access to enable support of Anglo American global mining activities. At mine level, personnel can only access their own data. At the next higher level, all data for mines in a specific business unit can be accessed. At the corporate level, all Anglo American information is accessible. However, the system is flexible, and access can be easily provided as required. The highest level is the system administration level, where the system is administrated, monitored, and maintained (Bester *et al.*, 2022).

For reporting purposes, customisable dashboards indicating status of dumps, risk levels or any other relevant information were created. All captured data is dynamically updated, ensuring that charts and dashboard show the latest information (Figure 4). The dashboards are also aggregated from Mine Level to Business Unit Level and to Corporate Level. Information is periodically updated with a management dashboard to track and ensure the accuracy and completeness of information. Document management functionalities that link to Sharepoint are also included in the system to ensure storage of all relevant information, for example design and associated material characterisation reports, photographs etc.

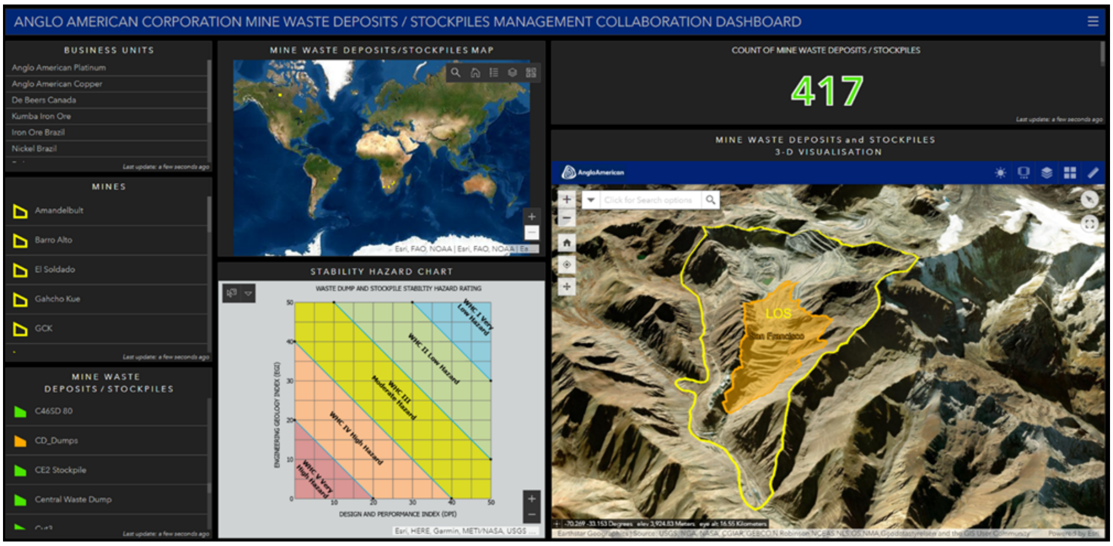


Figure 4. Example of GIS dashboard for waste dumps (rating data was removed for illustration purposes) (Bester et al.*, 2022).*

Geotechnical hazard management forms part of the Ground Control Management Plan that supports the Mine plan, following a risk-based approach. This is aligned with the elimination of fatalities strategy in Anglo American and is based on the principle that implemented controls are adequate in design and are verified for effectiveness on a regular basis.

The process aims to identify and mitigate any deviations and/or anomalies, as well as to support operational teams in the prevention of uncontrolled FOGs. Ground-related hazard management is usually legally mandated by law in most jurisdictions, and requirements are stipulated in the Geotechnical Standard for Mining. Having a robust process in place is therefore critical to deliver a Mine plan that has acceptable geotechnical risk and can deliver its objectives.

A review of this process, supported by the development of a Live Hazard Map in GIS, was implemented by the geotechnical teams at Sishen, Kolomela, Mogalakwena and Amandelbult open pits.

The Geotechnical Engineering Information Management System is also hosted on the Anglo network in the Azure cloud, utilising an SQL database that ensures full ownership of data is retained. Figure 5 shows the high-level system architecture that comprises a mobile application and a GIS frontend (web apps).

