Presidential Address: Managing geotechnical uncertainty and risk in mining

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Synopsis

The science of soil mechanics is 100 years old, and rock mechanics is about 80 years old. While methods of analysis and design have been developed and have evolved over time, these are relatively young sciences. The rapid increases in computing power and new technologies have enabled more sophisticated modelling and monitoring. However, there are still many aspects of soil and rock mechanics that are not well understood. Geotechnical failures, which have major consequences, still occur. These consequences may include environmental damage, major production holdups and associated loss of revenue, damage to infrastructure, and loss of life.

High-consequence events, which are rare, are more difficult to anticipate and to design for, because by their nature they involve extraordinary circumstances or conditions, often geological in nature. The risks are usually mitigated by conservative designs and monitoring. Detailed geotechnical investigations help us to understand the natural variability of soil and rock masses and identify unusual or unexpected conditions. Investigating and researching major geotechnical failures is essential to enable these unusual circumstances to be anticipated.

In the past, severe unanticipated events may have been treated as natural events or 'acts of God'. However, society now has much greater expectations and it is essential to have policies and procedures in place that enable appropriate management of these rare, high-consequence risks. A good example is the Global Industry Standard on Tailings Management (GISTM), which was introduced after the catastrophic dam collapse at Vale's Corrego de Feijao mine in Brumadinho, Brazil.

The address will explain the concepts of uncertainty and variability, and how they should be taken into account in geotechnical design. The challenges facing geotechnical engineers, mine owners, and managers will be discussed. referencing a number of real case studies.

Keywords

uncertainty, variability, risk, consequences, environmental, social, production, revenue, damage, geotechnical, soil mechanics, rock mechanics, design, mine layouts, GISTM, tailings dam, pillar, failure, mechanism, model, seismic, rockburst.

Introduction

Modern soil mechanics is generally considered to have begun in 1925, when Karl Terzaghi published his book *Erdbaumechanik auf bodenphysikalischer Grundlage* (Earthwork Mechanics based on the Physics of Soils). These theories were applied to rocks more than 20 years later and the science of rock mechanics became established. Methods of analysis and design have been introduced and applied, and have evolved over time. More recently, the rapid growth in computing power has resulted in more sophisticated analyses, and together with improved monitoring techniques, our understanding of geomechanics has grown considerably.

Despite this, geotechnical failures with major consequences still do occur. This is partly due to failure to transfer and apply the knowledge that has been gained, but also there are aspects of geomechanics that are not well understood.

Uncertainty and variability

Geotechnical engineering is subject to a lot of uncertainty and variability which need to be considered in the design process and in the management of geotechnical risks. This subject is discussed by several authors (Stacey, 2003; Christian, 2004; Stacey, Terbrugge, and Wesseloo, 2006; Hadjigeorgiou and Harrison, 2012; Joughin, 2017; Hadjigeorgiou, 2019; Wesseloo and Joughin, 2020; Joughin *et al.*, 2020). These terms can be defined as follows.

➤ Variability is a property of nature. Rock mass and soil properties, as well as loading conditions, span a large range of values, which can vary in space and time. Variability can be described with statistics and the probabilities related to variability can be interpreted in terms of frequency of occurrence (Figure 1).

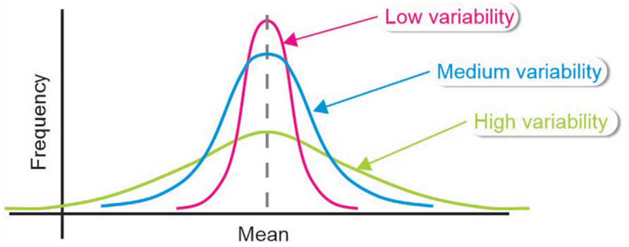

Figure 1—Data distributions and variability

- Uncertainty is a state of mind and is a function of our lack of knowledge. which can be reduced with more measurement and improved understanding. It may arise due to insufficient data, sampling bias, measurement errors, unknown or unexpected loading conditions, lack of knowledge of credible failure mechanisms, and imperfect models to represent failure mechanisms. Probabilities related to uncertainty are best interpreted as a degree-of-belief.

