

# Governance considerations for geotechnical engineering in risk management

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## Abstract

*Mining companies recognise that the sustainability of its business is, amongst other factors, dependent upon efficient risk management in the exploration, extraction and processing of mineral resources, including sound mine excavation design, operational execution and validation practices.*

*In the mining industry, discussions on risk management are often focused on the process, particularly the risk assessment component, with insufficient attention given to the foundation principles and the supporting framework, as defined for example in ISO 31000. However, at an executive level, management remains accountable for risk management but may not possess the necessary expertise required to fully grasp its complexities. It is therefore incumbent upon the various technical disciplines to clearly articulate the coordinated activities required for senior management to direct and control the company with respect to its risk attitude and appetite.*

*The paper provides guidance on business processes that incorporates elements from both the risk management principles and framework to support a company-specific governance approach, tailored to its unique operational context, that will benefit the business.*

*This is important to risk owners and technical personnel involved with risk criteria. Notably, where this involves geotechnical engineering, there needs to be transparent, repeatable, robust business processes in place for data management, geotechnical design, operational execution, performance validation, competency management, records management, and site-based assurance.*

*These business processes are discussed by highlighting the specific challenges in the geotechnical engineering discipline and addressing leadership, group risk and project management, mineral resource and reserve reporting, critical hazard management and a group geotechnical engineering standard.*

**Keywords:** *geotechnical engineering, risk management, governance, standard*

## 1 Introduction

Mining companies recognise that the sustainability of its business is, amongst other factors, dependent upon efficient risk management in the exploration, extraction and processing of mineral resources, including sound mine excavation design, operational execution and validation practices.

The majority of work activities in geotechnical engineering deals with the efficient risk management of fall of ground and inundation hazards through design and during operational execution. As such, geotechnical engineering has a large cross-functional footprint with input and output connections to several technical disciplines. Therefore, geotechnical engineers (whether site-based or contractors) and their line managers need to understand how the discipline fits into the broader company, what type of work needs to be done, when this work needs to be completed, and who are accountable for its execution and to what standard.

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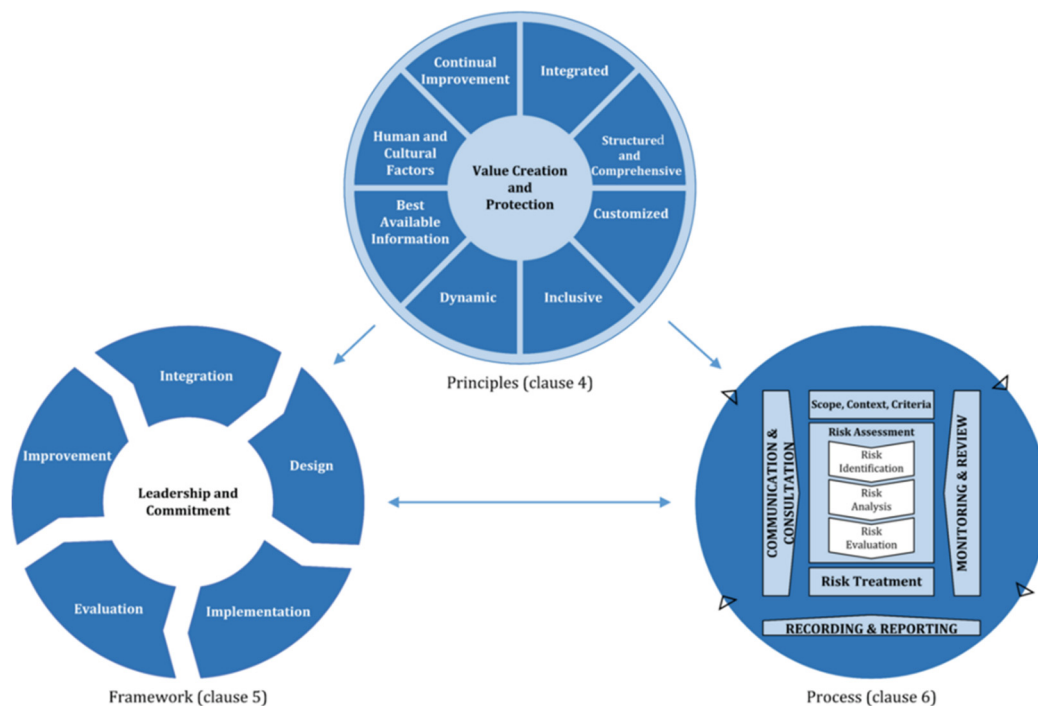
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Ultimately, all the geotechnical work activities should form part of specific group requirements (typically as policies, standards and guidelines) or contribute indirectly to these requirements.

Therefore, it stands to reason that the integration, interaction and inter-dependence of geotechnical engineering is an essential component in efficient risk management for any mining company. Consequently, the objectives for risk management within the discipline would need to be clearly defined.

Risk management is the creation and protection of value. To achieve that, risk management should aim to improve performance, encourage innovation and support the achievement of objectives (International Organization for Standardization 2018). For example, according to ISO 31000, risk management is based on three core components (see Figure 1):

- Principles: the principles provide guidance on the characteristics of effective and efficient risk management, communicating its value and explaining its intention and purpose. The principles are the foundation for managing risk and should be considered when establishing a risk management framework and processes.
- Framework: the framework assists the organisation in integrating risk management into significant activities and functions. The effectiveness of risk management will depend on its integration into the governance of the organisation, including decision-making.
- Process: the process involves the systematic application of policies, procedures and practices to the activities of communicating and consulting, establishing the context and assessing, treating, monitoring, reviewing, recording and reporting risk. It should be an integral part of management and decision-making and integrated into the structure, operations and processes of the organisation, applied at strategic, operational, program or project levels.



**Figure 1 Principles, framework and process as per ISO 31000 (International Organization for Standardization 2018)**

In the mining industry, discussions on risk management are often focused on the process, with insufficient attention given to the foundation principles and the supporting framework. However, at an executive level, management remains accountable for risk management but may not possess the necessary expertise required to fully grasp its complexities. It is therefore incumbent upon the various technical disciplines to clearly articulate the coordinated activities required, for senior management to direct and control the

company with respect to its risk attitude and appetite. These coordinated activities must integrate elements from both the principles and the framework to effectively support a company-specific process, tailored to its unique operational context.

The aim of this paper is to discuss aspects that need to be considered when developing these coordinated activities. The authors focus on aspects that support the principles in value creation and protection, and the framework in leadership and commitment.

The following sections will expand on the function of geotechnical engineering in mining, geotechnical governance processes (e.g. policies, standards, procedures and practices) and how that can be incorporated into a framework for risk management in geotechnical engineering.

## 2 Geotechnical engineering discipline

In academia, geotechnical engineering can be defined as the study and decisions involving problems comprising the engineering behaviour of all earth materials, which include minerals, water, soil and rock. It is founded on the engineering principles of soil mechanics, rock mechanics, hydrology, hydrogeology and engineering geology.

