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Rock mechanics best practice in underground mine operations – data, design tools and monitoring

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Review Article

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Abstract

Underground mine safety and productivity depend on robust geomechanical design and effective ground control management under conditions of inherent uncertainty. This paper presents an integrated, best-practice framework for rock mechanics in underground mine operations that links foundational geotechnical data collection and geology-led domaining to the selection and application of empirical, analytical, and numerical design tools. Central to the framework is the development and maintenance of a ground behaviour model and the use of performance-based design to explicitly connect predicted and observed ground response through monitoring, calibration, and continuous design refinement. The framework is structured around stage-based priorities across the mine life cycle, from pre-feasibility studies through early development, sustained operations, and late-life or remnant extraction, recognizing that data availability, decision leverage, and risk profiles evolve over time. Best practices for data acquisition, design tool integration, monitoring, quality assurance and quality control, and communication are discussed, emphasizing the need for closed-loop feedback between engineering design and operational performance.

1. Introduction

Underground mining converts geological resources into value under geomechanical conditions that are often uncertain and constantly evolving. Rock mechanics and, by extension, ground control engineering are key components of safe, economical, and efficient underground operations. Designing, building and then operating an underground mine with successful ground control management requires a balance between safety and cost efficiency: over designed and managed excavation are usually more expensive than necessary, while under-designed and poorly managed excavations introduce both safety and production risks. Underground excavations and their associated support systems should be designed to achieve negligible to minor deterioration over their intended service life under anticipated loading and environmental conditions. Though in some cases, a balanced design may tolerate excavation deterioration in a controlled and well-managed geotechnical environment, which can be achieved through an integrated geomechanical design optimization, ground control management and monitoring. Success in rock mechanics and ground control engineering requires robust geomechanical frameworks that integrate data collection and design inputs, design definition, design implementation, ground control management and monitoring, quality assurance and quality control (QA/QC) and continuous design refinement (workflow summarized in Figure 1).

A practical, mine-wide ground control framework is needed to ensure that designs integrate predicted and observed ground behaviour over the life of an operation. This requires a systematic, performance-based process to verify, calibrate, and adjust engineering designs over the maintenance life of an excavation, or the operating life of a mine. The framework must align with the dynamic nature of underground conditions and the design priorities that evolve with the mine life cycle. To that end, this article demonstrates integrated workflow for geomechanical design and ground control management that (1) begins with targeted data collection and geology led domaining; (2) guides selection of empirical, analytical, and numerical design methods and embeds calibration of designs with a site's ground behaviour model, instrumentation and observed performance; (3) ensures operational implementation through ground control programs, communication protocols and QA/QC across all project stages; (4) formalizes performance based design with monitoring plans and explicit prediction–observation comparison metrics.

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2. Integrated geomechanical design workflow and best practices

2.1 Foundational data collection

Foundational geotechnical data provides the parametric inputs to all types of design tools (empirical, analytical, numerical). At minimum, a best-practice characterization program comprises: (1) geological model; (2) structural model at fault- and joint-scales; (3) hydrogeology; (4) intact strength (including laboratory and index testing) and rock-mass characterization; and (5) in situ stress characterization. These inputs directly support all aspects of underground mine design inclusive of mining method selection, excavation sizing and stability design, excavation planning and sitting, ground support selection, quality assurance and quality control, and risk management.

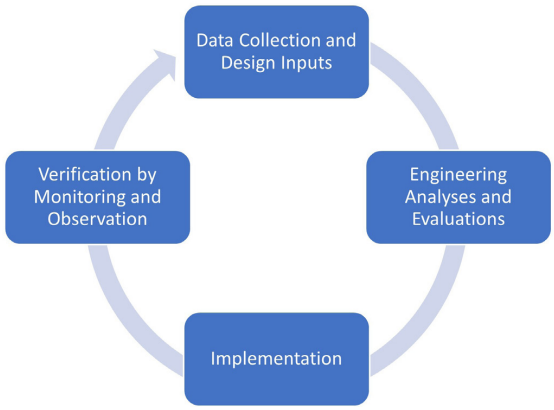


Figure 1. Integrated framework for geomechanical design and ground control management.

The type, location and the amount of data collected will depend strongly on timing across the mine life. A project stage-based approach, as illustrated in Figure 2 and described below, ensures that data collection aligns with decision leverage.