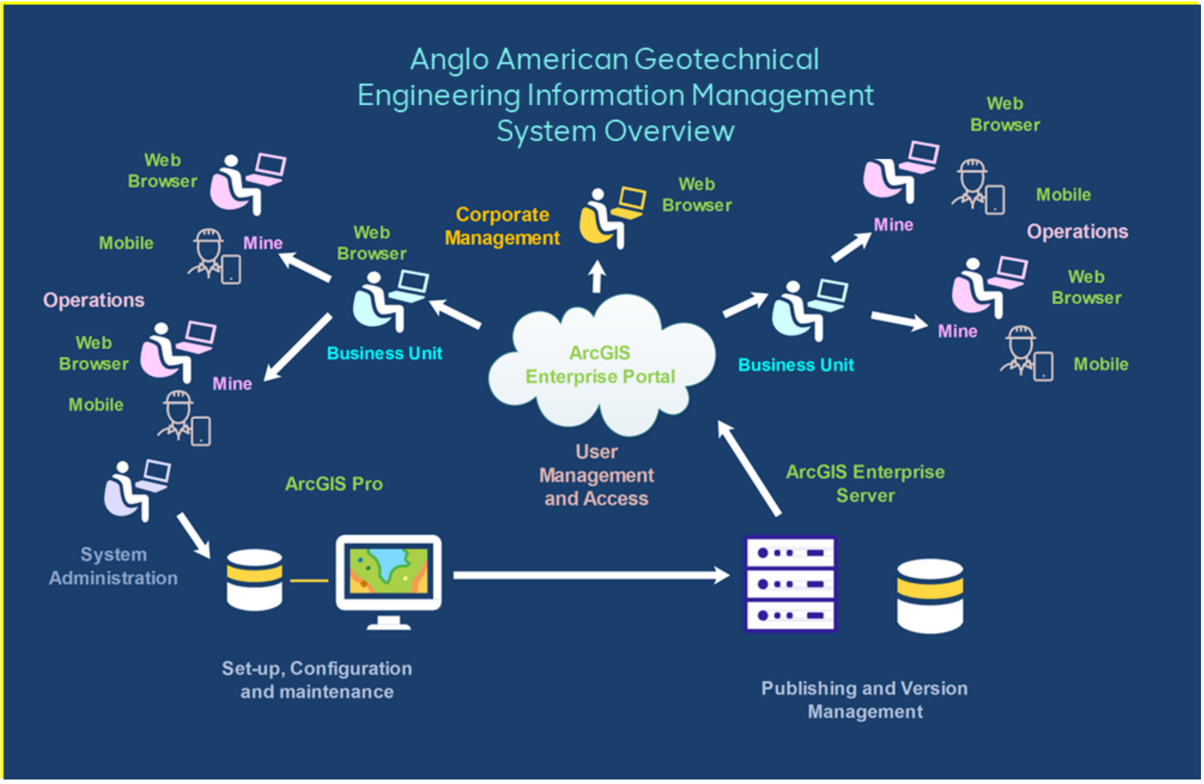


Figure 5. System overview and high-level architecture.

It adheres to all company Information Management security protocols. Furthermore, a no-code/low-code approach was followed, prioritising configuration over hard coding to facilitate in-house support and adaptability / flexibility. As the data is published on the internet by ArcGIS enterprise as a feature service, the data is accessible to any authorised application capable of harvesting web-based feature services. ArcGIS Server supports all the open data sharing standards, allowing other supporting applications to share information. This allows authorised systems to share data in a loosely coupled architecture.

The Live Hazard Map module was designed to be flexible; for example, it follows and supports the practical hazard management workflow in operations, because the development team believes that: 'Software must be on your way, not in your way or out of your way'.

Key Challenges and Solutions

During the initial stages of development, the team identified significant limitations in producing existing hazard maps. Most hazard maps were manually updated on a monthly basis, which often rendered them outdated and inadequate for addressing the rapidly evolving conditions of a dynamic mining environment. Furthermore, workflows between operations were found to be inconsistent and the maps frequently included excessive and, at times, irrelevant information, leading to unnecessary complexity.

Interviews conducted with frontline production personnel revealed that a considerable proportion of these individuals found the hazard maps unclear and ineffective in communicating specific actions required for mitigating risks. This feedback underscored a critical gap in the design and utility of hazard maps, highlighting the need for a more streamlined, actionable, and real-time approach to hazard communication to support operational and safety objectives effectively.