All of these are utilised during investigations of the groundmass materials and conditions to be encountered during surface and underground excavation and construction, and are further used to determine the relevant physical, mechanical and chemical properties of the materials in order to assess the potential risks posed by site conditions in relation to the planned design. In practice geotechnical engineering is important in civil engineering, but is also applied in mining, military and other engineering disciplines that may be concerned with construction occurring on the surface or underground.

Typically, in mining, all activities related to the delivery of the mine plan and the governance of projects and operations would be executed under a single point of accountability. The geotechnical engineering discipline (i.e. geomechanical, hydrological, or both) would typically be accountable for managing two key hazards in mine design and operation:

- Fall of ground: uncontrolled mobilisation of groundmass material, such as rockfall, rockburst, slope failure or ground collapse events would typically occur during mining and exploration activities).
- Inundation: uncontrolled influx or mass movement of water/ saturated materials, such as inrush, flooding or submergence (events would typically move into/through active working areas).

In mining, the purpose of geotechnical engineering (Hamman 2023) is threefold:

- Supporting the development of the mine plan with a geotechnical design:<sup>§</sup> this comprises the geotechnical design specifications, used in mine design and geotechnical modifying factors for conversion of mineral resource to mineral reserve. It is about limiting vulnerability in the mining schedule and incorporates guidance on expected rock mass behaviour and amelioration options, catering for expected consequences related to insufficient data which may otherwise drive non-optimal design decisions.
- Optimising the mine plan through ongoing design/process improvements: this concerns finding ways to reduce waste tonnes, increase ore extraction or reduce mining cost through geotechnical design improvements (Venter & Hamman 2018b). The knowledge and experience gained from new excavations is particularly important, as mining often starts with a feasibility level design based on only drilling data in hand. In reality, geotechnical hazards are omnipresent, whereas geotechnical optimisation needs additional data gathering and design effort.

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<sup>§</sup> Geotechnical design: documentation of all data, assumptions, analyses and defensive controls used to manage geotechnical risk in the mine plan.

- Protecting the mine from the consequences of geotechnical hazards: this is both a safety and an economic function, that includes scenarios such as temporary or permanent mine closure, loss of reputation and license to mine. A critical component for protection against geotechnical hazards is warning time, or latency (Venter & Hamman 2018a), which requires apt management of epistemic (lack of knowledge) and aleatoric (randomness) uncertainty. More latency increases optionality, which reduces the cost of dealing with hazards.

Therefore, geotechnical engineers need to understand the linkages between the various group standards and group guidelines, and the discipline-specific processes and tools, the engineering specifications and tolerances, and the operational implementation requirements captured in geotechnical engineering documentation.

As such, practitioners need to ask the following questions:

- Where does one get direction on best practice for the efficient risk management of fall of ground and inundation hazards through design and operational execution?
- Where does one get direction on the level of geotechnical engineering work required for a project or an active operation, and what could serve as a basis of the different input and output work flows?
- What are the accountabilities of geotechnical engineering practitioners, and what are the boundaries within which the geotechnical engineer should design and operate, to ensure consistency, repeatability and transparency in the processes followed?

The answers to these questions would benefit their businesses by:

- creating awareness of cross-functional components that mandates work geotechnical engineers carry out
- enabling mine planners and geotechnical engineers to identify and report material hazards in the mine plan
- enabling project and site management to aptly assess and manage geotechnical hazards
- reducing the likelihood for excavation failure causing force majeure
- reducing soil, rock and water related impacts on production and operations
- ensuring that the mine plan is optimised
- ensuring adherence to regulatory requirements
- endeavouring to achieve industry best practices
- implementing and commissioning fit-for-purpose research and systems
- providing a framework for globally consistent practices, and
- establishing a basis for a geotechnical community of practice.

As discussed, it is evident that the geotechnical engineering discipline plays a major role in not only protecting company investment, but also in creating value. Hence, it is vital that any geotechnical engineer doing work for a mine operation or project be familiar with the group processes and guidance, regardless of whether working for the company or contracted to perform certain tasks.

### **3 Corporate governance**

To manage any material impact that geotechnical and other hazards may have on a life of mine (LOM) plan or during operations, mining companies have controls in place to address the potential risk to the operation/project. These controls would be in the form of group policies, standards, guidelines and likely

frameworks, which cover several technical areas, and that sets the minimum processes the company employs when conducting the technical work and dealing with corporate governance.

Those that will typically demand direct/indirect geotechnical engineering considerations are discussed below under the headings of group risk management, group project management, mineral resource and mineral reserve reporting, critical hazard management and geotechnical engineering standard.

### 3.1 Group risk management

Risk management forms an integral part in the operation of any mining company. Although companies may have different approaches to risk management, all the processes and work are typically centrally managed through a framework. Core components typically include:

- Risk governance and culture: this establishes the overall structure and principles for risk management, detailing roles and responsibilities at each organisational level. It involves setting the tone at the top and creating a risk-aware culture across departments. This component usually includes oversight by the board and executive leadership, who define risk appetite and policies.
- Risk identification: this process systematically identifies risks that could impact the organisation. It encompasses internal risks (e.g. operational, financial) and external risks (e.g. regulatory, market). Tools such as risk assessments, interviews, and scenario analysis are commonly used for identifying and cataloguing risks.
- Risk assessment and measurement: once risks are identified, they are assessed for potential impact and likelihood. Assessment methods include qualitative techniques (e.g. risk matrices) and quantitative analysis (e.g. value-at-risk, stress testing). This step often prioritises risks according to their potential effect on organisational objectives and allocates resources accordingly.
- Risk mitigation and control: after assessment, mitigation strategies are developed to minimise or control risks within acceptable limits. This includes designing and implementing control measures such as process adjustments, technological solutions, and contingency planning. For high-priority risks, organisations may establish risk transfer mechanisms, such as insurance.
- Risk monitoring and reporting: continuous monitoring ensures risks are managed in real-time and controls remain effective. This includes periodic reviews, audits, and adjustments to mitigation strategies as new risks emerge. Regular reporting to leadership and stakeholders is critical, providing transparency into the risk landscape and the status of mitigation efforts.
- Risk communication and training: effective communication and training programs ensure that risk management processes are understood and adhered to at all levels. These programs promote a consistent understanding of risk policies, improve risk awareness, and reinforce a culture of accountability and proactive risk management.
- Incident response and recovery: a robust framework includes planning for incident response and business continuity. This ensures that, in the event of a disruption, recovery plans are in place to minimise impact and restore operations quickly. These recovery plans often include crisis management protocols and disaster recovery strategies.

These components collectively create a resilient risk management framework that aligns risk practices with business strategy, enabling organisations to navigate complex and evolving risk environments effectively.

A comprehensive group risk management framework is usually structured to identify, assess, mitigate, monitor, and report risks effectively across an organisation. It sets out the requirements for risk management in the group, with the purpose of ensuring the effective management of significant threats and opportunities within specified tolerances and thresholds, to ensure that business objectives are met. With this in mind, geotechnical engineers need to appreciate that:

- opportunities can only be realised by taking risk; so

- risk is present in all business and operational activities; which means that
- successful risk management is critical.

In order for risk management to be effective, all risks are to be identified, assessed, managed and reported. As such, it is important for employees to understand that risk management is everyone's responsibility, i.e. every person engaged in any business or operational activity must understand the risks within their areas of accountability and manage these risks within the approved risk tolerance thresholds.