Stage 1 (Pre-Feasibility Study/Feasibility Study)

At the pre-feasibility study (PFS) and feasibility study (FS) stages, geomechanical data collection and design work are intended to support economic evaluations and early mine planning, where there remains significant flexibility to modify layouts, sequencing and support concepts. At this stage, design efforts are primarily focused on identifying and mitigating geotechnical risks whose consequences are most commonly linked to financial investment, capital exposure, and project viability rather than operational execution. Data collection and characterization efforts rely heavily on drilling without underground access. This introduces biases during data interpretation linked to spatial data distributions, as such interpretation assumptions must rely heavily on well founded understanding of site geological conditions. Verification is essential once development begins.

Stage 2 (Early Mine Life)

Early mine life is characterized by a large amount of new underground development and the initiation of production activities. While operational constraints begin to increase, there remains meaningful flexibility to adjust excavation layouts, sequencing, and support designs as site knowledge improves. Geomechanical design efforts during this stage continue to focus on mitigating risks to financial investment and capital exposure; however, safety and production risks are progressively introduced as personnel exposure and operational dependence on excavation performance increase.

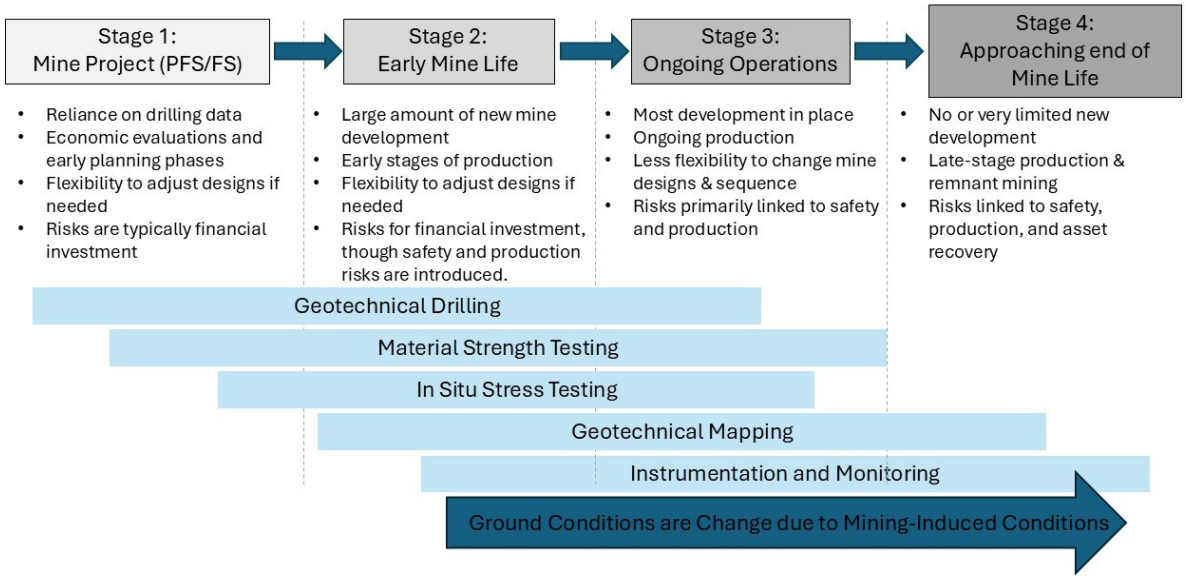


Figure 2. Data collection guidelines by project stage.

This stage represents a high-value window for data collection, during which efforts should be deliberately intensified to fully capitalize on the remaining flexibility to adjust designs. Early mine life data collection builds on the PFS/FS programs, with the added value of underground exposure allowing verification of assumed conditions. During this stage, teams refine geological and structural models and the site geomechanical characterization through systematic mapping, verification of rock strength indices, and underground in situ stress measurements. Instrumentation should be installed as early as practicable to monitor excavation performance in critical infrastructure (such as shafts, large spans in shops, crusher chambers, and ramps) which should be monitored throughout the mine life. Targeted instrumentation in production areas further enables design optimization by providing early observations of stope behaviour and ground support performance.

Further, this is also a critical stage for establishing as-built capacities of key design inputs, particularly ground support systems, through verification testing such as bolt pull testing, shotcrete thickness and strength testing, and installation audits to confirm the appropriateness of support standards and verify installed capacity under site conditions. Higher testing frequencies are typically justified at this stage compared to later mine life to reduce uncertainty and support calibration. Also, formal QA/QC programs should be established to govern ground support installation, drilling and blasting practices, and excavation performance verification.

