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Establishment of geomechanical risk profiles from inelastic continuum modelling results

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Abstract

The geomechanical risk assessment methodology described in this paper aims to provide a risk 'road map' for a given mining sequence. The approach makes use of mine-scale inelastic continuum numerical models. The primary objective of these models is to capture the mining-induced stress, deformation and yielding changes within the rock mass as the mining sequence unfolds. Modelling results are then used to establish geomechanical risk profiles based on mining-induced stress and plasticity criteria. Pre-mining conditions and post-mining states are investigated not only from a geomechanical viewpoint, but also from a production/operational perspective over the mine's life.

The assessment of the conditions just prior to mining is meant to evaluate how challenging mining of a given stope is expected to be. Two types of mining challenges are considered: (i) stopes anticipated to be mined under high stress conditions, and (ii) stopes anticipated to be mined under low/residual conditions (i.e. in relaxed and damaged areas). The assessment of the post-mining conditions around each stope also includes two other types of mining challenges: (iii) unplanned dilution off the exposed surfaces, and (iv) stopes likely to trigger an excessive energy release in the surrounding rock mass.

Stope risk ratings for each of these mining challenges are established in terms of the number of tonnes of production (or quantities of metal) likely to encounter these challenges over time; in quarterly intervals, for example.

Based on these risk profiles, relevant design adjustments, control procedures and/or monitoring programs can be put in place if, where and when necessary. The methodology can also be used to compare different mining scenarios, methods and sequences.

Keywords: *continuum 3D inelastic modelling, geomechanical risk profile, high stress, residual conditions, unplanned dilution, seismicity, life of mine simulations*

1 Introduction

An approach is proposed to efficiently use mine-scale inelastic continuum models for the management of geomechanical challenges related to deep mining. The primary objective of mine-scale numerical models is to capture the mining-induced stress, deformation and yield changes in the rock mass as the mining sequence unfolds. The geological interpretation, rock strength testing data and local stress measurements (or, when unavailable, some estimate) are used as direct inputs to the models.

Modelling results are usually plotted, which typically generates a substantial amount of graphs. Those can be stress-related (e.g. magnitudes along different orientations, principal components, deviatoric values), displacement and strain-related, velocity-related (at given grid points), plasticity-related (e.g. shear or tensile failure), etc. Understanding these plots, which represent physical quantities and mechanical behaviours, is

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often restricted to engineers, technologists and scientists. Making practical use of these direct outputs is also not necessarily straightforward.

The proposed approach is meant to provide an alternative and more practical manner in which to look at numerical modelling results. It is a visual tool, which allows numerical analysis results to be quickly converted to a format more comprehensible, understandable, and is better suited overall to other stakeholders. It is meant to be a decision tool for mine planners and/or managers to better appreciate the geomechanical risks associated with various mining sequences. It can be used to compare various extraction scenarios or sequences more reliably and easily, and within the time frame of interest, such as monthly, quarterly or yearly.

2 Methodology

A typical geomechanical risk profile provides the number of tonnes of production (or quantities of metal) likely to encounter a specific ground control-related challenge over time. For example, it can represent on a single image the number of stopes, tonnes of production or quantities of metal anticipated to be mined under high stress conditions over the life of mine in quarterly intervals.

Four geomechanical challenges for deep mining operations are identified and grouped into two categories:

- Category I focuses on the assessment of the ground conditions just prior to mining and is meant to evaluate how challenging the extraction of a given stope is expected to be. Two types of mining challenges are considered: (i) stopes anticipated to be mined under high stress conditions, and (ii) stopes anticipated to be mined under low/residual conditions (i.e. in relaxed and damaged areas).
- Category II focuses on the assessment of the post-mining conditions around each stope and includes two other types of mining challenges: (iii) unplanned dilution from the exposed surfaces, and (iv) stopes likely to trigger an excessive energy release in the surrounding rock mass, possibly resulting in seismic conditions.

One risk profile is produced for each of the four challenge types. Criteria based on mining-induced stress and plasticity (obtained from modelling results) guide the establishment of risk profiles. Thus the chosen criteria are central to the proposed approach. Their current formulation will be presented in Sections 3 and 4. Note that these criteria are constantly being refined and improved as experience is gained with this methodology.

Note also that the identified challenges are not exhaustive and that others could be contemplated, such as the anticipated behaviour of development. This paper focuses on stope excavation rather than development.

Undeniable advantages of the proposed approach are its repeatability, its quantitative aspect and its systematic nature. The criteria are scripted in Python, enabling the risk profiles to be easily extracted from simulation results. When comparing two mining sequences the same criteria are applied, making comparison easy. The fact that each of the four challenges can be visualised over time in one single image is a significant advantage over having to scan through a substantial number of plots, which can sometimes be analysed subjectively.

Note that this paper does not aim to discuss best modelling practices: the focus is instead on the exploitation of results.

The numerical simulations used to establish the proposed methodology were completed using *FLAC3D* software, an Itasca 3D continuum code designed to simulate stress changes throughout a rock mass with a plastic behaviour. The ability to represent materials using plastic constitutive models is essential for rock masses as it allows the model to reproduce changes in their behaviour as they fracture and lose strength. The model should have enough resolution to represent each individual stope in the mining sequence.

