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The role of a geotechnical risk profile to manage financial expectations associated with underground mine plans

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Abstract

One of the challenges in mine planning is to account for the geotechnical risk that may affect the feasibility and profitability of the plan. Geotechnical risk links to the uncertainty and variability of the geomechanical properties and behaviour of the rock mass that may impact the stability and performance of mine openings. Thus, geotechnical risk can have significant safety and financial consequences if not properly assessed and managed.

To address this challenge, a geotechnical risk profile (GRiP) is introduced as a tool developed internally to summarise and communicate the risk associated with a given mine plan in terms of the potential financial impact. The GRiP is based on a rating system that quantifies geotechnical risk using site-specific observations and mining outcomes. It considers the potential consequences of geotechnical failure in terms of safety, production, cost, and reputation.

A GRiP is a dynamic tool that can be updated periodically to reflect the changing geotechnical conditions and performance of the mine plan, and any changes introduced in the plan. The GRiP can also be used to compare different mine plans, scenarios and support risk-informed decision-making in mine planning.

The GRiP is not a substitute for detailed geotechnical analysis and design, but rather a complement that provides a high-level overview of the risk situation. The GRiP can help prioritise mitigation and improvement actions and communicate the risk to relevant stakeholders.

This paper discusses how to use geotechnical block models and other data sources to build a spreadsheet-based GRiP model that can help evaluate different scenarios and options.

The paper covers three aspects:

1. *Identifying what factors contribute to the geotechnical risk associated with a mining layout, plan, or schedule.*
2. *Creating a GRiP that supports design confidence, quantifies the monetary value of risk exposure, and allows for informed decision-making.*
3. *Visualising geotechnical risk in a 3D model using a simple approach.*

Keywords: *implicit modelling, extraction ratio, rock mass modelling, geotechnical model for rapid Integration, geotechnical risk profile*

1 Introduction

A need exists to be more accurate in mine plan budgets and forecasts across a mining portfolio. For any given mine plan, geotechnical considerations play an important role in understanding the relative level of risk associated within the plan. The geotechnical risk profile (GRiP) has been developed as the primary 'tool' to summarise and communicate the geotechnical risk associated with a given mine plan for underground

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operations. The GRiP quantifies geotechnical risk using a rating system based on site-specific observations and mining outcomes.

The approach of utilising practitioners' experience to quantify risks presents a significant shift from traditional risk assessment methodologies. By incorporating the insights and practical knowledge of seasoned professionals, this method bridges the gap between theoretical risk models and the nuanced realities of the field. It allows for a more dynamic and responsive risk management strategy, where qualitative observations are translated into quantifiable data. This can lead to more informed decision-making processes, as it provides a tangible measure of risk that can be weighed against potential rewards. Ultimately, this methodology acknowledges the value of human expertise in navigating complex risk landscapes.

Many factors could contribute to the geotechnical risk of mining an orebody. This could include amongst other things:

- poor or unknown rock mass conditions
- large-scale structures – associated with either poor conditions or in extreme cases seismic activity
- the use of aggressive mine planning parameters, which may exceed what the rock mass could sustain
- inappropriate mining sequence, which could result in localised high stress concentrations and additional ground support requirements
- inappropriate mining method, which can increase the access risk of the mining area as well as the opened stope stability
- inappropriate placement of permanent infrastructure, such as declines that are exposed to geotechnical hazards and adverse geotechnical conditions
- inundation from saturated materials or high water pressures encountered at depth in structurally controlled systems (faults/shear zones) or unsealed exploration holes.

The GRiP provides a platform for incorporating geotechnical design considerations against known production outcomes to measure compliance of a mine plan to design guidance.

This paper discusses how to use geotechnical block models and other data sources to build a GRiP that can help evaluate different scenarios and options. The reader should note that this approach is not intended to replace conventional engineering risk assessments, it is merely an alternative method for evaluating risk using a novel approach.

Comparing this approach with alternative methodologies for quantifying geotechnical risk yields notable observations. Certain methodologies prioritise statistical modelling derived from historical data, contrasting with others that emphasise expert judgment and qualitative evaluations. Each methodology possesses distinct advantages: quantitative models furnish robust, data-centric insights, while qualitative assessments excel in capturing nuanced aspects that evade easy quantification. Combining multiple methodologies could potentially establish a more holistic risk assessment framework, harmonising empirical data with expert insights to enhance decision-making efficacy in geotechnical projects.

2 Risk profile inputs

To construct an apt risk profile, it is imperative to have information on what is important in the physical geotechnical environment, for the specific mining method employed and for the risk appetite within the proposed mine plan. The typical main inputs into the GRiP are discussed below.