***Geotechnical engineers need to report on their fall of ground and inundation risk management activities to provide assurance to the operational/project risk owners that the key geotechnical risks, current treatments/controls, and risk response tasks for the operation/project is appropriate, or requires updating.***

### 3.2 Group project management

The purpose of a group approach to project management is to prescribe a governance process that will ensure capital is invested wisely and through diligent risk management, and to ensure that a company will be in a position to provide superior returns for shareholders in a safe, sustainable and, socially and environmentally responsible manner.

Good governance does not mean the removal of all risks. Rather, it means the treatment of those risks that a company is not prepared to accept while considering the explicit and conscious appetite of other risks, consistent with the companies' risk policy, business model and strategy. As such, a group project management framework will set minimum reporting requirements, while maintaining focus on the relevant key items throughout the total study period, with the objective to ensure that a company invests in opportunities that achieve positive returns. This is achieved by ensuring that:

- only viable investment opportunities are selected for execution
- investments achieve optimal value with an acceptable degree of risk
- uncertainties are understood and managed
- investments are aligned with a company's strategy and vision and are consistent with its business model
- investment decisions are made on a consistent, diligent basis
- investment returns, capital expenditure and the date when full operations are achieved are consistent with projections
- a company learns from its investments and thereby improves its ability to manage future investment opportunities.

As studies progress, more detailed information and additional analysis rigour is required. Typically, there are six phases through which a project will pass in its life:

- Concept study (scoping, order of magnitude)
- Pre-feasibility study (PFS) (potentially as phase A and phase B)
- Feasibility study (bankable, definitive, detailed feasibility study [FS])
- Design and construction (operational readiness, detailed design, execution)
- Operation
- Closure

During each of the study phases (i.e. concept through PFS to FS), the chapters dealing with the geomechanical and hydrological issues are typically summaries of specific technical work completed for the project. It is considered good practice that the work for each of the specific technical components be individually scoped

and completed by project appropriate personnel or contractors to meet the requirements specific to the project. The need for project appropriate personnel is more important than the need to simplify scoping and contract management by using a single service provider.

***To complete project work, the geotechnical engineers need to implement the necessary data collection programs, complete the required evaluation and analyses phases, document and communicate the findings and recommendations, and develop and manage the scope of work for the next project stage or operational mine plan.***

### 3.3 Mineral resource and mineral reserve reporting

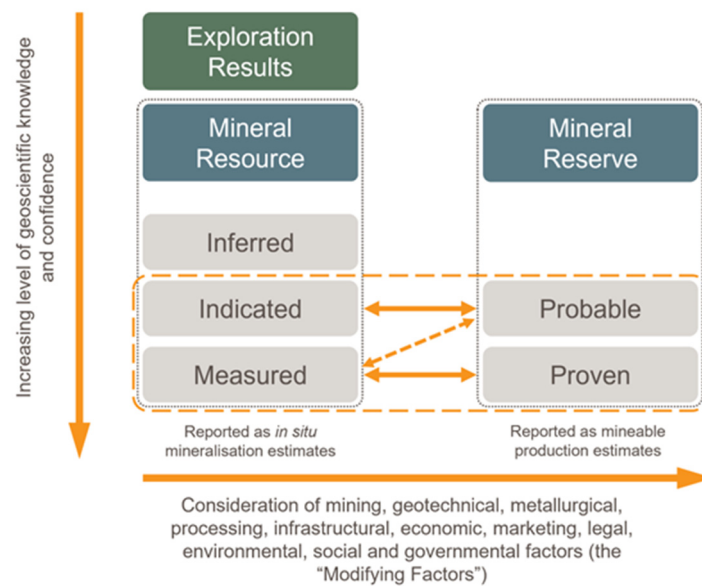
For any mining company to be listed on a recognised international stock market, the company requires a rigorous process for the reporting of a mineral resource and mineral reserve. High standards are set by the different reporting codes to promote transparency, consistency, and reliability, which are essential in the mining industry for several reasons:

- **Global standardisation and transparency:** some reporting codes like CRIRSCO, JORC and SAMREC establish common definitions and criteria, making reports globally consistent and comparable. This standardisation allows investors, analysts, and stakeholders to interpret and compare mineral estimates across different companies and countries, facilitating international investment and trade.
- **Investor confidence and market credibility:** accurate and consistent reporting builds investor confidence by providing a reliable basis for evaluating a mining company's assets. These codes ensure that mineral resource and reserve estimates are credible, which strengthens trust in a company's disclosures and, consequently, its valuation in capital markets.
- **Regulatory compliance:** many stock exchanges and regulatory bodies mandate compliance with CRIRSCO-aligned codes for mineral reporting. This includes, for example, adhering to JORC in Australia, SAMREC in South Africa, and SEC SK1300 in the USA. Compliance ensures that companies meet legal and regulatory requirements, minimising legal risks and protecting their license to operate.
- **Informed mine planning and risk reduction:** rigorous resource and reserve estimation helps companies make informed operational decisions, guiding efficient mine design, production scheduling, and financial planning. By following CRIRSCO-aligned codes, companies can minimise risks related to incorrect resource assessments, reducing the likelihood of costly errors in operational and financial planning.
- **Transparency and public trust:** mining companies operate with significant social and environmental impacts. Transparent reporting based on CRIRSCO codes helps companies communicate their resource management practices to communities, environmental groups, and regulators, fostering public trust and supporting social license to operate.
- **Corporate reputation and access to capital:** CRIRSCO-aligned reporting codes enhances a company's reputation within the industry and financial markets. Demonstrating compliance with these codes makes companies more attractive to investors as it reassures them of responsible and accurate resource estimation. This can provide better access to capital, partnerships, and favourable financing terms.

In summary, by adhering to the various codes (e.g. CRIRSCO, JORC, SAMREC), mining companies ensure that their mineral resource and mineral reserve reporting is reliable, transparent, and aligned with global best practices, which supports sound decision-making, regulatory compliance, investor confidence, and sustainable development.

In order to establish a mineral reserve through the mine design and planning process, modifying factors (i.e. physical, economic and technical) based on measurements are used (Figure 2). Mine specific geomechanical and hydrological specifications and considerations are technical modifying factors that

provide geotechnical engineering input to the mine design and planning process. These specifications and considerations are important as they do not only comprise input parameters in the geometry of the mining excavations, but also on the schedule, sequence and costs.



**Figure 2 The relationship between exploration results, mineral resource and mineral reserve**

As such, this requires a review of the selected LOM plan (or business plan) to ensure that all material fall of ground and inundation hazards are identified and have been assessed to understand their impact on the plan. This type of review is an iterative process between the mine planner and geotechnical engineer.

The uncertainty and natural variability of the unmined rock mass, together with any additional data and operational knowledge gained during the previous year, should all be considered in the business assumptions used for the annual updated mineral reserve.