Geotechnical data is invariably insufficient, due to timing and cost. Often the method of sampling prevents the collection of data at the tails of distributions. The weakest material properties and the most extreme loading conditions might not be recognized. This can give the impression that there is low variability, when there is in fact high variability. In nature, frequency distributions are rarely simple normal distributions, such as in Figure 1, but are generally more complex. They are more commonly exponential or lognormal, tend to be skewed, and may be multimodal, such as when there are different material types or different loading conditions. This highlights the importance of understanding the geological controls and potential loading conditions, in order to be able to recognize what important data may be missing from the sample of data collected.

Geotechnical engineers learn about failure mechanisms by observing failures and describing them. Unusual failure modes, from which others could learn, are not often observed or have not been described. Mathematical models that are used to represent the failure mechanisms can vary in complexity, but are always simpler than reality. The aphorism 'all models are wrong, but some are useful' is very apt.

Learning from uncommon high-consequence events

Stacey (2003) posed the question 'Rock engineering - good design or good judgement?' and suggested that good judgement is essential in rock engineering design. However, to apply good judgement, it is essential to learn from geotechnical failures. Low-consequence incidents that occur frequently are observed by many people and the failure mechanisms and simple models are generally well understood. Good practices can be implemented to prevent or limit the occurrence of such incidents.

Uncommon geotechnical failures are not as well understood and can have severe consequences, such as:

- Loss of life
- Environmental and social impacts
- Production delays, revenue loss, and force majeure
- Loss of infrastructure and equipment.

It is therefore essential that detailed investigations are carried out in a transparent manner whenever these failures do occur. The knowledge gained from these investigations needs to be transferred by publishing, sharing at conferences, and through training courses. Unfortunately, this often does not happen because of legal implications or company policies.

This address describes some uncommon, high-consequence events through case studies on the following topics, which have been well documented:

- Tailings dam failures
- Hard rock pillar collapses
- The Kiruna M_W 4.2 seismic event.

Tailings dam failures

The catastrophic dam failure at Vale's Corrego de Feijao mine in Brumadinho, Brazil resulted in the loss of almost 300 lives, in addition to the major environmental and social consequences and business interruption. This followed several other highly publicized tailings dam failures, which also had major environmental and social impacts, and triggered a global response. This resulted in the development of the Global Industry Standard on Tailings Management (GISTM) (https://globaltailingsreview.org/global-industry-standard). The standard is directed at operators, who are required to take responsibility for and prioritize the safety of tailings facilities through all phases of the life-cycle, including closure and post-closure. There are six topics that must be addressed (Figure 2).

Most South African tailings storage facilities are constructed using the upstream method, which is not suitable for significant water storage, and are more vulnerable to seismic loading. This method of construction is not allowed in certain countries. However, tailings management practice in South Africa has generally been very good (SANS 10286). The risks are mitigated through managing the rate of rise, good drainage characteristics of materials, good drainage design, storm water design, geotechnical investigations, slope design, and structured monitoring. When hazardous conditions are encountered, additional data is collected to reduce uncertainty or dewatering and buttressing are implemented to improve stability.

GISTM incorporates learnings from investigations of catastrophic dam failures and sets out requirements to address the uncertainties in tailings dam behaviour, which include:

- Identifying brittle failure modes and addressing them with conservative design criteria. Brittle failure involves a sudden loss in strength (the Brumadinho failure is an example),

Figure 2—Global Industry Standard on Tailings Management (https://globaltailingsreview.org/global-industry-standard)

which is more difficult to anticipate or monitor and hence a more conservative and more expensive approach is required to manage the risk. Some tailings or foundation materials tend to have brittle characteristics and will behave in a brittle manner under certain circumstances and with certain triggers. Most tailings dam designs in South Africa did not originally include the identification of brittle materials. Specialized sampling and testing methods are required to determine the degree of brittleness, and this is the subject of ongoing research. Conservative approaches are being applied until such time that the operator can demonstrate that brittle behaviour is not a concern.

- Dam breach analyses are required to be carried out to determine the potential consequences of a failure. This involves simulating the flow of tailings downstream from the facility to assess the potential impact on communities and watercourses. The results of the analyses are essential for determining the consequence classification for the dam. The extent of breaches (release volumes) is the subject of ongoing research.
- Seismic loading can possibly trigger a dam failure (through liquefaction), so it a requirement to carry out a seismic hazard assessment using probabilistic and deterministic methods. In Southern Africa, the seismic hazard is low compared with other parts of the world, and most of the seismic activity is mining-induced, rather than due to tectonic activity. Therefore, this was not previously considered an important criterion for tailings design. Guidelines are now specified for different consequence classifications and post-closure.
- As a result of climate change, extreme flooding events need to be considered in the design of tailings dams. GISTM requires operators to consider the Maximum Probable Precipitation (PMP) and Probable Maximum Flood (PMF) for Extreme Consequence Classification facilities and post-closure requirements. This influences the storm water drainage design and freeboard management.