2.1 Geology model

A sound knowledge of the latest lithological and large-scale structure exposures and the presentation of it in a model is essential for the development of a GRiP. The presence of weak lithological units or poor rock mass conditions associated with large structures has a significant bearing on the level of geotechnical risk associated with a particular stope design. Large structures could also be prone to seismic activity if the mining-induced stress state is conducive to the development of excess shear stress on the structure. Where the stability of mine excavations is impacted by the direction of mining in relation to structure orientation, this should be duly considered as a risk driver.

2.2 Physical geotechnical environment knowledge

All available geological and geotechnical data is used to construct a rock mass model and spatially represent important geotechnical observations. Whether the controlling factors are related to rock type, alteration, rock mass fabric, intact rock strength, rock mass strength or large-scale structures, it is important that the right data is collected with sufficient coverage to minimise uncertainty in the selected properties. Ultimately there must be a level of confidence that can be allocated to a rock mass model that represents the physical geotechnical environment.

2.3 Geotechnical model for rapid integration (GMRi)

A well-constructed GMRi combines geological knowledge, rock mass classification data and numerical modelling results in a comprehensive 3D space (Hamman et al. 2017).

In the underground context, the GMRi also captures suggested mine planning guidance, e.g. stable stope spans (hydraulic radius) or stable pillar dimensions. This information can then be used to characterise stopes in terms of the geotechnical setting.

2.4 Mine planning/production schedule

To associate a GRiP with any specific mine plan, the following information is the minimum required for the stope centroids included in the schedule:

- Stope name and ID
- Stope location (easting, northing, elevation)
- Orebody/domain
- Scheduled start and completion dates
- Schedule tonnes
- Schedule gold (Au) grade
- Scheduled Au ounces (oz)

This information is exported from mine planning scheduling software packages in CSV format to allow integration with geotechnical software.

3 Workflow to develop a geotechnical risk profile

The workflow to develop a GRiP consists of four steps, as represented in Figure 1, and are discussed by means of a sensitised real-world example in the following sections.

Figure 1 Stepped process of developing a geotechnical risk profile

3.1 Define the geotechnical risk drivers

In any mining environment there are several geotechnical hazards that need to be considered in the mine plan. Since the impact of these hazards will vary between mine plans, it is important to understand what drives the risk in the mine plan. As such, when defining the geotechnical risk drivers, consider how different hazards have impacted operations based on different layouts, sequencing and scheduled execution as specified in the mine plan.

The most effective way of determining the geotechnical risk drivers is to focus on experience based on local site observations and include items listed based on geotechnical design. Further consideration should be given to items that an experienced site-based geotechnical engineer or reviewer would normally consider in a geotechnical design for the specific mine plan.

The following is an example of the risk drivers used for a life of mine (LOM) evaluation of an underground mine:

- **Lithology:** Where stoping and development have occurred inside the Ultramafic lithology, production rates and stope overbreak have been impacted significantly due to the faster degradation in the exposed rock mass. Mitigation requires an understanding of where this unit is in space and when it will be intersected in the plan to allow for proactive ground control.
- **Structure (large-scale):** Some large-scale structures are known to impact production and ground conditions that may cause production delays.
- **Stress state:** As mining progresses deeper, the impact of mining-induced stress will need to be considered. A preliminary evaluation of the potential impact of stress is presented as a series of depths below surface (e.g. <700 metres below the surface (mbs) localised damage in drives and minor overbreak in stopes; <1,000 mbs spitting in brittle rock masses and squeezing in the highly altered rock masses; >1,000 mbs large seismic events). These elevations are currently viewed as trigger points where a step change in the rock mass response to stress is expected and needs to be validated through observations and further analysis.
- **Seismic response potential:** Current observations suggest that future seismic potential is likely to be associated with shear failure of large structures. The hazard rating considers an expected excess shear stress value obtained from numerical modelling, that is indicative of the in situ loading of the structure.

3.2 Define criteria to evaluate risk drivers

Risk drivers can be assessed individually, or as a combined risk factor by multiplying the individual ratings.

3.2.1 Individual risk driver assessment

This is done by first establishing a rating system for the assessment of each risk driver. The example shown in Table 1 explains the rating system determined for the set of risk drivers previously discussed.

The ratings assigned to the identified risk drivers for initial assessment are presently uncalibrated and strategically chosen to distinguish between favourable and unfavourable outcomes. Exploring potential improvements in future studies could involve considering more granular criteria or refining the rating scales to better differentiate between different risk factors. This could lead to a more nuanced understanding of each driver's impact on overall geotechnical risk.