Stage 3 (Ongoing Operations)

During ongoing operations, most major development is in place and production activities are well established. At this stage, there is considerably less flexibility to modify mine designs and sequencing, and geomechanical decision-making is increasingly constrained by operational realities. As a result, risks are primarily linked to workforce safety and production continuity, with design efforts focused on managing variable conditions, controlling dominant failure mechanisms, and maintaining excavation performance.

During ongoing operations, geomechanical data collection is used primarily to support tactical adjustments, such as localized ground support modifications or minor sequencing changes, and design tool calibration, with diminished opportunity for strategic redesign. Data collection at this stage is generally less detailed than during early mine life, though practices must be maintained to ensure changing conditions are detected. Data collection efforts should be prioritized based on the conditions that exhibit the greatest variability and those that control the most common modes of ground failure, including rock strength, jointing characteristics and rock mass quality, faulting or other structures, and groundwater conditions. Failure and damage mechanism observations are critical. Where conditions are highly variable, increased data collection is required; where conditions are consistent, routine verification such as spot mapping may be sufficient.

Routine damage mapping and LiDAR (Light Detection And Ranging) surveys should be initiated and maintained to establish baselines and track excavation performance over time. Routine quality control remains important. For example, pull testing is required to verify ongoing installation quality of ground support. Instrumentation systems should continue to be installed, expanded and maintained in new mining areas and where observed failure mechanisms warrant monitoring.

Stage 4 (Approaching End of Life)

Late-stage mine life is characterized by little to no new development, with production increasingly focused on late-stage extraction and remnant mining. At this stage, operational flexibility is minimal, and geomechanical risks are primarily linked to workforce safety, production continuity, and the recovery of remaining mineral assets.

In late mine life, the objectives of geomechanical data collection shift toward supporting remnant stoping, rehabilitation planning, ongoing design tool calibration, and understanding and managing elevated geotechnical risk. Ground conditions may continue to evolve as mining progresses, including increased rock mass damage and yielding, deterioration and corrosion of ground support, stress shadowing and/or loading effects associated with extensive stoping, and changes in groundwater inflow patterns and permeability. Data collection at this stage should therefore focus on routine inspections to identify changing conditions, including signs of ground movement and ground support degradation, supported by systematic verification of the performance of both new and aging support systems through pull testing and corrosion monitoring. Damage mapping and LiDAR surveys should be conducted to quantify rock mass deformation over time, while groundwater inflow mapping is required to track evolving hydrogeological conditions. These activities provide critical inputs for residual risk management and ensure that late-stage mining and asset recovery are conducted safely and effectively.

Effective and efficient collection of suitable geomechanical data requires a thorough understanding of the site-specific geological conditions (Palleske et al., 2017). Assessing susceptibility to different ground reaction mechanisms and the utilization of design tools appropriate for specific geomechanical design applications are critical to ensure focus on appropriate data types. With an in-depth understanding of the geological setting for the given project, a conceptual model of ground reactions that are likely to occur can be developed to ensure that the data required to characterize problematic areas or changing ground conditions is collected in sufficient detail. Figure 3 provides examples of tailored collection of geomechanical data types according to the expected rock mass failure mechanism. It is therefore important to know and understand the geologic setting at the outset of a project and then tailor the data collection for that particular environment (Kalenchuk et al., 2020).

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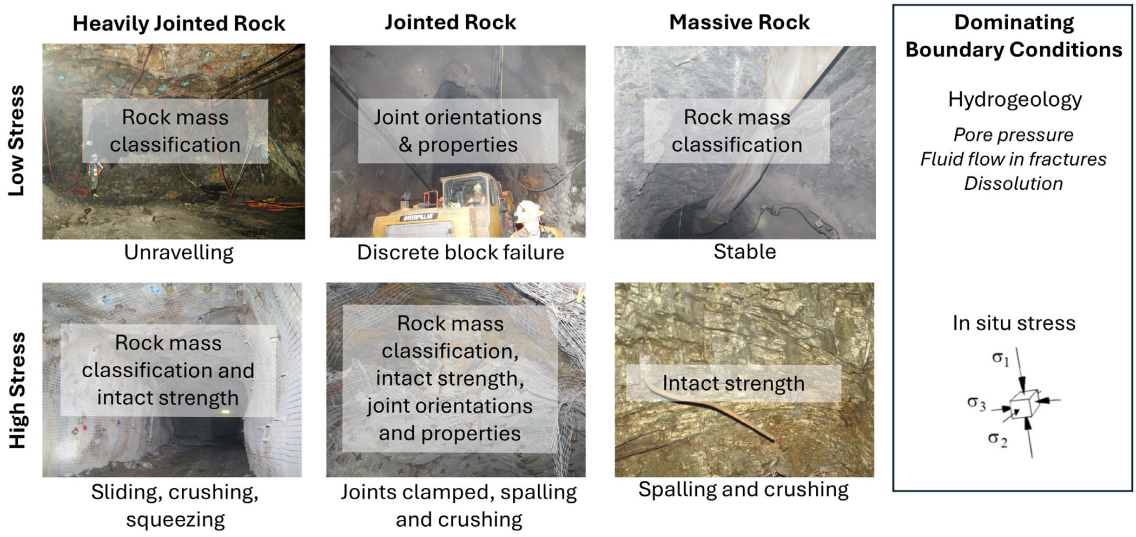