The proposed approach could also be used to interpret results from discontinuum codes, and further thoughts on the analysis criteria should then be given.

3 Assessment of the pre-mining conditions

The pre-mining conditions assessment – the evaluation of the geomechanical conditions that prevail in a stope just prior to starting its extraction – is intended to estimate how challenging that stope can be expected to be when entering production. The following subsections describe the methodology and criteria used to establish the geomechanical risk profiles for the two mining challenges associated with Category I, as well as examples of the results obtained.

3.1 Risk of mining under high stress conditions

Stopes excavated in highly stressed areas are likely to generate local seismicity, require more rehabilitation and/or be affected by drilling challenges, potentially causing, in turn, production uncertainties and risks such as schedule delays, rework and possibly some ore losses in the worst cases. Lead primary stopes are generally more prone to be excavated under high stress conditions but poorly designed secondary stopes can also be challenging.

Stress conditions during mining or, more accurately, at the onset of mining, are inferred from the *FLAC3D* modelling results. Each numerical zone (or element) within each stope in the model is classified low, moderate or high in terms of stress magnitude, based on its deviatoric strength ratio (DSR, expressed as $(\sigma_1 - \sigma_3)/UCS$)) just prior to mining. A global risk rating is then assigned to each stope, based on the percentage of its numerical zones that were assigned a low, moderate or high risk rating.

The criteria shown in Table 1 were applied to derive the risk rating for each numerical zone within the stopes based on Cotesta et al. (2014). Other authors (e.g. Board et al. 2001) have suggested lower category thresholds but those in Table 1, being higher, provide a more realistic risk profile in our view.

Table 1 Definition of the high stress risk rating for each numerical zone within the stopes

Risk category	Criterion
Low	$(\sigma_1 - \sigma_3)/UCS < 0.5$
Moderate	$0.5 \leq (\sigma_1 - \sigma_3)/UCS < 0.7$
High	$(\sigma_1 - \sigma_3)/UCS \geq 0.7$

For each stope, the percentage of numerical zones rated low, moderate and high is subsequently computed and assigned a stope risk rating based on the methodology shown in Figure 1a. In this ternary plot a stope is represented by a single point, with the percentages of low, moderate and high zones within it being read on each axis. An example is given in Figure 1b: this stope would be assigned a low stress rating based on the categories shown in Figure 1a.

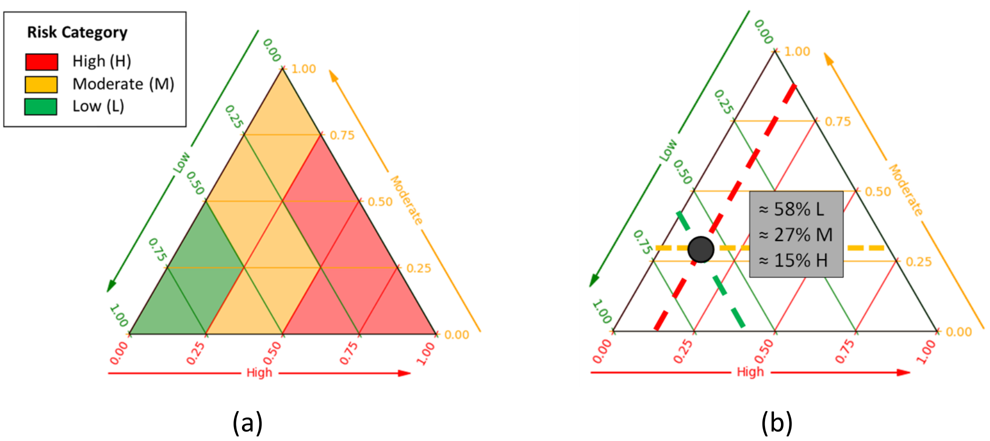


Figure 1 Methodology to assign a high stress risk rating to each stope from the deviatoric strength ratio in each of its numerical zones: (a) Stope risk rating criterion; (b) Data point example

It can be seen in Figure 1a that if at least 50% of a stope's numerical zones are highly stressed prior to mining (based on the criteria expressed in Table 1), the stope is ranked high, regardless of the percentage of low and moderate zones.

An example is given in Figure 2. Each data point on the ternary plot represents a stope to be mined, superimposed on the stope high stress risk rating criterion. The total number of stopes in each risk category is also shown. In this example, 130 stopes out of the 574 planned (or roughly 23%) are forecasted to be excavated under high stress conditions for the mining sequence considered.