Following modern cybersecurity rules and managing the information management protocols of a large organisation brought challenges, such as delays in workflows due to strict data access and sharing policies. The need for extensive approvals, audits, and user training further slowed progress and limited flexibility. While the team understood that these measures are essential for security and compliance, they required careful balancing to meet operational needs without compromising security protocols and governance.

The Geotechnical Risk Management system was developed to provide real-time hazard maps that systematically track the lifecycle of FOG-related hazards. This system leverages a GIS-based spatially enabled interface as the front end, integrated with a SQL database to manage and analyse geotechnical data efficiently. The process steps are as follows; illustrated in Figure 6.

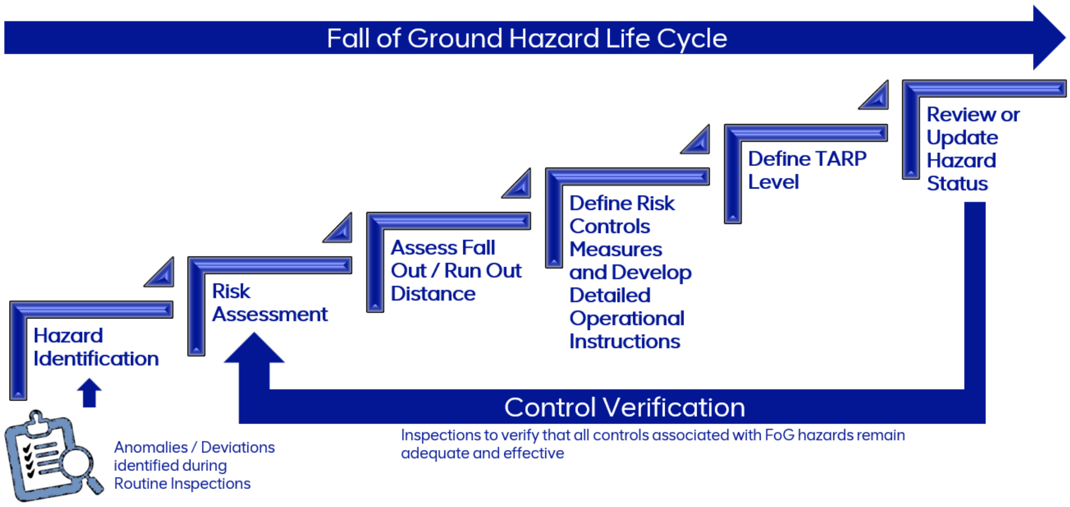


Figure 6. Fall of ground hazard life cycle.

Hazard Identification

Classify the hazard as a potential rock fall, single-, multiple bench failure/overall slope failure / subsidence.

Step 2: Risk Assessment

Utilise the Anglo Risk matrix to determine unmitigated risk for safety as well as other consequences such as financial for the unwanted event: uncontrolled FOG.

Step 3: Assess fall Out / Run Out distance

Assess fallout distance for rockfall hazards and runout distance for slope failure hazards to digitally map the zone of influence for each hazard. This enables the classification of 'No-Go Zones'. These are areas where access must be restricted for safety.

Step 4: Define Risk Control Measures and Develop Detailed Operational Instructions

Collaborate with production personnel to define and implement the controls required to maintain safe production.

Step 5: Define the TARP Level

The geotechnical engineer sets the Trigger Action Response Plan (TARP) level dependent on control status; therefore, the defined controls must be adequate in design and effectively implemented and functioning (Figure 7).

RANKING	PRIORITY	ACTION	DESCRIPTION
High	Stop & Fix	Controls are not in place and current control strategy will not function as intended	The situation must be rectified immediately. Stop work, implement interim controls, and implement controls to lower the risk
Medium	Fix within Shift	Control strategy is in place with gaps in other levels of controls such that the overall control strategy is unlikely to function as intended	The situation must be rectified urgently. Prioritise work required to execute identified controls
Low	Fix within Schedule	The overall control strategy is expected to function as intended with no immediate risk on the PUE, minor gaps exist on other levels of control.	Action to commence within a short-term schedule informed by mining plan, exposure
Mitigated	Normal operating conditions	Controls are in place; the control strategy is functioning as intended	No specific action is required, continue implementing the day-to-day standard operating procedures and controls

Figure 7. Example of a generic Trigger Action Response Plan.