Figure 3. Anticipation of failure mechanism and key data types for targeted data collection efforts.

The alignment of geomechanical data collection based on the understanding of the site geology is fundamental to effective and efficient data acquisition, and for the ability to confidently apply our geomechanical interpretations to site-specific conditions. Of note, it is also critical that data collection technique limitations are understood and acknowledged as demonstrated by Hadjigeorgiou (2012).

Emphasis on specific geomechanical data types may also vary according to the design application. For example, ground support design can be conducted by empirical, analytical and numerical tools. All of these rely on rock mass classification and mechanical properties of intact rock for the parameterization of ground conditions. Numerous rock mass classification systems exist for categorizing ground conditions, and understanding the geological setting enables practitioners to more effectively utilize appropriate systems for application to design. Consider the Q' and Q classification systems are most commonly applied systems to widely accepted empirical ground support design (Barton et al., 1974; Potvin & Hadjigeorgiou, 2016), while GSI (Geological Strength Index) (Marinos et al., 2005) is generally required for rock mass parameterization (Hoek & Brown, 2018) applicable to numerical modelling. However, in special cases, alternative classification systems may be more appropriate, for example to characterize very weak squeezing rock mass by W-MRM (Weak Rock Mass Rating) (Warren et al., 2016, 2018). While data collection is often tailored to specific classification systems, collection of "raw" conditions where practical is a best practice to ensure opportunity for multiplicity of data application to various classification systems. For example, describing a joint surface as rough and planar holds value over simply logging a Jr (Joint Roughness Number) value of "1.5" as "1.5" does not discern between rough and planar vs. slickensided and undulating.

Similarly, laboratory testing should focus on specific mechanical properties that are most relevant to the expected ground reaction based on the geological conditions. Beyond standard uniaxial, triaxial and tensile strength parameterization, more specialized testing less typical for underground projects may be appropriate. For instance: slaking susceptibility and/or swelling pressure tests are critical for rocks with high clay content, direct shear testing of natural fractures is critical for the parameterization of anisotropic conditions at the rock mass-scale.

Domaining geomechanical data is the process of identifying how ground conditions may vary spatially and temporally for a given project. To this regard, ground conditions include rock mass quality, rock strength, and boundary conditions as well as ground reaction and failure mechanism. Spatial domaining is almost always consistent with geological constraints, such as lithological units, changes in structural conditions, or alteration type and intensity. Therefore, it is best practice to align interpretation of spatial variability with geological controls. Defining geomechanical domains based on geological controls ensures alignment between geological and geomechanical interpretations, adding value to project development and execution by establishing a shared, consistent framework for decision-making.

Further, mining projects typically have significantly more geological data available than geomechanical data. When geological and geomechanical interpretations are integrated, the existing geological data can be used as a proxy for geomechanical data allowing the extrapolation of geomechanical characterization throughout a domain defined by the more extensive geological information. However, extrapolation to a larger geological data set requires reliance on a sound geological database. As such, when planning a data collection program, it is relevant to ensure that the geological characteristics which will control stability are being logged in meaningful manner.

For instance, if rock strength is affected by alteration, the type(s) and intensity of alteration should be explicitly included in the geological logging process using standardized descriptors for the project. These geological characteristics can then be used to define and refine geomechanical domaining which may not be obvious from geomechanical data alone.