***The geotechnical engineer needs to provide an annual update on mining geometry parameters, sequencing and extraction specifications, tolerances and associated design implementation options, geotechnical risks (threats and opportunities) to the mine plan, risk amelioration specifications, and operational considerations for the selected plan to be used in the reserve declaration.***

### 3.4 Critical hazard management

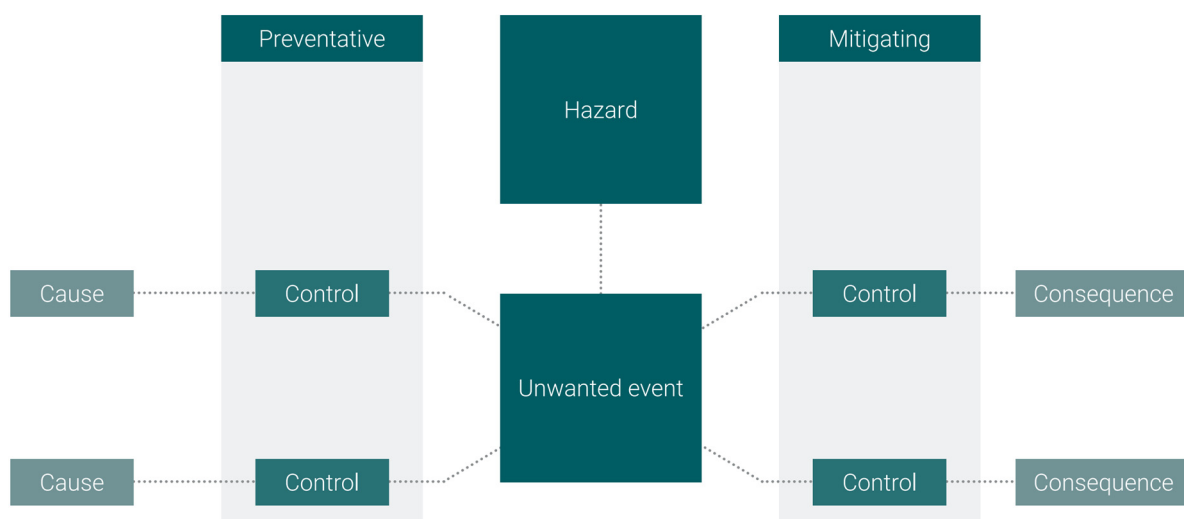
All mining companies will have some form of critical hazard management standard that sets out the controls for managing critical (or principal/major/fatal) hazards to eliminate or minimise the likelihood of work-related injuries or fatalities.

Each mining operation is different, and operational conditions will change over time. As a guide (WorkSafe Western Australia 2025), critical mining hazards may include:

- instability of geotechnical structure (i.e. mining excavation or soil/rock construction)
- inrush of any substance
- mine shafts and winding system
- roads or other areas where mobile plant operate
- fire or uncontrolled explosion
- gas outbursts and spontaneous combustion in an underground coal mine

- air quality or dust or other airborne contamination (such as from asbestos, silica, radiation or sodium cyanide exposure)
- structural integrity or failure
- lone and isolated work
- arc flash and electrocution
- natural disaster from flood, cyclone, storm or earthquake
- proximity to old workings
- uncontrolled release of pressurised hazardous chemicals
- working at heights
- working in confined spaces.

These standards usually present leading practice control requirements (Figure 3) to eliminate the likelihood of experiencing an occupational fatality or high severity incident within the context of a specific activity or risk area. It will also include a means to verify that critical controls are well designed, understood, in place and working at the front line where the risk exists. There will very likely be a component in the standard on hazard control that deals with fall of ground events and, in some mining environments, also inundation.



**Figure 3 Typical bow-tie analysis indicating preventative and mitigating controls (WorkSafe Western Australia 2025)**

Although this type of standard will primarily focus on safety critical controls, the successful implementation thereof can play a major part in efficiently managing the economic impact from either fall of ground or inundation hazards.

***The geotechnical engineer has a role to play as the custodian of the relevant geotechnical documentation, specifications and inspection data, and the effective communication thereof, that enables a safe working environment to all employees and contractors.***

### 3.5 Geotechnical engineering standard

Major mining houses would very likely have a specific standard for geotechnical engineering. Whether or not such a standard exists, the authors believe that a geotechnical engineering standard should be built on seven pillars (Hamman 2023):

1. Geotechnical data management (physical environment knowledge)

2. Geotechnical design
3. Operational considerations
4. Integrated monitoring (performance validation)
5. Competency management
6. Records management
7. Assurance

Capturing these seven pillars in a geotechnical engineering standard would form the basis for any risk management of fall of ground or inundation hazards. These pillars are designed to support the development of the mine plan with a geotechnical design, optimise the mine plan through ongoing design/process improvements, and protect the mine from the consequences of fall of ground and inundation events.

***To realise the seven pillars of a geotechnical engineering standard, the geotechnical engineer needs to plan and execute the necessary work to the level of effort required to aptly manage the risk in line with the company's risk appetite and tolerance. This includes an annual update of the geotechnical design and the operational execution thereof to support the mine plan.***

The pillars covered under this section are listed as headings with introductory paragraphs explaining the importance of each pillar, followed by sub-bullets that discuss the key goals, that can be grouped into geotechnical standard items.

### ***3.5.1 Pillar 1: geotechnical data management (physical environment knowledge)***

A geotechnical design can only be effective and efficient once a thorough understanding of the physical geotechnical environment (i.e. geomechanical and hydrological) has been developed and then maintained as part of a structured process. This understanding needs to be continuously evaluated as part of the mining process to include information on new exposures and operational performance as it becomes available. Having such a process in place will reduce the complexity introduced through uncertainties and variabilities within the physical geotechnical environment pertaining to:

- geology (i.e. lithology, alteration, weathering, oxidisation, foliation, bedding)
- major structure (i.e. faults, shears, thrusts, contacts)
- rock mass
- stress regime
- hydrology
- hydrogeology, and
- geohazards.

One of the main challenges is that geotechnical data collection typically occurs in small batches, spaced out over time as projects mature and as rock exposures increase, and that the data is collected by different people using different technologies. As such, it is easy to lose the ability to integrate all the available data, resulting in each batch being useable only in isolation. This destroys the value that can be had if data accumulated over the life of a project/operation can be integrated. Furthermore, small batch data collection always makes it easy for unvalidated data to pollute the database. To prevent data related value loss, several elements can be employed in a structured process to maximise the data value:

- Data collection strategy: this starts with documenting, implementing and adhering to a geotechnical data collection strategy based on industry accepted methodologies as far as reasonably practicable.

Establishing a geotechnical data collection strategy is essential to ensure that an adequate working understanding of the physical geotechnical environment is consistently maintained where a company operates (or plans to operate). It is therefore important to decide what data needs to be collected, when and where this data should be collected, how it will be collected, and where it will be stored.

Geotechnical engineers need to appreciate that not all geotechnical data may be relevant in managing the risk in certain parts of the mine for a particular mining method and/or scenario, and that the resolution of data collection needs to fit the purpose of its use, e.g. systematic, broader spaced data collection to validate a predetermined domain, or targeted, closer spaced data collection to enable detailed assessments.

The data collection strategy should include mine/project specific factors, and ensure that all relevant geotechnical data are collected with timestamps and spatial location, that systems are in place to ensure that this data is accurate and complete, and that it is done to international standards (e.g. International Society for Rock Mechanics for rock and Unified Soil Classification System for soil).