GISTM also defines specific roles and responsibilities:

- Accountable Executive (AE)
- Responsible Tailings Facility Engineer (RTFE)
- Engineer of Record (EOR)
- Independent Tailings Review Board (ITRB).

MacRobert *et al.* (2022) carried out a survey of the tailings community of practice to determine the required traits and qualifications of the individuals that fulfil these roles, since little guidance is provided in the GISTM. The authors suggest ideal requirements for GISTM appointees based on an analysis of the survey. One of the challenges for the global mining industry is to educate and train sufficient suitable qualified engineers to fill and support these roles.

Another challenge that arises is addressing the important requirement to meaningfully engage with affected communities, while still grappling with the uncertainties. In particular, the assumptions applied in the dam breach analysis affect the extent of the downstream area impacted by the breach, which determines the communities that are likely to be affected.

The SAIMM has established a Tailings Working Group in collaboration with the South African Institute of Civil Engineers (SAICE) to address the Southern African mining industry requirements.

Hard rock pillar collapses

In most shallow, narrow, tabular hard-rock mines (gold, platinum, and chrome mines of the Witwatersrand Gold ields, Bushveld Complex, and Great Dyke), pillars are generally very stable, due to the high strength of the rock. In fact, some mines are reaching the end of their life and are investigating partial extraction of pillars, because they were probably larger than necessary. Pillars have traditionally been designed using tributary area theory and the hard rock pillar formula (Hedley and Grant, 1972). While this method has worked reasonably well for most shallow narrow, hard-rock tabular mines, it is very basic and does not take some of the geotechnical complexity into consideration. Malan and Napier (2011) provide an excellent review of pillar design in narrow, tabular, hard-rock mines, which highlights several challenges and uncertainties that still need to be resolved.

While most mines only need to deal with the challenges of pillar cutting and localized instabilities, there have been at least three incidents where major pillar collapses have occurred (Spencer, 1999; Walls and Mpunzi, 2017; Muaka *et al.*, 2017; Malan and Couto, 2023a, 2023b). In all three cases, the pillar collapse affected a large area, including the larger protection pillars supporting the central decline cluster, preventing access to the mining area. New accesses needed to be developed, taking many months, during which time there was no production. Fortunately, the pillars deteriorated gradually over many months, exhibiting ductile rather than brittle failure. As the extent of mining increased the deteriorating pillars would transfer load to adjacent pillars, until eventually even the larger decline protection pillars failed. This allowed mine management to implement visual and instrumented monitoring, and all workers were safely evacuated prior to the collapses. Figure 3 shows a mine plan of the pillar collapse at Everest Platinum Mine in December 2008.

Pillar failure mechanisms

The main difference between these collapsed areas and other operations is that there were weak alteration layers in the pillars that significantly reduced their strength (Figure 4). These weak layers contained clay and were more than a hundred times weaker than the rock comprising most of the pillar. If exposed to water, the clay-filled layers became even weaker. Weak layers change the failure mechanism in the pillar.

Pillars are loaded vertically in compression and deform horizontally outwards. Shearing occurs within the weak layer, due to the horizontal deformation. Since the low strength material has less resistance to shearing, tensile splitting occurs along sub-vertical joints or through intact rock much more easily. Loose rock blocks at the pillar edges topple and become dislodged, reducing the pillar size and therefore its strength. The failed pillars then transfer load onto adjacent pillars, which become overloaded and fail.

At Everest Platinum Mine (Couto and Malan, 2023a, 2023b) the weak layer was consistently at the hangingwall contact, while at Wonderkop Chrome Mine (Spencer, 1999) it was consistently at the footwall contact. At another operation, the weak layer (a shear zone) undulated so that it was sometimes within the hangingwall, sometimes within the pillar, and sometimes in the footwall. The pillar failure mechanism varies depending on where the weak layer is located.

The empirical pillar strength models are unable to represent the effect of different modes of failure and the considerably lower strength of the pillar. Tributary area theory and elastic numerical models do not address the load transfer from failed pillars.