Stress Rating	Count	%
High	130	22.7%
Moderate	151	26.3%
Low	293	51.0%

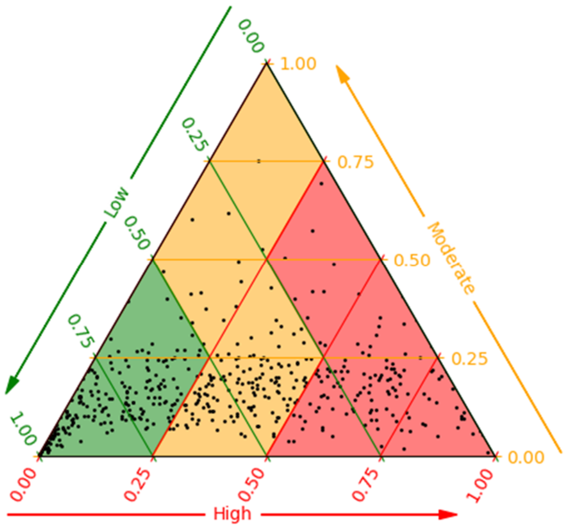
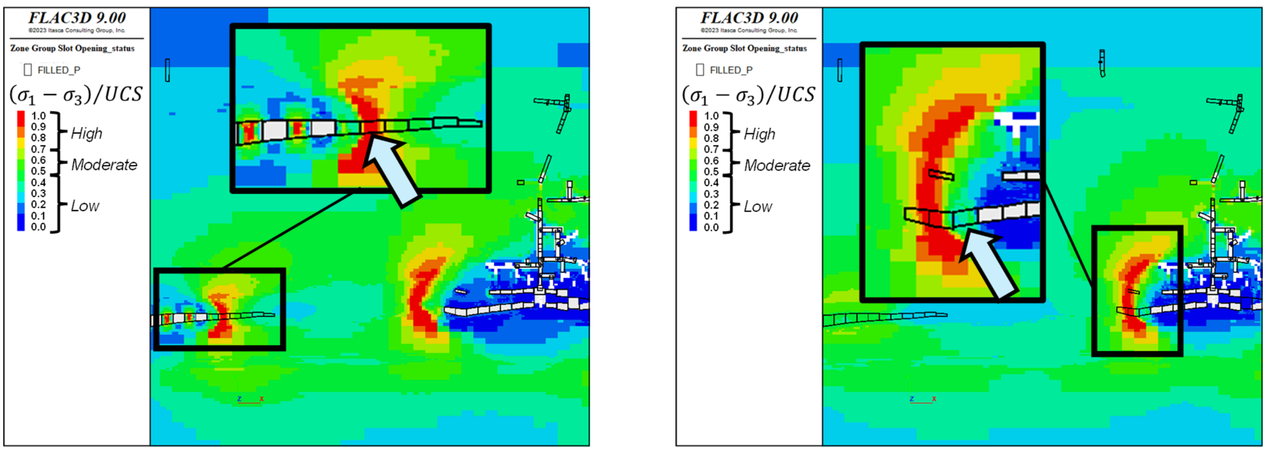


Figure 2 Example of high stress risk rating associated to a given mining sequence

The risk rating can also be plotted spatially to investigate trends (using Deswik attributes, for example). In the example above, further investigation of the spatial risk rating distribution has shown that high stress stopes are mostly primary stopes, whereas low stress stopes are mainly either secondary or pillarless stopes.

Plan view plots of the DSR showing pre-mining conditions around a primary and a pillarless stope are shown in Figures 3a and 3b, respectively. These plots do show the pre-mining conditions of each stope, but their full assessment and appraisal for each and every stope can be quite tedious. Not all primary stopes will necessarily be highly stressed prior to mining: in fact, only 55% of the primary stopes are rated high in the example shown. The proposed approach provides an immediate and systematic appreciation of how many stopes will be affected by high stress conditions when recovered.

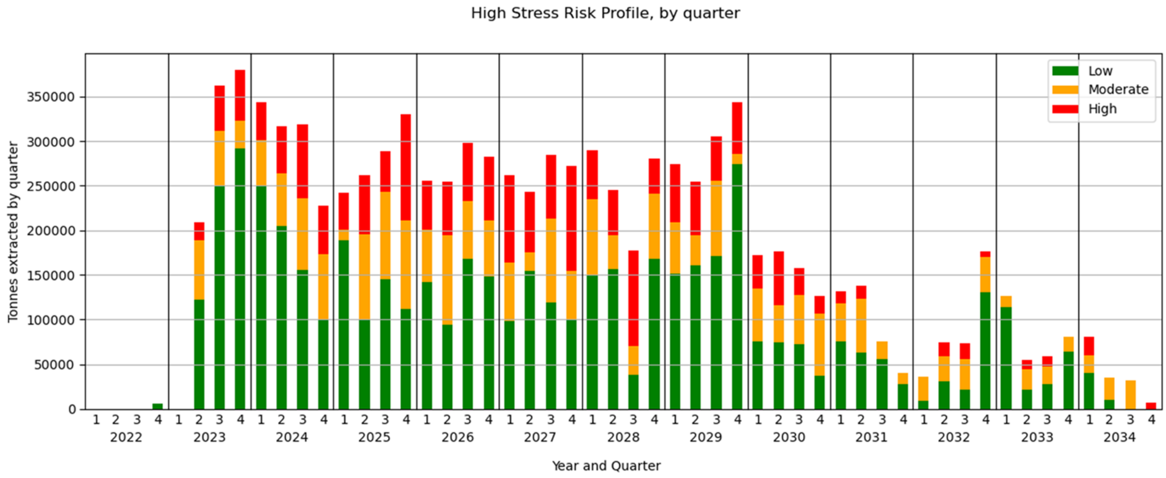


(a) (b)