Step 6: Review or update the Hazard Status

Maintain a comprehensive database of the life cycle of all ground-related hazards. The status of a hazard can change if it is fully eliminated or if the risk changes due to interventions that reduce exposure, thereby mitigating potential consequences. For instance, installing a catch fence (an engineering barrier) or designing a step-out bench can effectively remove or protect personnel and equipment from the hazard, or in some cases it can be eliminated.

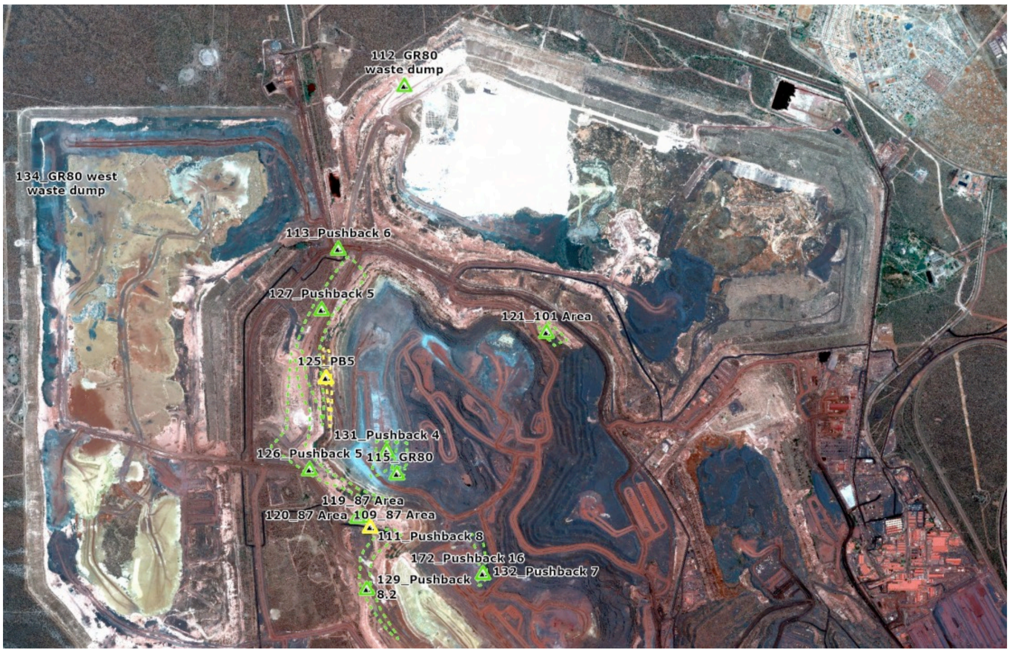
Step 7: Conduct verification inspections at set frequence

If the hazard status is active, the frequency of follow-up verification inspections is set, following a risk-based approach to ensure all controls remain in place and effective for all active hazards.

Benefits and Outcomes

The information system can instantly generate various reports from the real-time data, enhancing the efficiency of geotechnical engineers and strata control officers. The reporting format supports simple, effective communication and ensures timely management of hazards as they arise (Figure 8).

AngloAmerican EXAMPLE - SISHEN NORTH MINE HAZARD MAP WITH TEST DATA



TARP Level Description

RANKING	PRIORITY	ACTION	DESCRIPTION
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Mitigated		Controls are in place; the control strategy is functioning as intended	No specific action is required, continue implementing the day-to-day standard operating procedures and controls