Table 1 Individual risk driver assessment

Driver	Risk driver assessment		
	Potential impact	**Description**	**Rating**
Lithology	Low	Andesite	1
	Moderate	Ultramafic	2
Stress state	Low	Work level above 1,600 mRL	1
	Moderate	Work level between 1,600 and 1,300 mRL	2
	High	Work level below 1,300 mRL	3
Structure (large-scale)	Low	No structures within 25 m of a stope	1
	Moderate	One structure within 25 m of a stope	2
	High	Two or more structures within 25 m of a stope	3
Seismic response potential	Low	ESSEXP < 1 MPa	1
	Moderate	ESSEXP up to 3 MPa	2
	High	ESSEXP > 3 MPa	3

The individual hazard rating integrates site-specific knowledge and observational data, complemented by back-analysed numerical modelling results. This comprehensive approach ensures that the rating accurately reflects the actual performance of a site. When sufficiently reconciled, this system can be effectively linked to a formal site risk ranking matrix, enhancing the decision-making process for risk management and mitigation strategies.

3.2.2 Combined risk

The risk drivers can each contribute to a combined risk. It is thus important to consider the compounding effect of the individual drivers through the multiplication of the numeric risk values as shown in Equation 1:

$$\text{Rating}_{\text{Lithology}} \times \text{Rating}_{\text{Stress}} \times \text{Rating}_{\text{Structure}} \times \text{Rating}_{\text{Seismic Potential}} = \text{Overall Risk Rating} \quad (1)$$

Once the compounded risk value has been calculated, three risk categories are defined based on a numerical range that would best explain the risk context as can be experienced onsite. Table 2 is an example of how the risk values are contextualised.

Table 2 Geotechnical risk profile context

Potential impact	Overall risk rating range	Context (site specific)	Considerations
Low	<=4	Normal operating conditions	Maintain sound operational discipline
Moderate	4–12	Potential for minor stope overbreak and operational delays	Consider a discounted production rate, additional ground support or rescheduling
High	>12	Significant overbreak is expected and operational delays are inevitable	Strict geotechnical controls required. Consider resequencing, or accept a significantly discounted mining rate

3.3 Building the GRiP

The geotechnical risk model must be constructed in such a way that it is easily representable graphically, statistically and visually in any mine planning software package. Hence, the simplest approach to meet this demand is to build the model as a table in CSV format (e.g. Microsoft Excel). This allows for integration with mine scheduling and visualisation software and provides an opportunity to make use of pivot tables to summarise data.

The following sections show an example of how the individual risk drivers are evaluated and rated.

1. Export stope centroids with associated mine planning/scheduling data
    - This information is typically obtained from mine planners and forms the basis for the geotechnical risk model.
2. Associate geotechnical risk driver information with stope centroids
    - This process is best completed using specialised software (e.g. Leapfrog Geo [Seequent 2023] or Gem4D [Basson 2023]) to superimpose information from a resource block model, GMRi and structure model onto each centroid.
3. Create risk model summary table
    - The risk model summary table combines all the inputs and allows for the calculation of a compounded risk rating using the criteria determined for the site using simple spreadsheet capabilities. The summary spreadsheet, which ultimately forms the final GRiP, will contain the following main components as demonstrated in Figure 2.

Mine scheduling Information												
Easting	Northing	Elevation	DOMAIN	Start Year	Start Month	SOLID_ID	Volume	Tonnes	Density	au	Ounces	lithology
49546	100185	1512	A	2027	6	1	3031.9	8687.7	2.9	1.7	476.4	AND
49525	100219	1470	B	2028	9	2	9003.7	25665.7	2.9	2.0	1691.1	AND
49536	100214	1494	C	2028	5	3	7962.0	23083.8	2.9	2.3	1734.8	BIF
49684	100532	1515	D	2028	8	4	15316.9	43205.3	2.8	5.3	7369.0	SCH
49715	100628	1568	E	2025	8	5	21116.0	57518.2	2.7	3.2	5876.9	AND

Risk Driver Ratings				Risk Calculations		
Litho rating	Stress rating	Structrure rating	Seismic rating	Overall score	Overall Rating	Rating Class
1	2	1	2	4	1	Low
1	2	3	2	6	2	Mod
3	3	3	3	12	3	High
1	2	1	1	2	1	Low
1	2	1	2	4	1	Low

Figure 2 Main components of the geotechnical risk profile

3.4 Presentation of the geotechnical risk profile

The GRiP is generally presented graphically to provide an overall presentation of the geotechnical risk associated with a specific production schedule in a mine plan. It is preferable to express risk in terms of the potential to impact ounces, but it can also be presented as the impact on other production metrics such as ore tonnes produced, or development metres achieved.