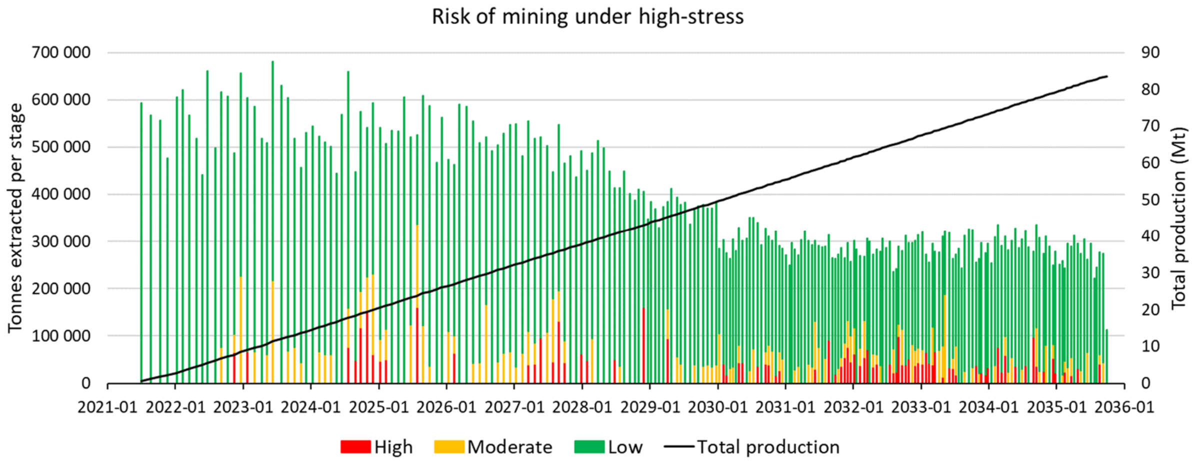
Figure 3 Plan view plots of deviatoric strength ratio showing pre-mining conditions: (a) Around primary stopes; (b) Around a pillarless stope

Two examples of risk profiles obtained from evaluation of the high stress hazard are presented in Figure 4. These bar charts show time (quarterly based) on the *x*-axis and the tonnes of ore planned at each of these time steps on the *y*-axis, subdivided by low (green), moderate (yellow) and high (red) categories of high stress conditions. Each vertical bar represents the production planned during the corresponding quarter (Figure 4a), or by groups of 10 stopes in sequential order of extraction (Figure 4b). The mine in Figure 4a is deeper and more highly stressed than the one in Figure 4b and is already existing (the risk profile was hence established for the remaining life of mine sequence). The mine from Figure 4b starts at shallow depth and gets deeper over time, and its risk profile was established over the entire planned mine life. The following is observed:

- In Figure 4a, high stress stopes are forecasted at nearly every quarter over the remaining life of mine, except towards the end. At the end of the life of mine there are less lead stopes and more (largely yielded) secondary stopes.
- In Figure 4b, there are no high stress stopes at the beginning of the sequence. Further investigation of the spatial risk rating distribution in this case has shown that peaks of high stress stopes correspond to the mining of sill pillar stopes and/or when mining fronts were merging.



(a)



(b)

Figure 4 Examples of risk profiles for high stress mining conditions: (a) Case corresponding to Figure 3 (deep mine); (b) New mine starting at shallow depth

These graphical representations provide a rapid answer to questions such as at what moment in the mining sequence, or at what point in time, sill pillar stopes or converging mining fronts can be expected to start becoming challenging to recover. The difference between a pillarless stope approach and a primary/ secondary sequence can be visually ascertained quickly with this type of plot.

3.2 Risk of mining under residual conditions

At the other end of the spectrum lies the situation where mining is conducted under residual post-peak conditions (i.e. far past its peak strength and in significantly damaged rock, and under low confining stress). Stopes mined under such circumstances are likely to cause ground support challenges and production delays due to rehabilitation, blastholes ravelling and subsequent redrilling. Stopes mined under residual conditions are typically secondary stopes.

The softening index can be used to assess this rock mass condition. It is defined by Equation 1 and shown graphically in Figure 5. It equals 1 if the rock mass has not yet reached failure, and 0 if the residual strength has been reached.

$$Softening_{index} = \frac{(\text{Actual value} - \text{Residual})}{(\text{Peak} - \text{Residual})} \tag{1}$$

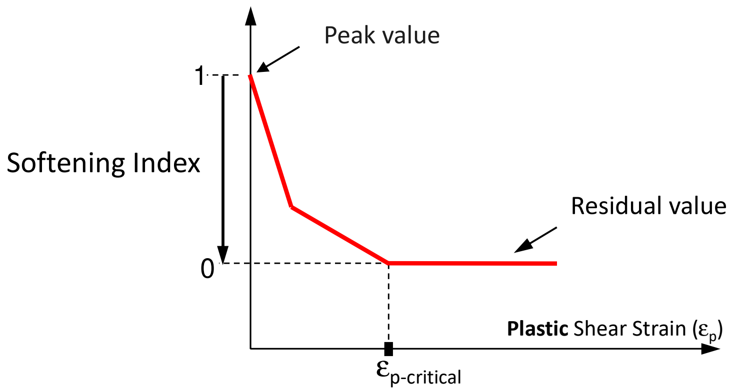


Figure 5 Schematical definition of the softening index

The softening index (or normalised plastic shear strain) is used instead of the actual plastic shear strain for the interpretation of modelling results because the critical cumulative plastic shear strain ε_p (the strain at which the rock mass reaches its residual properties) depends on the size of the numerical zones (Lorig 2013). This justifies the need to normalise the plastic shear strain.