Hazard ID	Risk Level	Hazard Type	Tarp Level	Instructions	Additional Instructions
119(87 Area)	High	Multiple bench failure	Mitigated (Green)	Implement effective dewatering / depressurisation, Implement effective slope monitoring	
120(87 Area)	High	Multiple bench failure	Mitigated (Green)	Implement effective dewatering / depressurisation, Implement effective slope monitoring	
121(101 Area)	High	Overall Slope Failure	Mitigated (Green)	Implement effective dewatering / depressurisation, Implement effective slope monitoring	A butters berm has been constructed across the toe of the failing material to retain the material. This has resulted in a significant reduction in the rate of deformation of the failure.
126(Pushback 5)	Medium	Inter-ramp / stack failure	Mitigated (Green)	Implement effective dewatering / depressurisation, Implement effective slope monitoring	
127(Pushback 5)	Significant	Inter-ramp / stack failure	Mitigated (Green)	Implement effective dewatering / depressurisation, implement effective surface water control, Implement effective slope monitoring	
134(GR80 west waste dump)					
125(PB5)	Significant	Rock fall	Low - Fix Within Schedule (Yellow)	Additional Instructions	Scale the highwall after loading and ensure the berm is constructed across the ramp
131(Pushback 4)	High	Rock fall (overspill)	Mitigated (Green)	Implement exclusion zones, Additional Instructions	Ensure that the dig line limit is loaded on Provision to prevent interaction of mining activities.
109(87 Area)	Significant	Multiple bench failure	Perform more rigorous design work required to improve reliability of the geotechnical design, ensure accurate mine to design, Implement effective surface water control, Implement effective slope monitoring, Implement operational controls		
111(Pushback 8)	Medium	Single bench failure	Low - Fix Within Schedule (Yellow)	Implement limit control, implement exclusion zones, Implement operational controls, Additional Instructions	This is a test
115(GR80)	Medium	Multiple bench failure	Mitigated (Green)	Implement exclusion zones, Implement operational controls	

Geotechnical Engineering	Technical Services Manager	Mining Operations	Survey	Safety	Mine Planning
SIGN:	SIGN:	SIGN:	SIGN:	SIGN:	SIGN:
DATE:	DATE:	DATE:	DATE:	DATE:	DATE:

Figure 8. An example of an auto-generated hazard map from the system (using test data for illustration purposes).

As discussed before, the fourth pillar of the risk management system focuses on learning from past FOG incidents to continuously improve safety. To facilitate this, a spatially-enabled database that captures detailed geotechnical data on FOG incidents was developed, allowing for in-depth analysis and identification of trends to enhance future safety strategies. (See Figure 9 for an example of the dashboard used to visualise this data and track progress). The following are captured for each FOG incident:

- Date / Time / Reported by
- Area name / Design sector
- Mining activity
- Incident type – single bench, rockfall etc.
- Failure mode
- Detailed description of incident
- Dimensions (volume)
- Run out / fall out distance
- Operations affected
- Evidence observed
- Explosives details
- Blasting practice
- Primary and secondary lithology
- Surface condition / structure / GSI / rock mass class
- Weathering
- Excessive rainfall recently recorded
- Seepage in face observed
- Extent of seepage
- Excessive ponding on the crest
- Incident classification-based safety and financial consequences
- Controlled /uncontrolled / significant / reportable.