Figure 3 shows an example of how individual risk drivers are represented as a function of risk to ounces for individual orebodies.

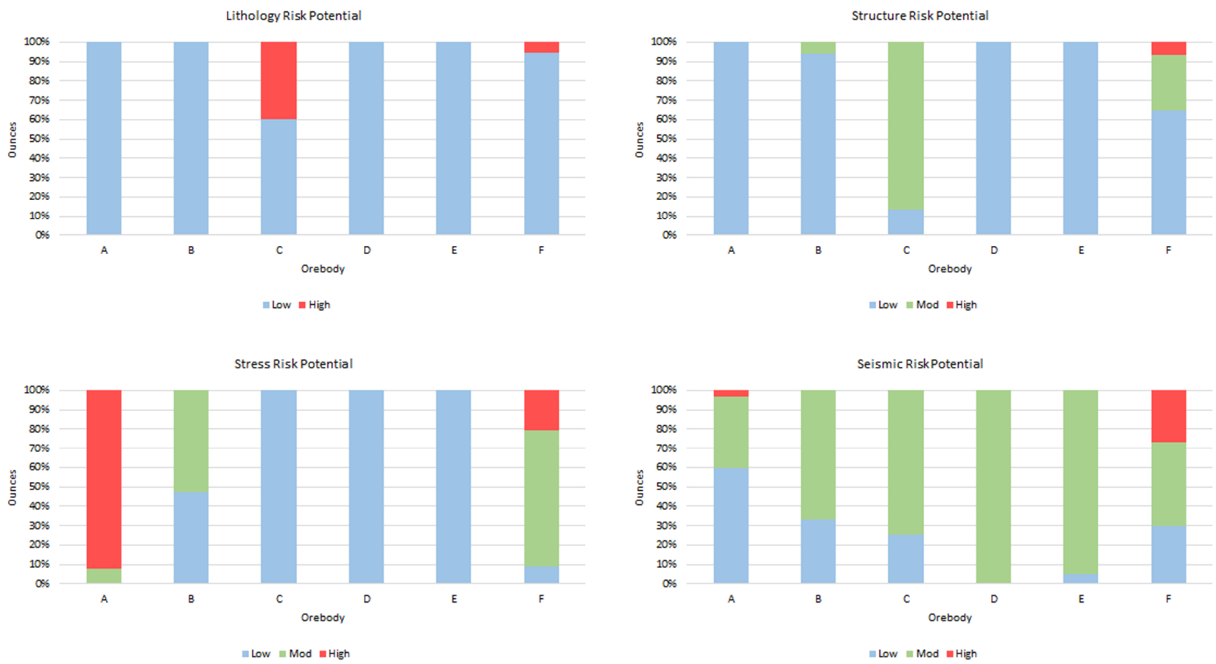

Figure 3 Representation of individual risk drivers

A key input into a mine's quarterly updated plan is an explanation of the geotechnical risk associated with the plan. This could comprise a detailed view of a 12-month schedule or an overall impression of the LOM schedule as per Figure 4.