The rock mass state and confinement conditions prior to mining each stope in the sequence are again inferred from the *FLAC3D* modelling results. Each numerical zone in each stope in the model is evaluated at the mining step just prior to its extraction and it is verified whether:

- the zone is post-peak
- the softening index is lower than:
  - 0.2 for the cohesion and friction angle
  - 0.999 for the tensile strength (this higher value reflects the brittleness of the rock mass tensile failure).

If applicable, a numerical zone is then classified as potentially residual. Its stress state is then verified and, if the confining stress (σ_3) magnitude is lower than 2 MPa, that numerical zone is considered residual.

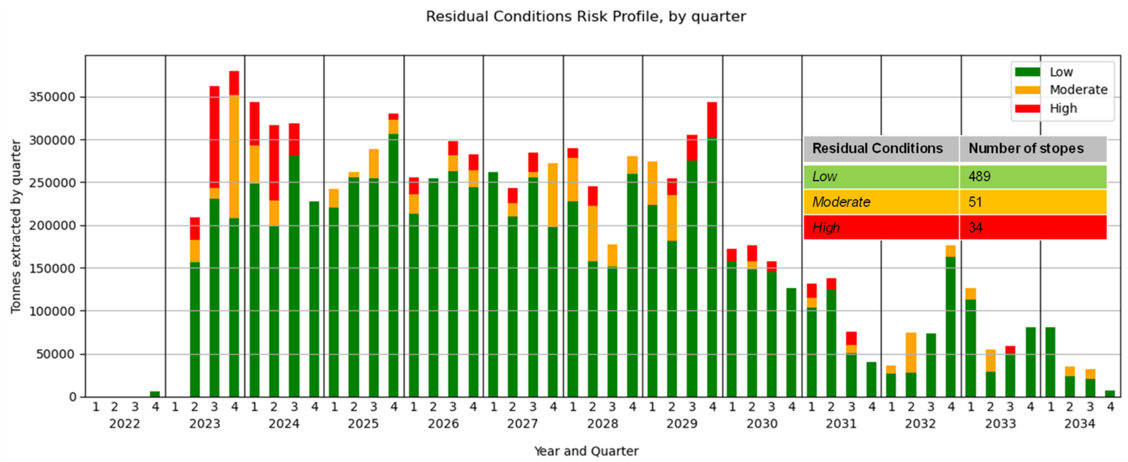
When the above criteria are met the rock mass can be expected to be significantly damaged and the confinement insufficient to hold the unstable ground together. The residual state is verified for each numerical zone just prior to mining. A risk rating (again low, moderate or high, to remain consistent) is then assigned to each stope based upon the percentage of its numerical zones that were classified as residual. The stope risk rating criterion currently used is shown in Table 2.

Table 2 Definition of the residual conditions risk rating for each stope

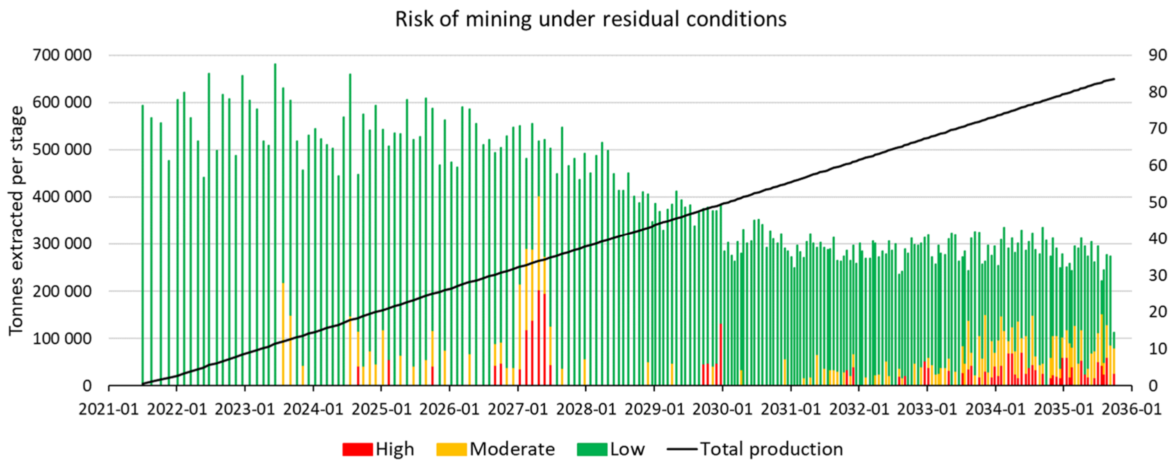
Risk category	Criterion
Low	Residual stope volume < 15%
Moderate	15% ≤ residual stope volume < 30%
High	Residual stope volume ≥ 30%