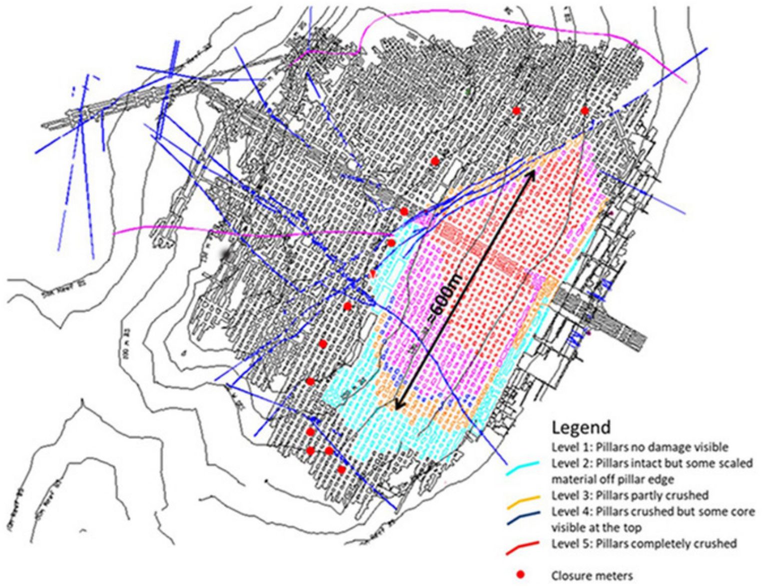

Figure 3—Mine plan showing the pillar collapse at Everest Platinum Mine in December 2008 (Malan and Couto, 2023a)

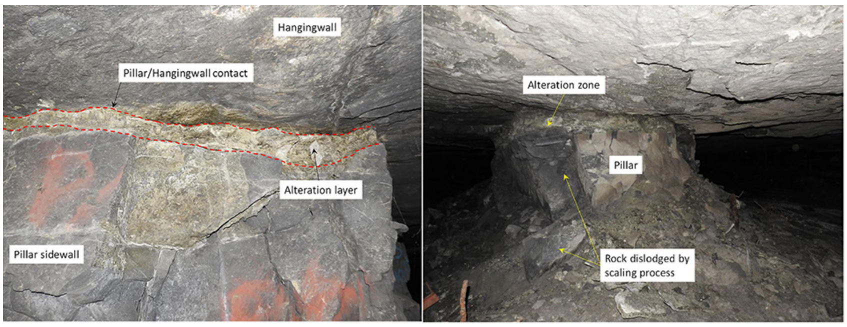

Figure 4—Failed pillars at Everest Platinum Mine (Malan and Couto, 2023b)

Pillar scale numerical models

It is possible to numerically model the details of the failure mechanism in a single pillar. Figure 5 shows the results of two-dimensional distinct element models, which are described in more detail in Muaka *et al.* (2017). For these models, two discrete fracture networks were created to represent two possible permutations of the natural jointing in pillars (left and right columns). The range of joint characteristics (dip, dip direction, spacing, persistence and shear strength) was determined from underground mapping. Models were then analysed with no weak layer (shear), and with weak layers in the footwall, hangingwall, and within the orebody. The strength of the weak layer was determined by collecting samples underground and testing them in a soil mechanics laboratory.

The failure mechanisms were represented realistically in the models, including buckling of the hangingwall and footwall heave, when the weak layer is located in the hangingwall or footwall, respectively. Each combination of joints and weak layer, and different pillar sizes produces a unique result. Therefore, it is useful to present the reduction in strength as a function of the location of the weak layer, and to show it as a range of percentages. The weak layer effectively reduced the strength of the pillar to between 22% and 72% of an equivalent pillar with no weak layer, taking all the models into consideration. It is also apparent that when the weak layer is in the hangingwall or footwall, there is a greater strength reduction, than when it is within the orebody.