Ideally, data collection, assembly and interpretation evolve to the development of a ground behaviour model. A ground behaviour model is a compilation of all available site geomechanical data (Palleske et al., 2017). During early design phase (pre-construction) this may include raw geotechnical data (geotechnical mapping and core logging, laboratory results, etc.), specific domains of rock mass conditions, geology (lithology, structure, alteration, etc.), excavation design geometries, groundwater data. Once construction is underway, additional information should be added to the ground behaviour model, for example: additional raw geomechanical data (mapping, core logs, laboratory results), updated domains of rock mass conditions, more detailed geology (lithology, structure, alteration, etc.), as-built excavation and updated design geometries, instrumentation data, ground support performance, damage and mechanism mapping, falls of ground or failures, water (volume or rates of inflow, changes in ground water state induced by the excavation construction).

The development and ongoing maintenance of a ground behaviour model is a critical element of the geomechanical design process, particularly in environments where evolving conditions or unexpected ground response can have significant safety or economic consequences (Kalenchuk et al., 2020). The systematic compilation, analysis, and spatial interpretation of data, together with the identification of hazard implications, supports a robust understanding of the underlying mechanics prior to design definition. This process streamlines design development and promotes pragmatic, defensible design outcomes.

Once the ground behaviour model has been developed, it can be used to classify ground response. Ground response categorization defines the significance of observed or anticipated ground reactions in relation to hazard and risk and is typically site-specific, reflecting the available risk-mitigation measures. Individual ground responses can often be linked to a particular stress–strain path (within an acceptable tolerance) or controlling geological feature. Consequently, for forward prediction, practitioners can reasonably infer that similar stress–strain paths or geological controls are likely to result in comparable categories of ground response.

2.2 Integration of design methods

Effective geomechanical design in underground mining requires the appropriate selection and combined use of empirical, analytical, and numerical design tools, depending on the level of study (e.g. pre-feasibility, feasibility, early mine life) and on the design application. Empirical tools leverage rock mass classification systems and case histories to provide design constraints. Analytical tools (closed-form or simplified models) test specific mechanisms (for example, wedge stability). Numerical models (continuum/explicit) resolve constitutive response to imposed stress and/ or strain states. Numerical models are ideal for evaluating interaction effects, complex geometries, and influence of excavation/ extraction sequences; they are indispensable for mine-scale studies. Sophisticated numerical stress models often rely on a broad suite of specific input data, the quality and quantity of which can be highly variable. While advanced modelling tools are valuable, simple models applied with limited but well-understood data can still provide meaningful insight. In the absence of deliberate efforts to identify and collect the geomechanical information required to support higher-fidelity analyses, even the most sophisticated models may be constrained by input uncertainty and risk being mistaken as more precise or reliable than justified by the supporting input data. A disciplined calibration framework is required to generate a reliable representative numerical model.

Usually, design tools are inter-related (e.g. numerical stress models are required to define inputs for empirical evaluations; for example, empirical stope design (as demonstrated by Potvin, 1988; Mawdesley et al., 2001) and empirical pillar design (as demonstrated by Martin & Maybee, 2000)) and are almost always applied in unison. This emphasizes the idea that no single design method is sufficient on its own, because each tool type provides a different lens through which rock mass behaviour can be interpreted, validated, and optimized at a certain project stage. Practical workflows often begin with analytical and empirical checks when mechanisms are clear and geometries are simple; and then numerical analyses are introduced as complexity grows or where interactions and stress path evolution control rock mass behaviour.

The robust application of any design tool depends on accurate site characterization and ground behaviour models. However, small changes to assumed classification and/or material properties, or to boundary conditions can shift predicted rock failure modes impacting local excavation stability or broader global mine design; hence, best practice is to conduct sensitivity and scenario analyses. In operational settings where monitoring and observational data are available, design tool calibration can replace parametric and boundary condition sensitivity testing, though scenario analyses for forward prediction often remain relevant to support trade-off evaluations and design decision making. Calibration turns monitoring into design guidance.

2.3 Communicating design, design implementation, and QA/QC

Effective design communication, implementation, and quality control collectively form the critical link between engineering intent and operational practice. Even the best geomechanical designs require disciplined execution to ensure that the assumptions, inputs, and safety margins embedded in the design are faithfully carried out underground.

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Effective design communication requires clear exchange of technical information among key technical stakeholders, including rock engineering, geology, and mine planning, and the translation of design intent into practical work instructions. Robust communication protocols are foundational to an effective ground control program. Among technical stakeholders, best-practice ground control communication focuses on establishing a shared and consistent understanding of geological and geotechnical conditions, while remaining pragmatic and relevant to operational teams. This is supported by the use of standardized descriptors and terminology. For example, explicitly linking geomechanical domains to geological controls, which ensures that data collection and interpretation by different personnel are comparable, objective, and meaningful for downstream analyses. Consistent terminology enables stakeholders to speak a common language and supports the integration of geological and geomechanical interpretations, providing opportunity to maintain continuity in the assessment and communication of ground behaviour throughout the mine life.