Two examples of a risk profile for residual conditions are given in Figure 6. The following observations are made:

- In both cases, most stopes (85 and 88%, respectively) are rated low and consequently are not forecasted to be mined under residual conditions.
- In both cases, most stopes rated high and moderate are secondary stopes (60 out of 85 stopes [71%] for the case presented in Figure 6a).
- Further examination of the spatial distribution showed that a cluster of stopes rated high in Figure 6a was located on levels close to historical mining. The concave shape of the historical mining front in that area most probably explains the residual rock mass conditions prior to mining.
- Similarly, the peak observed in Figure 6b in 2027 corresponds mostly to secondary stopes from shallow levels located near historical mining.



(a)



(b)

Figure 6 Examples of risk profiles for mining under residual conditions: (a) Case corresponding to Figure 4a; (b) Case corresponding to Figure 4b

For the first example (Case a), sensitivity analyses were conducted on the criteria as follows:

- The softening index threshold was raised from 0.2 to 0.3, resulting in a numerical zone being considered potentially residual earlier in the damage process.
- The deconfinement threshold was raised from 2 to 4 MPa, resulting in a numerical zone being considered deconfined at a higher level of confinement.

It was found that the risk profile was not significantly affected by these changes. Changing the softening index threshold to 0.3 resulted in having 16% of the stopes rated high or moderate instead of 15% (as originally). Increasing the deconfinement threshold to 4 MPa resulted in having 22% of the stopes rated high or moderate.

3.3 Global pre-mining conditions assessment

Merging the risk of mining under high stress conditions with the risk of mining under residual conditions into a single global production risk profile can further simplify the assessment of a given mine design, mining method and/or extraction sequence. Only stopes to which a high risk was assigned for either high stress or residual conditions hazards are considered in the global risk profile. A given stope cannot be rated high for both hazards: the rock mass needs to be close to intact to sustain high stresses and, inversely, a damaged rock mass cannot sustain high stresses. To simplify the interpretation of this analysis, moderate stopes are excluded.

Accordingly, each stope can globally be flagged either as a high stress stope, a residual conditions stope or an 'ok' stope. A fourth category was added to highlight those stopes with one portion highly stressed and another portion highly damaged. These stopes are referred to as combined stopes.

An example of this risk merging is shown in Figure 7. This case is the same as in Figures 4b and 6b.

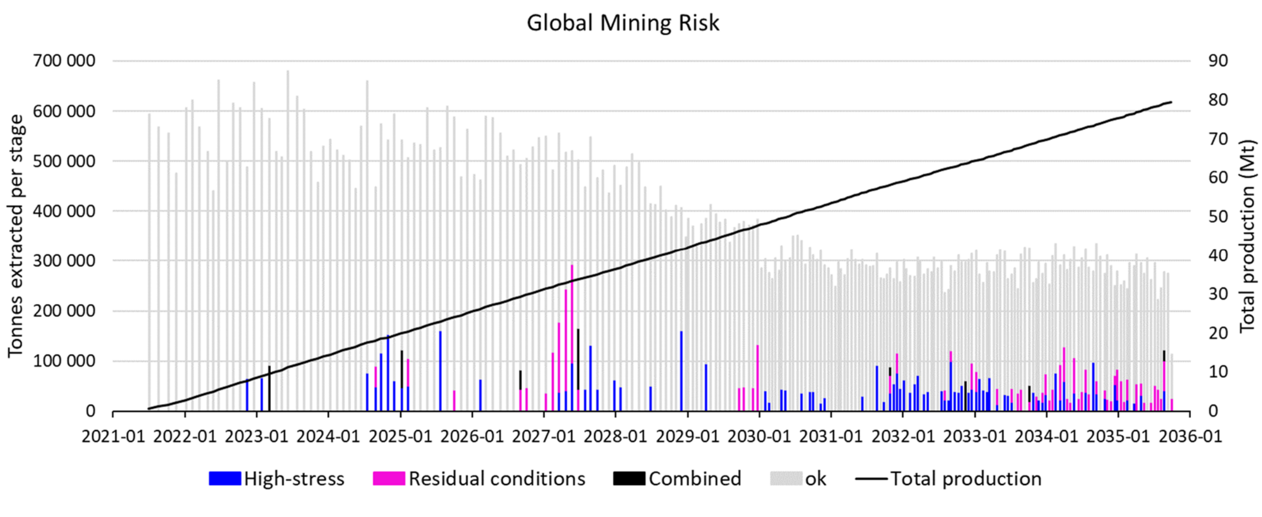


Figure 7 Examples of risk profiles for global pre-mining conditions

4 Post-mining assessment

The pre-mining conditions assessment discussed in Section 3 focused on the rock mass conditions of the stope itself. The post-mining assessment discussed in this section focuses on the surroundings of a given stope. The distance of interest will depend on the criteria being evaluated. The following subsections discuss the two identified mining challenges associated with post-mining conditions.