- Instrument and equipment maintenance: the maintenance and calibration of equipment is crucial to ensure that instruments/equipment are working within specified tolerances, thus providing accurate and reliable data.

Data collection is a time-consuming activity, and it is strongly advised to introduce instruments/equipment that can reduce human effort and errors, while still maintaining reliability in the data. However, the cost and resources required to operate, maintain or calibrate instruments and equipment used in data capture, are often underestimated. As such, when a particular instrument/equipment is selected for collecting geotechnical data (e.g. physical properties, characteristics, stability monitoring, QA/QC, etc.), the required data resolution, operational constraints and maintenance requirements must be considered as well.

- Database layout and maintenance: central to this process is maintaining a geotechnical database of all geotechnical data used to validate the geotechnical design and managing geotechnical risk in the mine plan.

Data collection is a critical task that requires detailed planning and resourcing to execute efficiently. In order to ensure that this investment is realised, the collected data need to seamlessly import into a relational database\*\* from where geotechnical engineers can utilise the data to validate the geotechnical design and to efficiently and effectively manage existing and identify new geotechnical risks (Hamman et al. 2017).

It is important for mine/project management to appreciate that when certain data is not available at a specific point in time, mining in the impacted area may not be able to continue within the original specified parameters and accepted risk, thus impacting the schedule. Thus, investing in the development and administration of a geotechnical database is central to managing fall of ground and inundation hazards. As such, adequate consideration must be given to the budget, schedule and resourcing that will be required to execute the geotechnical data collection and maintenance of physical properties, characteristics, groundmass response (including water) and quality assurance and quality control (QA/QC) that feed into the validation of the geotechnical design and risk management in the mine plan.

- Database security and auditing: lastly, it is essential to ensure that the geotechnical, relational database is secure, transparent and auditable, and linked to a central group database for redundancy.

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\*\* A relational database is built using the structured query language.

Establishing a secure relational database and conducting routine audits against the data collection strategy will provide continuity in reliable data between project, operational, expansion and closure phases for a mine, and allow for standardised tools and reporting functionality (Hamman et al. 2017) to be developed.

There needs to be clarity on where the different access protocols and accountabilities lie to enter, verify, validate, export and maintain the different geotechnical data sets in the relational database (e.g. core logging, face mapping, damage mapping, QA/QC, laboratory testing, water monitoring, etc), and how and where to access the latest supporting information including geology (i.e. lithology, structure, alteration and weathering), stress regime, hydrology, hydrogeology, voids and geohazards. This is to ensure that there is one version of the truth when it comes to the data being used in risk management.

And lastly, some degree of redundancy can be incorporated by uploading the site database to a central group database on a regular frequency, e.g. monthly.

### 3.5.2 *Pillar 2: geotechnical design*

Mining excavations need to be designed in a manner to aptly manage major safety (i.e. fatalities and injuries) and major economic (i.e. ore losses, overbreak, reduced access serviceability and equipment damage) incidents arising from falls of ground or inundation, whether as a result of mining activities and/or natural events, and to realise opportunities identified during the course of mining.

The evaluation of geotechnical data is to highlight factors that contribute to potential risk scenarios (safety and economic). The analyses and geotechnical design are to define how the risk scenarios can be managed. Therefore, when completing a geotechnical design, aspects that need to be considered, documented and reviewed for the project/mine in order to quantify and manage fall of ground and inundation risks, include:

- Expected failure mechanisms: identify and define ground control and inundation mechanisms that can impact excavation stability or access serviceability.
- Design acceptance criteria: define the safety, economical and operational criteria.
- Amelioration options: excavation geometry, sequencing and ground support/inundation management options to maintain an acceptable level of risk are to be defined through performance assessments and specified for inclusion in the mine plan and schedule. Ground support standards are to be compiled to cater for instability mechanisms relevant to the different excavation geometries and sequencing on the mine.
- Performance assessments: the performance (stability/behaviour) of mine excavations and critical areas are to be demonstrated through appropriate monitoring and analyses.
- Operational considerations: tasks/actions relating to excavation stability monitoring, geotechnical design validation, geotechnical risk management and resource requirements (staffing complement and competencies, and equipment) are to be defined and specified for inclusion in the LOM plan and schedule.
- Abandonment: site-specific abandonment guidance is to be developed for each mining area and the operation as a whole.

In the design of all mining excavations and supporting infrastructure (e.g. diversion channels, pumping, backfill) the aim is to minimise uncertainty, balance economic threats and opportunities identified during the course of mining, and eliminate/minimise the likelihood of major safety incidents relating to fall of ground or inundation. To achieve these goals, several key elements (Hamman & Venter 2019) need to be considered and are discussed below:

- Geotechnical design process: firstly, define and implement processes to develop and update a geotechnical design and document any variations.

It is important to ensure that, for any given geotechnical design, all relevant data is used for evaluation, that the correct analyses are considered, and that operational considerations are practicable in the field, in order to reduce uncertainty in the mine plan.

In order to assist in selecting design parameters and providing operational guidance for different mining methods and schedules, and to limit the risk associated with the inherent uncertainties in the physical geotechnical environment, a minimum work effort for gathering data and analysis is required and a structured design process needs to be followed such as those proposed by Bieniawski (1991) and Stacey (2009). The goal is to help the geotechnical engineer in developing an understanding of and communicate the inherent risk coupled to a certain set of geotechnical design specifications.

The design of a mine is an ongoing iterative process, with the geotechnical design component for excavations having various input and output links with the mine planning, mine production, geology, and metallurgy departments. These links, deliverables and accountable persons need to be clearly defined.

- Competent geotechnical engineer: secondly, it is important to develop the geotechnical design with a competent geotechnical engineer experienced in the mining method and expected conditions.

Due to the variability of natural materials and changing conditions experienced in an active mine, a large component of geotechnical design is experience based. Mining operations/projects rely on competent geotechnical engineers with several years of experience (typically >10 years' experience) in a particular mining method, prevailing ground conditions and expected excavation behaviour to provide guidance on managing geotechnical risks in the mine plan.

The objective is to have a geotechnical design, signed off by geotechnical engineers able to defend both the economic and safety impact of their design against peers, and to contribute as a technical specialist in the mineral reserve conversion process.

It is important that a mine/project have access to a competent geotechnical engineer. This person would not necessarily be employed on site or in the project per se. Typically mining companies will make use of consultants to conduct the design work, or to review and validate internal work.

A word of caution – geotechnical design competency requires a thorough practical and experiential knowledge of the mining method combined with sound geotechnical engineering knowledge. As a result, a geotechnical engineer should not be deemed competent in a mining method when lacking the necessary operational or design experience, regardless of their theoretical knowledge.

- Risk-benefit analysis: thirdly, the geotechnical design should be based on a risk-benefit analysis that incorporates operational performance.

Uncertainty is omnipresent in mining, whether it is due to the natural variability in the physical geotechnical environment, price fluctuations in the market, or operational performance. Each aspect can, however, be analysed to deliver an optimised mine plan where the risks and benefits are assessed in line with the risk appetite of the company.