Equally important is the clear communication of ground control design bases and intent to non-technical stakeholders. Support patterns, excavation geometries, sequencing strategies, and monitoring requirements must be conveyed in practical, actionable formats suitable for operational supervisors and crews. Ongoing, bi-directional exchange of observational data, hazard indicators, and monitoring results are critical. Continuous communication between technical and operational teams facilitates early detection of changing ground conditions and ensures that key observations, such as deformation, ground support deterioration, or unexpected geological features, are rapidly incorporated into the ground behaviour model and associated risk-management workflows. This feedback loop strengthens decision-making by keeping interpretations aligned with real-time conditions and enabling timely adjustments to designs, support strategies, and operational plans.

Rock engineering provides the technical basis for excavation geometry, sequencing, and support requirements, etc., while ground control programs define how these designs are developed, implemented, monitored, and adapted. Rock engineering, ground control, mine planning, and operations must be effectively integrated to ensure that geomechanical designs can be executed though safe and productive underground practices. Designs must be developed with a clear understanding of development schedules, production priorities, and resource availability, ensuring that engineering intent is achievable within operational constraints.

Close coordination with mine planning ensures that excavation layouts, sequencing strategies, and production rates are compatible with stability requirements constrained by geotechnical knowledge. Changes to geometry, sequence, or schedule, can alter stress paths, exposure times, and excavation interactions. Further planning-motivated design changes can potentially invalidating rock engineering design assumptions if not reviewed and managed. Similarly, operational realities, such as equipment availability or access constraints, must be considered during design development to avoid operationally imposed deviations that introduce may ground control risk.

Collaboration between engineering, planning, and operations supports a proactive rather than reactive approach to ground control. Multi-disciplinary integration strengthens the alignment between design constraints and actual mining conditions and reduces the likelihood of unplanned ground control hazards. Ultimately, effective integration across these disciplines improves decision-making, enhances safety, and supports production efficiency by ensuring that ground control risks are actively managed within the broader operational framework of the mine.

Quality control and quality assurance are fundamental to achieving the expected geomechanical performance and maintaining the integrity of design. Typical QA/QC activities in ground control focus on ensuring that ground support systems and excavation practices meet design intent and perform reliably in the field. These activities commonly include routine pull testing of ground support to verify installed capacity, shotcrete quality assurance such as thickness and strength checks, and installation audits to confirm proper bolt length, spacing, resin mixing, and plate seating. They also involve ongoing inspections and damage mapping to assess excavation performance, identify deterioration, and validate design assumptions. In addition, QA/QC procedures incorporate instrumentation monitoring; for example, bore hole instruments (such as extensometers), instrumented ground support elements (such as SMART cables) and high-resolution survey technology (such as LiDAR scans) measure deformation and support performance, forming a critical feedback loop for continuous excavation stability and support system design refinement.

Design communication, design implementation and QA/QC are integral components of best-practice ground control management in underground mining operations. Design defines the engineered intent. Effective communication ensures that the right information is provided to the right people in a timely manner. QA/QC confirms that work is executed correctly, consistently, and to the required standard. A resilient and adaptive ground control framework integrating these components enhances safety, reduces uncertainty, and supports efficient production across all stages of mining. Such a framework is often established as, or within, a Ground Control Management Program (GCMP).

A well structured GCMP integrates geotechnical data, design tools, monitoring outputs, and risk-mitigation procedures to manage ground stability throughout the mine life. Robust GCMPs emphasize best practice, engineering rigor, and continuous improvement. The core components of a GCMP include:

- Documented standards and procedures for excavation design, ground support selection, installation practices, QA/QC, rehabilitation, and hazard identification;

- Training and competency development expectations for ground support crews, miners, engineers, and supervisors. All of whom require role-specific training to understand ground hazards, proper operational methods, and how to recognize deviations or warning signs;
- Ground hazard assessment and management controls including routine inspections, damage mapping, risk assessments and trigger-action response protocols (TARPs). Well established ground hazard assessment and managing controls ensure timely identification and appropriate escalation of changing ground conditions;
- Communication and reporting procedures which integration engineering interpretations, monitoring alerts, worker observations, and operational decision-making. Clear communication channels reduce the likelihood of unrecognized or poorly understood hazards;
- Management of Change procedures which formalize processes that include engineering review and risk assessment to ensure that modifications to sequencing, excavation geometry, support standards, or other aspects of ground control are managed.