4.1 External stope dilution potential

When the rock mass around the excavated stope is significantly damaged and deconfined, waste rock can cave into the stope, causing dilution. Several factors influence external dilution (Clark 1998; Stewart 2005). Dilution will depend upon the dimensions and geometry of the stopes, their orientation relative to the orientation and spacing of the local joint sets, the discrete structural features in their vicinity, the mechanical properties of the local rock mass (including potential mining-induced damage), and the stress state. Mining operations (undercutting of the stopes, drilling and blasting practices, and backfilling), along with the speed of mining, can also be expected to have a significant influence on dilution. It is important to note that *FLAC3D*, being a continuum formulation, is not designed to examine the detailed structural behaviour of rock masses. The method and criteria used still provide, in our opinion, a good appreciation of the level of dilution that can be anticipated, but the results should not be considered as absolute.

From a purely stress perspective, two mechanisms can lead to external dilution:

- Stress relaxation – low stress conditions or deconfinement have the potential to destabilise stope surfaces, including hanging walls and footwalls, particularly in rock masses of fair to poor quality, and/or subjected to persistent structures (e.g. in blocky formations).
- Stress-induced damage – the ground in backs, hanging walls and footwalls that were damaged by stress concentrations during adjacent mining can fail and cause dilution.

The dilution potential is evaluated in the hanging wall and footwall of each stope. For scripting purposes in *FLAC3D*, a possible dilution group of numerical zones (search volume) is defined for each stope. That search volume is a parallelepiped which is defined based on the centroid coordinates, average dip and dip direction of each stope. It includes the hanging wall and footwall areas but excludes the end walls and the back, which, if unstable, generally do not generate waste dilution (these surfaces can, however, be considered if required). It also only includes waste rock material (and excludes paste backfill and ore). Note that these choices are arbitrary: the method could easily be adapted to consider dilution from the crown and/or end walls.

The numerical zones located within the search volumes are flagged as dilution (a volume that is ultimately not expected to be self-standing) if they meet one of the following criteria:

- zones with a softening index < 1.0 (near intact) – dilution from relaxation when $\sigma_3 < 0$ MPa (in tension)
- zones with a softening index ≤ 0.2 (damaged) – dilution from stress damage when $\sigma_3 < 500$ kPa.

Those criteria may be site-dependent and should be validated through back-analysis.

An example of a potential for external dilution profile is shown in Figure 8. In this bar chart, the mining levels were chosen to be displayed on the *x*-axis. Each vertical bar represents the total tonnes affected by dilution coloured by dilution type (relaxation or stress damage). Additionally, overlain on the bar chart is the total dilution volume (based on the modelling results) divided by the total planned mined volume, per level. Once more, this illustrates the versatility of the method to plot results.

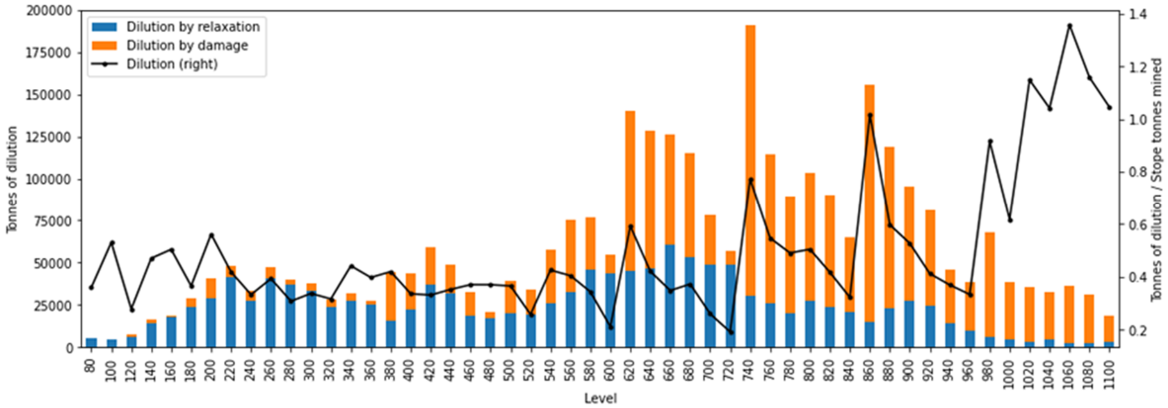


Figure 8 Example of a risk profile with potential for external dilution

The following can be observed:

- At depths shallower than about 600 m, relaxation is the dominant mechanism in this example. Between 600 m and 1,000 m, stress damage becomes the more dominant mechanism. Deeper than 1,000 m, stress damage can be expected to be the main source of dilution.
- The ratios of total dilution volume to total planned mined volume are relatively high. That is because the mine used in this example is a narrow vein mine.

ELOS (equivalent linear overbreak/slough, [Clark 1998]) values are often used as inputs for planning and economical purposes. To support this, modelling results can also be used to compute ELOS values for each wall of each stope (volume of dilution in that wall/average area of that wall). The spatial distribution of the ELOS values can help in determining zones of higher or lower expected dilution levels.