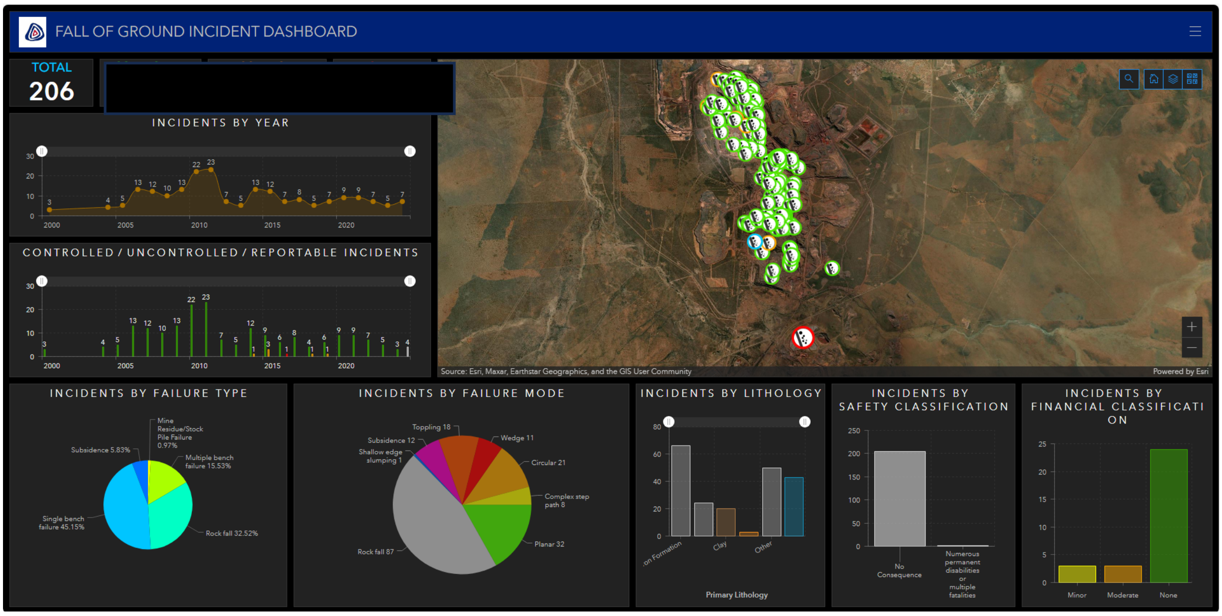

Figure 9. Example of fall of ground database with test data.

This system is further supported by a decision tree, aligned with the company FOG reporting framework, which classifies incidents based on criteria such as controlled, uncontrolled, significance, and reportability. This classification enables trend analysis to identify where controls may have failed.

DISCUSSION

Impact of Information Systems on Geotechnical Risk Management

The development of an information system that provides live hazard maps has significantly transformed and advanced the management of geotechnical risks, by enabling the tracking of the status of risk controls of all active FOG hazards in the operation, enabling improved decision-making and more effective geotechnical risk management. State-of-the-art drone technology and capturing all data in a spatially-enabled database enables the geotechnical engineer to provide clear instructions on what controls are required. Geotechnical engineers and mining operations can now track and assess hazards with greater precision, allowing for proactive risk mitigation. This system has streamlined workflows, enhanced collaboration between departments, and improved the accuracy of hazard maps, ultimately increasing safety and operational efficiency. Figure 10 shows an example of the live hazard map at Mogalakwena mine and a photo of a failure being managed operationally.

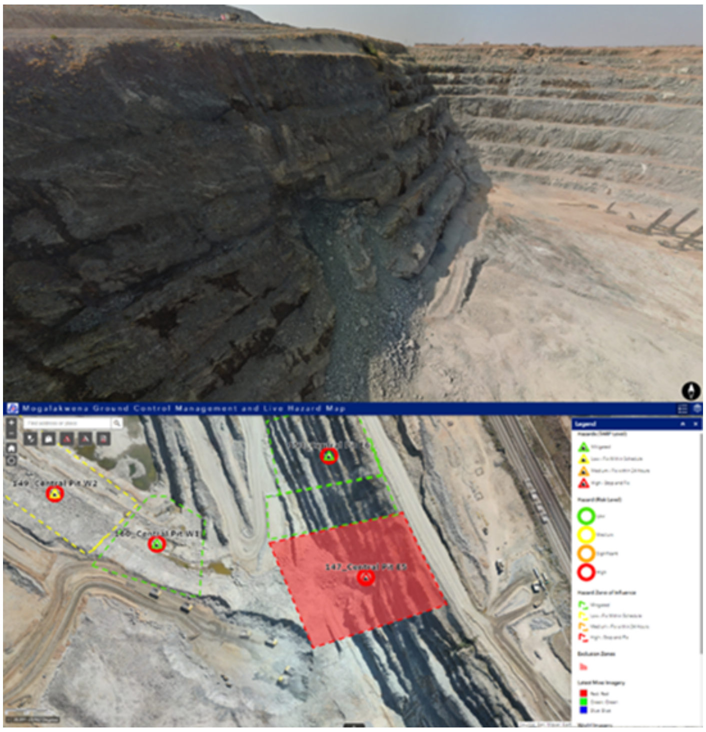

Figure 10. Example of live hazard map showing risk level and TARP level and zones of influence / no-go zones.

As the mining environment continues to evolve, the importance of continuous improvement in these systems cannot be overstated. The dynamic nature of mining and rock mass behaviour, coupled with technological advancements, necessitates regular updates and refinements to ensure that risk management practices remain relevant and effective. Continuous adaptation of information systems is crucial for maintaining the agility needed to respond to emerging threats and to maintain a culture of safety that evolves alongside the mining industry's needs.