2.4 Performance-based design: continuous design refinement and residual risk management

A key objective of geomechanical engineering in underground mines is to develop design solutions that are mutually safe, productive, and economical while meeting a range of project and operational constraints. Success in achieving this lofty objective is challenged by two key limitations inherent to geomechanical engineering practice: (1) data limitations and parameterization uncertainty and (2) lack of universal guidance regarding the acceptability of rock engineering design.

Uncertainty is intrinsic to rock engineering practice in underground mining; geomechanics practice is fundamentally constrained by inherent data limitations, even in well-instrumented and mature operations. A primary limitation arises from the sparse and biased nature of geotechnical data acquisition. Subsurface conditions are spatially heterogeneous and only partially observable, requiring engineers to infer rock mass behaviour from limited and often imperfect data. Key design inputs, such as rock mass strength and deformability as well as in situ stress are rarely directly measurable at the scale relevant to underground excavations and mining operations. Temporal variability further complicates geomechanical data reliability. Rock mass behaviour evolves as mining progresses due to stress path changes, damage accumulation, time-dependent deformation, groundwater redistribution, etc. Data collected at one stage of mine life may not remain representative as conditions evolve, reducing confidence in static design assumptions and emphasizing the need for continual verification.

Hoek (1991), in the First Müller Lecture, emphasized that there are no simple or universal rules governing the acceptability of rock engineering designs. In particular, Hoek (1991), highlighted the absence of a direct relationship between factor of safety and excavation performance. No universal factor-of-safety threshold can guarantee successful integration of safety with acceptable performance for underground excavations in complex rock masses. Engineers are required to interpret and predict how rock masses will behave and align that behaviour with excavation performance objectives. This relies on critical integration of engineering judgement informed by a combination of practical experience and rigorous theoretical analyses. Where established guidelines are lacking, reliance on engineering judgement and practical experience may become a significant source of risk, especially for practitioners with limited field exposure or site-specific knowledge.

Performance-based design directly addresses data limitations and parameter uncertainty, and the absence of universal criteria for determining the acceptability of rock engineering designs. Reliance on observation and measured ground response and applying this to design tool verification and calibration is the premise of performance-based design. Performance-based design is effectively the application of feedback loops to rock engineering and ground control. Implementation iteratively requires field performance observations, monitoring data, so that remediation activities can feed back into the design process, enabling refinement and continuous improvement. Performance-based design concepts have long been applied in the field of geomechanics. Martin (2023) provides a comprehensive demonstration of this applicable to slopes design, with overarching themes transferable to underground mining context.

Critical to performance-based design are geomechanical monitoring systems. The type and application of geotechnical monitoring systems is wide ranging, inclusive of instrumented ground support systems, surficial and sub-surface deformation monitoring, micro-seismic monitoring, hydrogeological monitoring, and more. Both short and long-term monitoring can be applied to performance-based design. Monitoring periods can be distinct to design tool calibration objectives; broadly, the application of short- or long-term monitoring are typically local and global design applications, respectively – though exceptions are made.

Performance-based design shifts the focus from strictly prescriptive standards (design assumptions) to observed and measurable ground behaviour (e.g. expected displacement, support load, stress redistribution, failure mode), enabling engineers to refine and optimize designs based on how the rock mass responds during mining. Rather than assuming that input parameters and modelling outputs are representations of reality, performance-based design uses real-time information to validate, challenge, and improve design assumptions.

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The design remains dynamic; adaptable to continuous refinement of geological interpretations, site geomechanical knowledge base and mining progresses. Continuous refinement ensures the design remains aligned with actual conditions. Mechanisms for continuous refinement include (1) updating of key design parameters, (2) integration of monitoring data into calibration of all design tools (inclusive of numerical, empirical and analytical methods), (3) adaptive hazard and failure mechanism assessments, (4) feedback loops with operations.

As a best-practice principle, performance-based design should be incorporated in some form to all underground mine operations. By focusing on observed ground response, continuous monitoring, and adaptive design refinement, performance-based design becomes fundamental not only to safety, but also to the optimization of ground control strategies and mining outcomes. Though, despite the substantial benefits of performance-based design to rock engineering and ground control, uncertainty can rarely be fully eliminated - even from the most robust and continuously refined designs. Residual risk management closes the loop of the integrated geomechanical design workflow by ensuring that all remaining hazards are identified, actively monitored, controlled and mitigated. Effective residual risk management involves tracking changes in ground conditions through routine inspections, instrumentation, damage mapping, and groundwater monitoring, ensuring that unexpected ground reactions are identified early and incorporated back into the ground behaviour model for continuous refinement. It also requires anticipating likely failure mechanisms and maintaining the ability to adapt excavation designs and support systems or operational plans as new information emerges. Where controlled deterioration is acceptable, residual risk management defines the tolerance limits within which excavation behaviour remains safe and economical, emphasizing that not all ground reaction indicates failure but must still be actively monitored and managed.