Whether a geotechnical design is used in a business plan, LOM plan, or strategic option, it is important that the design is used in the correct context, within the specified tolerances and representative of actual operational performance, thereby providing assurance that the specific mine plan can be delivered to a degree of certainty. As such, consideration needs to be given to what constitutes an acceptable geotechnical design and what processes can be followed to complete and document an acceptable geotechnical design for the specific mine plan.

Finally, it is crucial that the sensitivities of mine planning parameters linked to the geotechnical design must be understood before committing to a final mine plan, and the risk-benefit analyses for the final mine plan accepted.

- Senior management alignment: lastly, there needs to be a formalised process in place for the senior site manager delivering the mine plan to align on the geotechnical design and associated geotechnical risk profile<sup>††</sup> prior to execution, and to align on any changes required to the geotechnical design due to changes in the design acceptance criteria.

It is essential for project/mine management to be familiar with the geotechnical risks, cognisant under what scenarios these risks may become material, and to comply with the selected risk management option.

Therefore, it is important that the senior manager, accountable for delivering the mine plan, is adequately informed on the geotechnical design, geotechnical risk profile (Venter et al. 2024; du Plooy & Hamman 2024), and risk treatment action items for the selected mine plan. This manager would normally have the authority to manage geotechnical risks in the mine plan (or from changes to the mine plan), and thus accountable for what change management, amelioration activities and resourcing is required to deliver the mine plan to the selected level of risk.

### 3.5.3 Pillar 3: operational considerations

During the operational phase of a mine, the mining excavations and site layout need to be constructed and operated in a manner to effectively and efficiently manage fall of ground and inundation risks that may arise as a result of mining activities and/or natural events.

An integral part of this process is to conduct risk assessments on planned excavations to ensure that the mine plan caters for the inherent, material, geotechnical risks in the design and/or schedule. Identifying the hazard, determining the risk scenarios, and defining means to ameliorate are all critical in understanding the optionality in the mine plan.

The effective and efficient execution of such a mine plan requires developing operational execution plans based on the operational considerations listed in the geotechnical design and from experience gained on site. To achieve a true multi-disciplinary solution to manage fall of ground and inundation risks, several factors need to be considered:

- Site-specific ground control management plan (GCMP) and flood control management plan (FCMP): to manage the risk in the mine plan during execution necessitates developing, implementing and maintaining a GCMP and FCMP specific to the operation.

Every operation is unique in the geotechnical conditions and the risk accepted in the mine plan. This drives the roles and KPIs/KPAs of the different technical disciplines in developing a knowledge base and understanding of the physical environment and operational performance. The unique nature of the geotechnical conditions at each mine requires the mine management to take ownership for the development, implementation and annual update of suitable risk management plans for fall of ground and inundation.

The concept of a GCMP is already accepted industry practice and a regulatory requirement in certain jurisdictions (Department of Mines, Industry Regulation and Safety [DMIRS] 2019). The GCMP can be described as a document that outlines strategies, procedures and cross-functional responsibilities and activities required to manage the risks associated with fall of ground hazards, to ensure the stability and safety of mining excavations (Human 2015). It is to promote best operating practices, facilitate auditing, and capture the standards and procedures necessary to design the mine workings according to the information available, construct the workings according to the design, and monitor the stability of the workings, such that safe operating conditions can be sustained over the life of the mine.

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<sup>††</sup> Geotechnical risk profile – outlines the geotechnical risk to the mine plan in production and/or financial terms.

The authors believe that a similar concept should be applied to the risk management of inundation hazards. The outline and technical content for the FCMP should essentially be similar to that discussed above.

The GCMP and FCMP are both central to a risk management system for fall of ground and inundation related losses in the mining operation, thereby enhancing safety and productivity. As such, it should be noted that the formal appointment of suitably trained and qualified persons in key mine production and technical positions, that will actively contribute to risk acceptance and the inherent risk management process, is critical to the success of the system.

- Mine construction and operation: it is important to construct and operate all mining excavations in accordance with the GCMP and FCMP approved for the selected mine plan.

Although there may seem to be an overlap with the previous goal, experience has shown that there is a big step between establishing the site-specific control plans and in practice incorporating the inherent promises and controls as part of the way that a mine is constructed and operated. This goal aims to address that gap by having control plans in place that are suited for the selected mine plan and having a process in place that ensures all stakeholders sign off on the control plan.

As such it is important that senior site management take ownership for the approval of the GCMP and FCMP, for execution of the mine plan in accordance with the control plans, for adherence to these control plans during operations, and for allocating resources as required by the control plans.

- Control deviation: two crucial components in change management are to document any deviation from the GCMP or the FCMP and to obtain approval from senior site management.

The inherent uncertainties in mining will ultimately result in scenarios where the mine plan being executed will not align with the controls set out in the GCMP or FCMP. In this case the senior manager accountable for the mine plan needs to be informed on the change management process that was followed, and the hazards and associated risks that will be introduced by the deviation from the GCMP or FCMP during operational activities. As this senior manager will have the authority to manage the introduced risk, he/she needs to take ownership for the risk treatment activities and resourcing required to execute the mine plan with the deviation.

- Excavation reconciliation: to assess the performance of the geotechnical design, the site team needs to establish and maintain a process that assesses how well all mined excavations followed the approved geotechnical design.

The technical team on site needs to develop an understanding and appreciation on the groundmass (including water) response and tolerance on adherence to the geotechnical design. Survey, production, QA/QC and monitoring data must be readily available to complete a geotechnical reconciliation of the actual as-mined excavations. The identification of factors contributing to, or controlling, underbreak and overbreak is essential when assessing the performance of the geotechnical design.

As such, reconciling the implemented ground support, excavation geometries, sequencing, layout and schedule against the geotechnical design will help differentiate between operational drivers, variability in the physical environment and introduced unknowns.

### **3.5.4 Pillar 4: integrated monitoring (performance validation)**

Geological and geotechnical models play an important role in the geotechnical understanding of the mining environment. These models are often based on limited data, especially in areas where only drillhole intersections are available. As soon as mining excavations have exposed the rock mass and detailed mapping and measuring becomes possible, reconciliation of these models needs to be performed to ensure greater certainty in future designs.

The concept of integrated monitoring (Venter & Hamman 2018) refers to the methods of measuring the groundmass response to construction and mining, and mapping changes in groundmass characteristics for the purpose of reconciling actual with assumed groundmass conditions, i.e. it is a form of performance validation. It covers the design, commissioning and maintaining of fit-for-purpose monitoring and data collection strategies and systems suited to the expected failure mechanisms and mining/operating environment.

Key elements include the measurement of changes in the groundmass, the sampling of key groundmass characteristics (water, rock and soil properties), the preparation and analysis of groundmass samples, the processes to capture data, the statistical interpretation of data and trends, and the presentation of the relevant information. This is underlain by the capacity on site to synthesise the information, decide on suitable solutions to operational challenges that can impact production and reconciliation, and the effective and efficient communication of the information and solutions.

To establish a fit-for-purpose solution for integrated monitoring on a mine site, the following need to be considered:

- Integrated monitoring system: the primary goal here is to establish and maintain an integrated monitoring system to validate that geotechnical design, criteria, procedures and controls are effective.