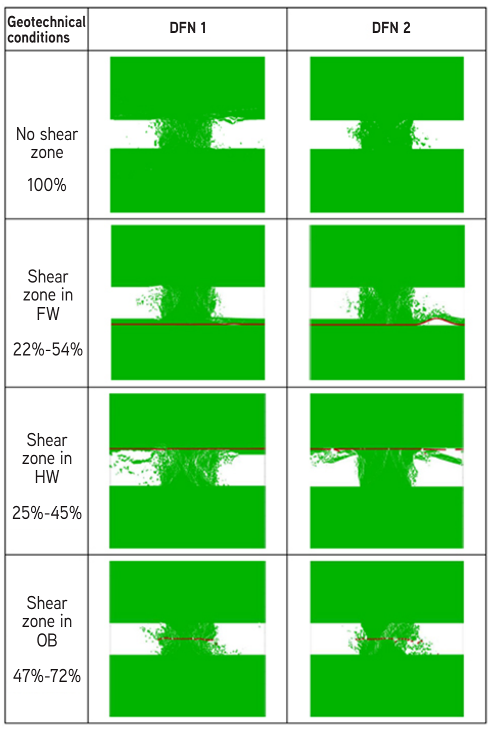

Figure 5—Results of detailed pillar modelling (Muaka *et al.*, 2017)

Mine scale numerical models

The type of complex model described above is only useful to gain an understanding of the variability in pillar strength due to the presence of a weak layer. It is not practical to carry out this type of complex modelling on a mine-wide scale, even with currently available computing power.

Boundary element elastic modelling is much simpler and enables mine-scale modelling of pillars (Figure 6). Limit equilibrium models (Figure 7) have been incorporated in these codes to provide a simple representation of the pillar failure mechanism (Napier and Malan, 2007, 2021, 2023; Esterhuyse, and Malan, 2023; Ile and Malan, 2023; Couto and Malan, 2023a, 2023b). The limit equilibrium model effectively represents a shearing layer at both the hangingwall and footwall contacts and progressive spalling of the pillars. As pillars in the model fail, they transfer load to adjacent pillars, which enables the simulation of a pillar collapse on a mine scale. The effect of support, such as backfill, can also be simulated using the limit equilibrium model.

Identifying weak layers in borehole core

During geotechnical investigation for a new mine, it can be quite a challenge to find these weak layers in borehole core (Figure 8). Invariably, when the geotechnical investigation is carried out for mine design purposes in hard rock mines, all of the core has already been drilled using double tube drilling. However, triple tube drilling is normally carried out for geotechnical purposes to prevent the washing out of fine materials, such as clays. The recovery of hard rock with double tube drilling is normally very good, but any fine soil material is lost. In these circumstances, the only way to determine that there is a problem is to diligently measure the core recovery to identify core loss. It is possible to determine that there is, say, 20 cm of core loss within a drill run of 3 m, but the actual location cannot be determined, nor can the material characteristics.

In all three cases cited, core loss was not identified as a persistent problem and the weak layers were not identified until mining started. The pillars, including the decline protection pillars, were designed using tributary area theory and the hard rock pillar formula.

To address this challenge, it is necessary to diligently log core recovery, identify core loss in close proximity to the orebody, and carry out additional triple tube drilling to determine the exact location and material properties of the weak layers. It is also suggested that a structural geologist should analyse the data to interpret and model the weak layer and its potential location within pillars throughout the mine.

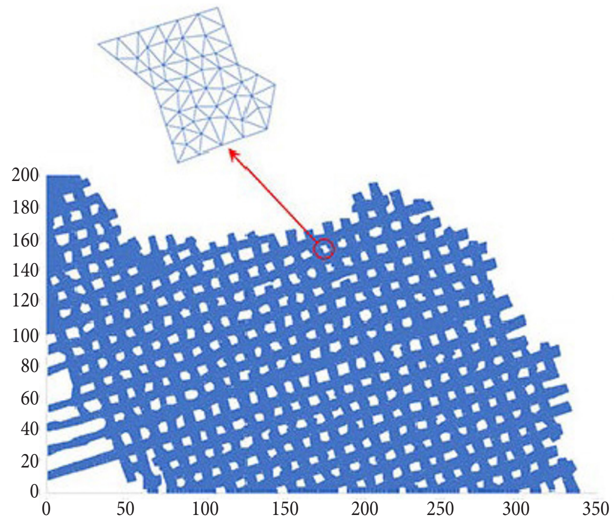

Figure 6—Boundary element elastic modelling of a mine layout on a large scale (after Napier and Malan, 2023)