3. Conclusions and recommended practice

Effective rock mechanics and ground control in underground mining require an integrated, performance-based approach that recognizes and actively manages uncertainty throughout the mine life cycle. This paper has demonstrated that geomechanical design cannot be reduced to a single method, model, or set of prescriptive criteria. Instead, robust and defensible outcomes are achieved through the deliberate integration of targeted data collection, geology-led domaining, appropriate selection and calibration of empirical, analytical, and numerical design tools, and disciplined implementation through ground control management systems.

Inherent limitations in geomechanical data availability, quality, and representativeness mean that design assumptions must be treated as hypotheses rather than fixed truths. Performance-based design provides a structured mechanism to progressively test, verify, and refine these assumptions using observed ground behaviour, monitoring data, and operational feedback. By explicitly linking prediction to observation, performance-based design reduces uncertainty, improves confidence in engineering decisions, and enhances both safety and productivity.

The effectiveness of any geomechanical framework ultimately depends on execution. Clear communication of design intent, rigorous QA/QC, consistent terminology, and strong integration between rock engineering, geology, mine planning, and operations are essential to translating engineering design into safe and reliable underground practice. Ground control management programs provide the operational backbone through which this integration is achieved and sustained.

Finally, while uncertainty can rarely be eliminated, it can be actively managed. Continuous design refinement and residual risk management ensure that changing conditions, unexpected ground response, and late-life challenges are identified early and addressed systematically. Mines that institutionalize these practices are better positioned to balance safety, production continuity, and economic performance over the full life of operation.

Based on the integrated framework presented, the following practices are recommended for underground mining operations:

- Establish a structured workflow that links data collection, ground behaviour modelling, design tool selection, monitoring, and design refinement across all mine life stages;
- Use geology-led domaining and anticipated ground response to prioritize data types, locations, and intensity of collection, focusing effort where decision leverage and risk are greatest;
- Apply empirical, analytical, and numerical methods in complementary fashion, recognizing their respective strengths, limitations, and data requirements. Avoid over-reliance on high-fidelity models unsupported by adequate input data;
- Use monitoring, observation, and operational feedback to calibrate design assumptions, verify predicted behaviour, and refine support and excavation strategies over time;
- Deploy instrumentation and observational programs early in mine life, focusing on critical infrastructure and dominant failure mechanisms, and maintain these systems to support long-term calibration and risk management;
- Ensure that ground support installation, excavation practices, and monitoring data are verified against design intent through consistent QA/QC procedures and clearly defined communication channels;
- Coordinate design, sequencing, and operational decisions to ensure geotechnical assumptions remain valid as mine plans evolve, and manage changes through formal review and risk assessment;

- Recognize that not all ground response indicates failure, but all significant response must be monitored and evaluated. Define acceptable performance limits, trigger thresholds, and response actions tailored to site-specific risk tolerance;
- Maintain and update the ground behaviour model as a living record of observed performance, and use lessons learned to improve future designs, standards, and practices.

By embedding these practices within a structured ground control management program, underground operations can move beyond reactive ground control toward a proactive, adaptive, and performance-driven approach that supports safe, efficient, and resilient mining throughout the mine life.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Katherine S. Kalenchuk: conceptualization, methodology, writing – review and editing. Carla M. Carrapatoso: conceptualization, writing – original draft. Anna Perry: conceptualization, methodology.

Data availability

No dataset was generated or evaluated in the course of the current study; therefore, data sharing is not applicable.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) Copilot with the aim of ensuring content developed by the authors is presented in concise and well-structured language as well as in summarizing paper content for the abstract and conclusion. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

FS	Feasibility Study
GCMP	Ground Control Management Program
GSI	Geological Strength Index
Jr	Joint Roughness Number
LiDAR	Light Detection And Ranging
PFS	Pre-Feasibility Study
QA/QC	Quality Assessment / Quality Control
SMART	Science Monitoring And Reliable Telecommunications
TARP	Trigger-action response protocol
W-MRM	Weak Rock Mass Rating

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