The intent is to ensure that the geotechnical design and associated processes remains efficient and effective throughout the mine life in managing fall of ground and inundation hazards that may arise from mining activities and/or natural events.

In developing, altering and maintaining any integrated monitoring system, the following aspects need to be considered:

- Stability monitoring: excavation monitoring requires a baseline reference to assess the implementation and effectiveness of the ground control system and integrity of the mining layout to calibrate the geotechnical design and to identify areas of developing hazards. The requirements need to be defined and included in the mine plan.
- Monitoring equipment: equipment considered for excavation monitoring require sufficient reliability, accuracy and precision to meet the tolerances imposed by the failure mechanisms.
- Vibration monitoring: where there is potential for seismicity, air-blast, or blasting damage to occur, seismic and/or vibration monitoring and recording need to be carried out.
- Monitoring contingency: adequate contingency for excavation monitoring needs to be considered to ensure that a multi-tier excavation monitoring system can be implemented.
- Trigger action response plans (TARP): these need to be defined by considering the mining and monitoring strategies and the prevailing and expected conditions in the areas of concern.
- Requirements review: the performance and suitability of the monitoring systems and practices need to be reviewed annually to ensure they can support the selected mine plan.
- Domain and damage mapping: the systematic collection and analysis of geotechnical characteristics data and excavation conditions should be done to ensure that ground conditions can be predicted and changes to conditions proactively communicated. Inspections, rock mass damage mapping and geotechnical characteristics mapping per domain need to be representative of all mining areas. This data needs to be collated in 3D visualisation environment with all other available geotechnical information (Hamman et al. 2017).
- Integration: the data from all recording and measuring systems need to be integrated with data from other sources (geotechnical, geology, mining layouts, numerical modelling, etc.) to facilitate identification of potential damaging events (Hamman et al. 2017).

- Validating excavation performance: collect and analyse geotechnical data to validate the performance and monitor the stability of excavations, structures and supporting components.

It is important to highlight the different degrees of effort and competencies required to collect data, maintain related systems and analyse trends. This incorporates an appreciation for differences between the various types of data to be collected, and the required frequency and resolution for data collection.

The aim here is to ensure that senior mine management enforce the adequate completion of work necessary to validate the geotechnical design. This includes conducting back-analysis on failures and stand-up time for stable excavations, reconciliation between planned, expected and final mined geometries, and calibration of strength criteria and model behaviour based on actual measurements.

Ultimately, this is about demonstrating that reasonable measures have been taken to ensure that the geotechnical design caters for the induced demand, and that all defensive controls are implemented and reviewed annually, or when conditions require.

- Data presentation: to effectively share and communicate geotechnical information, it is crucial to ensure that capturing, analysis and presenting of geotechnical performance is done in 3D.

There needs to be a process to enable the collection, evaluation, presentation and visualisation of all relevant geotechnical data in a 3D space that correlates with the mine environment and digital assessments. The aim is to make use of a 3D environment, insofar as reasonably applicable, to present excavation performance monitoring, water management monitoring and QA/QC data together with data on the physical environment and empirical/numerical analysis, i.e. comparing appropriate geotechnical performance data against the models, inputs and assumptions used for geotechnical design.

It is recognised that for certain reporting options, the required spatial and time components of the performance data may not be applicable.

### **3.5.5 Pillar 5: competency management**

An efficient geotechnical engineering service is required in a mining operation to apply rock/soil mechanics, hydrology and strata control principles for the safe and economic design and operation of mine workings. The level of service required here will be related to the complexity of the mine and the risk appetite adopted in the mine plan.

Maximum benefit can be obtained from a geotechnical engineering service when it acts proactively, identifying potential high-risk situations and taking/recommending remedial action before persons are injured, equipment damaged, and mine workings damaged resulting in ore loss, excessive dilution or loss of access. To achieve this, it is advisable that such a service be closely associated with mining operations by operating as follow:

- Participating in planning activities to identify and advise management on potentially dangerous or damaging situations created, or likely to be created, by mining operations or external factors such as geohazards.
- Designing and assisting in implementing systems, procedures and processes/techniques which will eliminate or manage fall of ground or inundation hazards.
- Initiating and implementing monitoring, recording and reporting systems and procedures which ensure that relevant information is timeously provided to the accountable personnel in planning and operating functions.
- Ensuring that mining systems employed will provide conditions conforming to those required by local regulatory authorities.

- Assisting with training of all levels of mine personnel in geotechnical engineering aspects relevant to their roles and areas of operation.

For the geotechnical discipline to operate in this manner, it must be adequately equipped and staffed with suitably qualified and experienced personnel strongly associated with, but independent of, the production department. It is therefore essential that senior mine management ensure that the right person is appointed in the right position at the right time. This requires consideration of the following:

- **Geotechnical department:** maintain discipline health by ensuring the right structures are in place and all roles are filled by capable people, who can deliver on the requirements. This includes appropriate succession planning.

This goal intends to ensure that senior mine management is cognizant of the material geotechnical risks within the mine plan and formally appoint sufficient, suitably trained, qualified and experienced personnel in geotechnical engineering positions that will actively be involved in the risk management of design, planning and implementation of the mine plan through the GCMP and FCMP and according to the geotechnical design.

The availability of suitably experienced geotechnical personnel is an industry-wide concern. Consultants and contractors can address gaps in the short-term, where the scope of their work is clearly defined and managed by site. Secondments from other operations in a company can ensure continuity in the medium-term, as these geotechnical engineers will already be familiar with internal processes. However, in order to maintain continuity in the long-term, consideration should be given to contracting a suitable person to do the necessary work or to review the work done on site, until such time that the junior geotechnical engineers can demonstrate the required level of competency.

Earlier appointment of suitable, high-potential successors, where their original positions are filled and they can work under guidance (i.e. coaching and mentoring) in the new role, is encouraged; however, these successor incumbents will require clear goals and a fit-for-purpose development plan.

The ongoing development of professional personnel is extremely important, even more so for those that reach the experience level to qualify as a competent geotechnical engineer. There are several professional bodies (e.g. AusIMM, SANIRE, SME, EA) that provide chartered/professional accreditation to practitioners who can demonstrate an advanced level of competency and experience, and are up-to-date with new industry developments and ongoing professional developments.

In establishing the department, the following aspects need to be considered:

- **Roles and responsibilities:** roles and responsibilities need to be assigned to ensure the apt management of the geotechnical risk through the execution of the GCMP and FCMP by competent persons.
- **Geotechnical risk owner:** the senior manager, responsible for managing the geotechnical reporting line on the operation/project, and having the authority to manage the introduced risk, should be appointed as the geotechnical risk owner by the general manager. Geotechnical risk owners need to determine and regularly review the competency and training needs of all personnel involved with the mining operations. The geotechnical risk owner needs to be in a position of authority where they can resource the geotechnical team and make staffing changes.
- **Competent geotechnical engineer:** any mine needs access to a competent geotechnical engineer, who has the relevant skills and experience in the mining method, ground conditions and excavation conditions in the mining operation. This person should sign off on all

geotechnical recommendations given on all updates to LOM plans, inputs to mineral reserve conversions, and geotechnical updates to the GCMP and FCMP.