Ideally the potential for external dilution obtained from modelling results should be calibrated on real dilution values. For example, the numerical zones around a stope that were flagged as dilution should be compared to the shape of the corresponding subsequent cavity monitoring scan. Calibration is generally best performed on 'failed' cases with significant dilution instead of 'good' cases where no instability occurred. This is unfortunately not possible when planning greenfield mines. It is therefore necessary to rely on sensitivity analyses to build confidence in the results and make informed choices regarding the numerical modelling-inferred ELOS values used in economic models.

A sensitivity analysis was conducted on the example shown in Figure 8. A softening index threshold value of 0.15 was used instead of 0.20. This means that to be considered as dilution from stress damage, a numerical zone must be 'more damaged', with its mechanical properties closer to their residual values. It was found that the threshold value has a noticeable effect on the predicted external dilution volumes. The final choice of criteria used for planning purposes becomes a question of how conservative, or aggressive, the tolerance is to risk.

As stated at the start of this subsection, the amounts of dilution predicted from continuum modelling results should not be considered as absolute values: too many factors affecting real dilution are not considered. However, applying systematic criteria over the entire mine and sequence provides an understanding of areas more prone to dilution and can help refine the planned dilution used in economic projections.

4.2 Stress-induced seismic response assessment

The post-mining conditions assessment is meant to evaluate how likely a stope can be expected to trigger an excessive energy release in the surrounding rock mass. Such stopes are likely to induce local seismicity. To anticipate the time periods in the life of mine susceptible to generating higher levels of seismicity, a new exploratory methodology is introduced: the stress-induced seismic response index (SRI).

The SRI was developed by conciliating the results of the numerical simulations with catalogues of recorded seismic events. More precisely, the SRI was established based on an aggregation of source parameters from a collection of seismic events occurring after stope blasts, correlated with various numerical indicators extracted from the mine-scale *FLAC3D* simulation.

The SRI must not be taken as a prediction of individual seismic events but rather as an indication of whether the considered mining design and sequence are likely to trigger a more or less potent level of seismicity. The seismic response is particularly relevant when it is grouped over time periods (such a yearly quarters) or through geographic criteria (a specific mining front, for instance). These time and/or spatial groupings leverage the variance inherent to every correlation. The reader is referred to Séguineau de Préval et al. (2024) for further details on that particular assessment.

For the completeness of this paper, the definition of the SRI from an example case study is shown in Figure 9. In this figure, each data point represents the seismic response related to the excavation of a given stope. From the calibration dataset, stopes with a strong seismic response are rated 1 (SRI = 1) and stopes with a weak seismic response are rated 0 (SRI = 0). The SRI thus built can then be used in forward simulations.

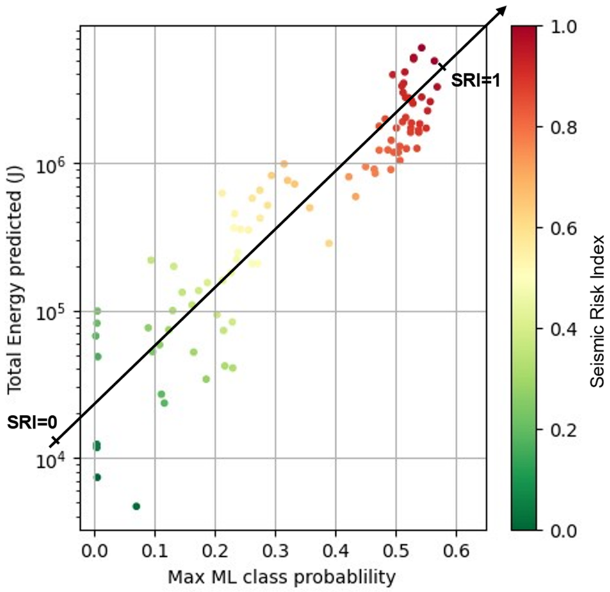


Figure 9 Definition of the seismic response index from the calibration stopes of an example case study

5 Conclusion

The proposed geomechanical risk assessment methodology makes use of inelastic continuum modelling results to provide a geomechanical and ground control 'road map' of a given mining method/sequence. The primary objective of such models is to examine mining-induced stress, deformation and yielding changes within the rock mass as the extraction sequence unfolds. Geomechanical risk profiles are subsequently established by applying criteria to the modelling results. The choice of criteria is central to the methodology. Its scriptable character offers the advantage of providing systematic, rapid and objective analyses and comparisons.

The geomechanical risk profiles produced are meant to be part of the mine's planification tools, with the ability to quantitatively compare different mining approaches. They can be used to optimise mining-induced stress management by assisting in the planning of monitoring and mitigation measures during certain time periods flagged in these analyses as potentially problematic (with high stress risk or high SRI, for example). Mitigation measures can include plans for remote operations, increasing monitoring requirements, modifying re-entry protocols, reducing production rates, modifying the mining sequence, and installing additional and/or stronger different ground support, among others.

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