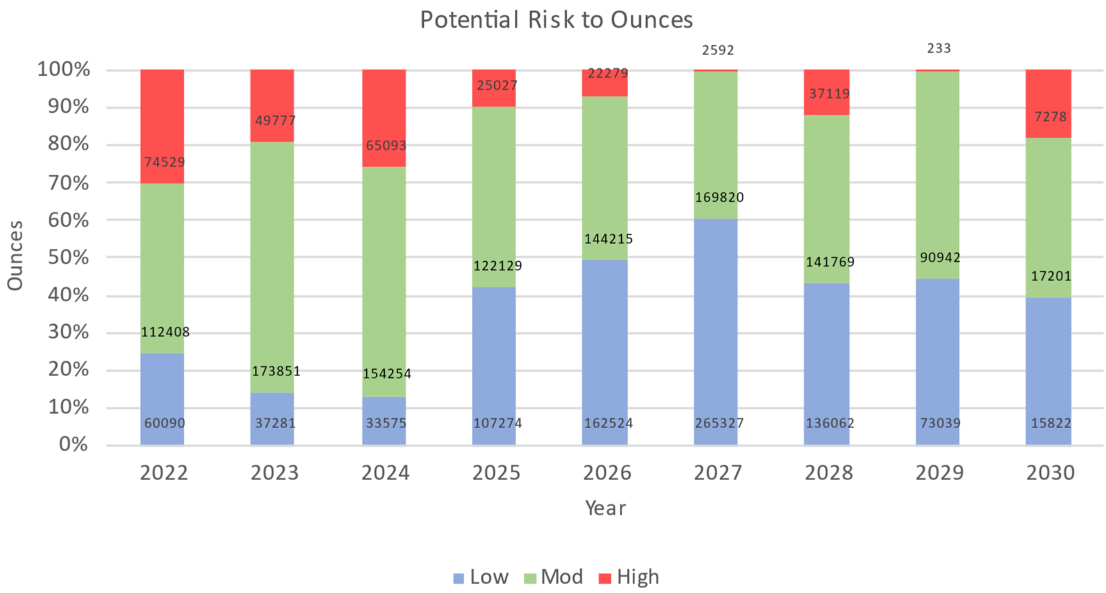

Figure 4 Geotechnical risk to ounces for a LOM production plan

Because the GRiP is available in CSV format, a 3D visualisation is also possible which will allow users and reviewers an opportunity to relate to the risk profile in real space and time. Figure 5 shows an example of a 3D visualisation of the GRiP.

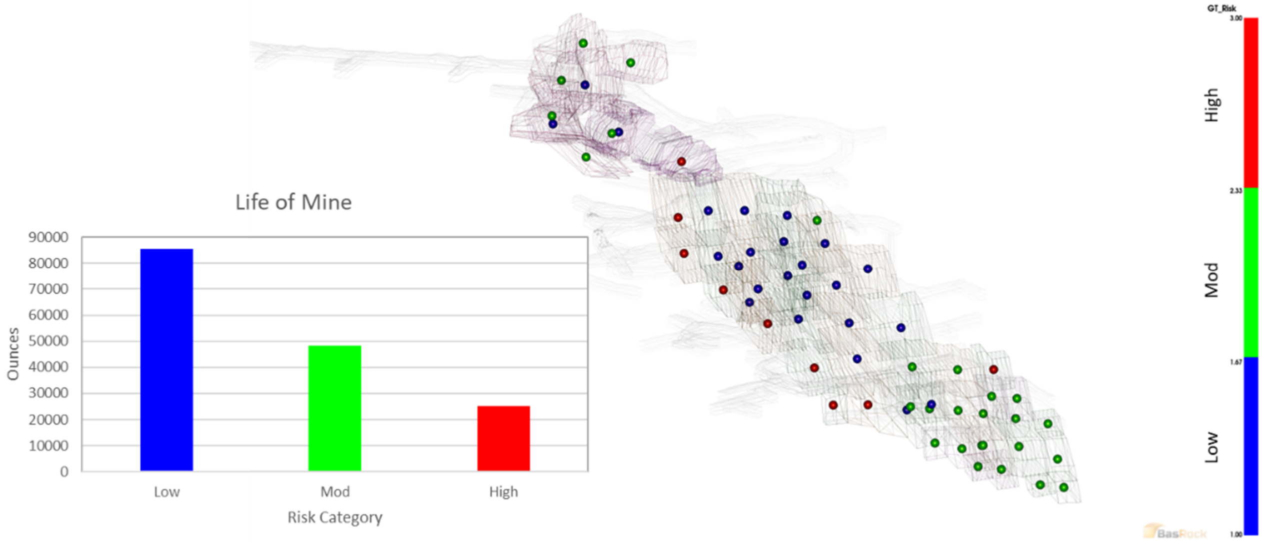

Figure 5 Spatial representation of a geotechnical risk profile

The GRiP output should be fed back into the production schedule to provide mine planners with prompts to manage and address geotechnical risk aspects.

4 Conclusion

Geotechnical risk plays a critical role in the mine planning process as it has a significant impact on the feasibility of the project. This risk is primarily associated with the geological and geotechnical characteristics of the site and involves evaluating factors such as rock mass stability, groundwater conditions and soil properties. Accurate assessment and management of geotechnical risk are essential to ensure the safe and efficient operation of the mine, as well as the economic viability of the project.

The GRiP system provides valuable support in the context of risk-informed decision-making endeavours aimed at prioritising mitigation actions and communicating risks to stakeholders. The GRiP functionality streamlines the process by identifying the highest priority mitigation activities, while also conveying pertinent risk information to stakeholders clearly and concisely. By leveraging the capabilities of the GRiP system, mining executives can make informed decisions that are based on a comprehensive understanding of risks and their potential impact on the financial outcome of a business plan.

Acknowledgement

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Numerous other readily accessible publications exist online that endeavour to confront this challenge. The authors duly acknowledge the contributions of others and seek to underscore that while the underlying concept is not new, their proposal introduces a fresh practical approach designed to assist site practitioners in assessing risk.

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