- Competency: adequate and appropriate ongoing professional development need to be provided for personnel involved with the design, operation, and abandonment/closure of the mine/working area. By extension, this should include senior management as well to ensure that they have an adequate understanding of the work to make the right decisions.
- Competency training: consideration needs to be given to providing training and competency assessment to employees and contractor involved in ground control and inundation control activities, and ensuring only authorised persons conduct any activity in relation to ground control and inundation control.

The intent here is to support the development and providing of competence-based training of people involved in ground control and inundation control activities to ensure they can conduct their work effectively and efficiently.

Since these employees spend most of their time in the mining excavations, they are the first to be impacted by geotechnical events, but they can also be the first capable of recognising any precursors to an event. As such, their involvement and contribution in the overall risk management of geotechnical hazards, are essential to its success.

In defining such a training program, the aspects covered should be relevant to their roles and areas of operation, and would typically include:

- requirements for the different work activities to be conducted
- recognition of change indicators, i.e. cracking, increased seepage, abnormal movements
- identifying and reporting abnormal geological, hydrological and geomechanical conditions
- black-box understanding of excavation design, ground support, dewatering
- hazard control plans (e.g. GCMP, FCMP) and emergency response plans
- proper making safe techniques, and safe approach distances/directions, and
- on-the-job training and assessment.

### **3.5.6 Pillar 6: records management**

Any operating mine or project needs document control and storage systems in place to manage and secure records of documentation and data (physical environment, monitoring, QA/QC and analysis files) used to manage fall of ground and inundation hazards.

It is vital that all technical disciplines use the same up-to-date files and references. There can only be 'one version of the truth' and to achieve this, the following need to be considered:

- Records management system: it is essential to establish systems to manage and secure records of documentation, data and analysis files used to manage fall of ground and inundation risks.

A key component in the overall risk management is the development and maintenance of a comprehensive records management system that covers the management of geotechnical risks in the entire LOM design and schedule and is accessible to all users.

To achieve this goal, records should be kept in a structured and consistent format that allows for analysis and reporting in a way to support design and risk management processes. All information needs to be digitised and stored within a secured platform that will ensure transparency and eliminate the potential for data loss. This can be achieved using a central relational database (structured query language) and digital data collection, integration and storage technologies (e.g. Teams) currently available in the industry.

- Geotechnical engineering reporting: one key aspect in managing geotechnical risk is maintaining fit-for-purpose geotechnical engineering reports.

Geotechnical risk is omnipresent, it changes as mining progress and in certain scenarios it has a seasonal component. The goal here is to introduce all the reporting required to manage fall of ground and inundation risks. In defining the reporting requirements, consideration should be given to the following geotechnical specific documentation:

- Incident reporting
- Geotechnical registers
- Geotechnical design
- Hazard awareness
- Reserve reporting
- Shift change
- Monthly reporting

### 3.5.7 Pillar 7: assurance

Independent and internal audits are routinely completed in the industry to provide assurance that geotechnical risks have been identified and are being managed to acceptable standards. During these audits, due consideration is usually given to the following geotechnical aspects:

- data collection, data sources and data management
- domain definition, major structures and design criteria
- mechanisms, design methodology and analysis
- engineering practices and controls
- groundwater management
- ground support and reinforcement
- excavation stability monitoring systems and practices
- design validation processes
- risk management practices, and
- expertise available to site.

To support these audits, it is essential to routinely conduct site-based assurance that journal the geotechnical risk management activities. This ownership needs to be established, and the process need to incorporate all the goals discussed above:

- Site-based assurance: conduct a monthly site-based assurance that site systems and processes are used to manage fall of ground and inundation hazards are in accordance with all the above goals.

Given the inherent uncertainty and potential impact that geotechnical hazards can have on an operating mine, it is essential that the geotechnical department on the mine complete a site-based audit to demonstrate that site systems are active and applicable in the management of fall of ground and inundation risks in the mine plan.

These assurance activities can form part of what gets reported on routinely, for example a monthly geotechnical report. Note that this assurance exercise is not to provide any resolution to issues identified and it should be limited to evaluating whether a particular design, process or system is still aptly fulfilling its risk management function.

## 4 Discussion

The effectiveness of risk management in mining is fundamentally tied to the integration of sound technical and operational practices with robust corporate governance structures, particularly in geotechnical engineering which requires careful alignment between site-specific operational realities and corporate risk appetite.

This paper has highlighted that geotechnical engineering is not merely a technical function, but a strategic enabler of value creation and protection of the mine plan. The discipline's role in managing fall of ground and inundation hazards places it at the fulcrum of safety, productivity, and long-term asset integrity. However, the complexity of geotechnical risk – driven by natural variability, data uncertainty, and evolving operational conditions – demands a structured and repeatable approach to design and governance.

The seven pillars proposed for a geotechnical engineering standard – ranging from data management to assurance – offer a practical framework for embedding geotechnical risk management into the broader business. These pillars are not standalone; they are interdependent and must be integrated into group-level business processes such as project management, mineral reserve reporting, and critical hazard control. For example, the alignment between the geotechnical design and the LOM plan is essential for a robust mine plan and confidence in the reserve declaration, while the GCMP and FCMP serve as operational vehicles for risk mitigation.

A recurring theme is the need for clarity in roles, responsibilities, and communication. Senior management remains accountable for risk outcomes, yet often relies on technical disciplines to interpret and operationalise risk frameworks. This underscores the importance of competency management, not only in technical execution but also in the ability to communicate risk in a way that informs strategic decisions.

Furthermore, the paper reinforces that risk management is not static. It must evolve with new data, changing conditions, and lessons learned. The inclusion of site-based assurance and performance validation mechanisms ensures that geotechnical risk controls remain effective and aligned with business objectives.

Ultimately, the coordinated activities described in this paper demonstrate how geotechnical engineering can support a company-specific governance model that is both technically rigorous and strategically aligned. By embedding these practices into the operating model of the organisation, mining companies can enhance resilience, improve decision-making, and uphold their license to operate.

## 5 Conclusion

This paper has explored the governance considerations for geotechnical engineering within the broader context of risk management in mining. It emphasised that effective risk management is not solely dependent on the robustness of the process, but equally on the integration of aspects covered under the foundation principles and supporting framework.

For mining companies to manage geotechnical hazards such as fall of ground and inundation effectively, technical disciplines must clearly define and communicate the coordinated activities that support informed decision-making at all organisational levels. Geotechnical engineering plays a critical role in both protecting and creating value for mining operations. To fulfill this role, practitioners must understand and apply the linkages between group standards, discipline-specific processes, and operational requirements.

The seven pillars of a geotechnical engineering standard – data management, design, operational considerations, integrated monitoring, competency management, records management, and assurance – provide a structured foundation for managing geotechnical risk in alignment with a company's risk appetite and tolerance. By embedding these pillars into business processes and aligning them with group governance frameworks, mining companies can enhance their ability to deliver safe, efficient, and resilient operations.

Ultimately, the coordinated activities outlined in this paper offer a pathway for geotechnical engineers to support sustainable mining practices through disciplined risk management and technical excellence.

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