Collaboration Across Disciplines

Collaboration between geotechnical engineers, systems engineers, surveyors, mine planning and production personnel is critical for addressing the complex challenges in mining operations. Managing FOG-related hazards are inherently interdisciplinary, requiring the expertise of various professionals to ensure safety and efficiency. Geotechnical engineers provide technical insights into soil and rock behaviour to timeously identify ground related hazards, subsequently working with operational personnel to design and implement the required controls to ensure safe delivery of the mine plan. They are supported by Survey, utilising various technologies to ensure precise spatial data is up-to-date and accessible. Automated information systems can then facilitate data management and decision-making by converting raw data into actionable knowledge. By working together, these disciplines can develop comprehensive solutions that are both technically sound and operationally viable. The system enhances collaboration and communication by integrating a wide range of information sources, including hydrogeology, surface water management, waste dump risk, structural geology, geotechnical design risks related to safety and financial considerations, as well as monitoring data from INSAR for example (See Figure 11). This integration supports not only current operations but also future pushbacks.

Figure 11. Supplementary information can be made available for effective communication; for example, fault traces from the structural geological model, intersected with the current topography.

Collaboration fosters innovation and allows for more effective risk mitigation, improving overall mine safety and efficiency. Effective communication and real-time data sharing supports setting priorities and the right decisions. Tools like this therefore play a key role in facilitating this cross-disciplinary cooperation, ensuring that complex geotechnical challenges are addressed effectively and efficiently.

Future Directions

With the foundation of sound geotechnical information systems being implemented, the next frontier involves leveraging artificial intelligence (AI) to transform risk management processes. AI has the potential to automate and enhance decision-making by analysing large volumes of geotechnical data in real-time, identifying patterns, and predicting potential anomalies and/or deviations. Future research and development should focus on the integration of AI into existing information systems, enabling more accurate risk assessments and proactive hazard identification. Key areas for exploration include machine learning models that can predict FOG events, the development of intelligent geofencing systems that dynamically adjust based on real-time data, and AI-driven optimisation of mine design to mitigate geotechnical risks. Additionally, evolving best practices will likely focus on the use of AI to enhance risk assessments, and continuously improve operational safety. The integration of AI into geotechnical risk management will not only improve operational efficiency but also reduce risks, setting the stage for smarter, safer mining practices in the future.

CONCLUSION

In conclusion, leveraging real-time data and fostering effective communication through spatially enabled information systems has proven to be a vital step in identifying and effectively managing FOG hazards and associated risks promptly. This proactive approach enhances the efficiency of geotechnical engineers and strata control officers, enabling timely interventions that significantly mitigate FOG-related risks and contribute to a safer working environment. A key breakthrough of this contribution was the opportunity to improve the quality and effectiveness of hazard plans while establishing a consistent process for identifying risks, assessing them, and effectively communicating control measures. The integration of technology and process-driven information management strategies sets a robust foundation for sustainable and effective geotechnical risk management.

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Marnus started his career in 2000 as a professional in training at the project, which is today the Kolomela Mine, after which he got appointed as a Geotechnical Engineer at Sishen Mine. In 2005 he relocated to Rosh Pinah Mine in Namibia to gain underground mining experience. Returning to Sishen Mine as Chief Geotechnical Engineer he has been involved in all geotechnical aspects relating to large open pit mining and mine dewatering as well as operations as a Production Manager. In 2012 he was appointed as Principal Geotechnical Engineer / Hydrogeology at Anglo American Kumba Iron Corporate Office with involvement in all operations and projects relating to Geotechnical Engineering and Hydrogeology. During this time, he completed his Ph.D. at Wits University under Prof Thomas Stacey. His thesis, A risk-based methodology to improve the definition of geotechnical design sectors in slope design, dealt with the optimisation of slope design through the application of Synthetic Rock Mass Modelling approaches and 3D modelling of the interaction of geological features with slope geometries. In 2020 he accepted a position at Anglo Corporate Office where his main responsibility is global mine waste dump and stockpile risk management for Anglo American as well as various other surface and underground projects.