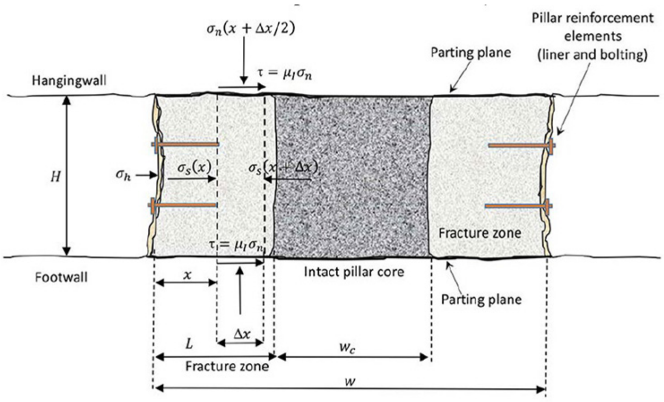

Figure 7—Example of a force equilibrium diagram, which represents the effects of a shearing layer, pillar spalling, and support (after Esterhuyse and Malan, 2023)

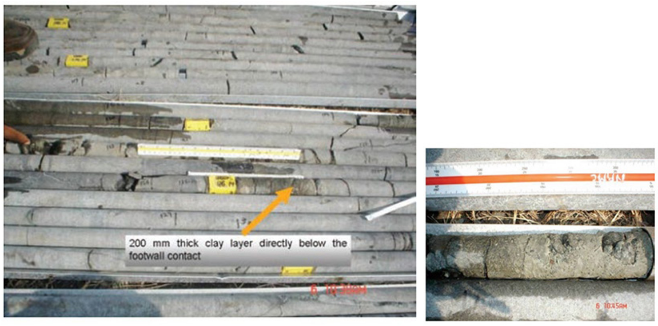

Figure 8—A weak layer in borehole core (Malan and Napier, 2011)

Managing uncertainty through mine design

Given that it is very difficult to find weak layers in drill core and determine the potential effect on pillars at the project stage, the early mine design needs to take this uncertainty into consideration. Increasing the factor of safety in a conventional pillar design may not be sufficient, because the actual pillar strength may be as low as 1/5 of the typical pillar strength determined using simple empirical methods.

Incorporating a system of very wide barrier pillars to compartmentalize the mine is an effective way of mitigating the effect of pillar failures (Figure 9). The effects of geological weaknesses in very large barrier pillars are far less significant than in small pillars. Couto and Malan (2023b) analyse different barrier pillar layouts.

It is good practice to design these barrier pillars pragmatically and conservatively, given the uncertainties. The example in Figure 9 is a good approach because the barrier pillars incorporate three pillars and two bords. If the weak layer is not present or does not have a significant effect on the pillar strength, the bords can easily be extracted at a later stage when the uncertainties have been resolved.

The barrier pillars do not affect productivity and profitability. They could be included in the mine reserves, but initially defined as Probable Reserves and later as Proven Reserves when confidence has been established. Therefore, it is smarter to design larger barrier pillars than to attempt to optimize them, before sufficient information is available.

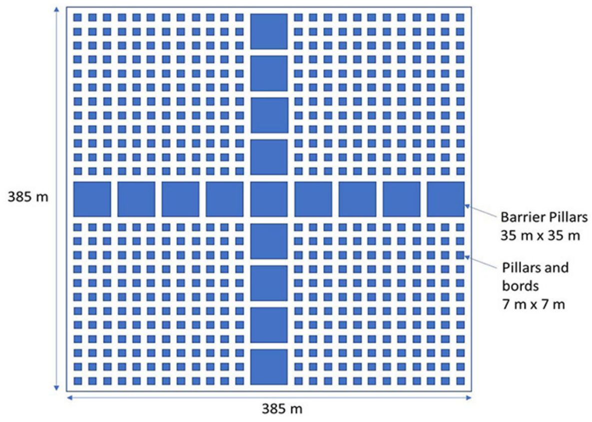

Figure 9—Barrier pillar layout (after Couto and Malan, 2023b)

Most importantly, the central decline cluster and other important access ways must be protected by barrier pillars. The barrier pillars should therefore be designed on a risk management basis, using simple methods. It is better to be approximately correct and manage the risk, than to be precisely wrong.

Optimization of pillars should incorporate more sophisticated methods and models once the pillar composition and behaviour are well understood.

The Kiruna M_W 4.2 seismic event

In May 2020, Kiirunavaara mine (Kiruna) in Sweden experienced a major seismic event, which caused extensive damage over more than 1000 m in tunnels on several levels (Boskovic 2022; Dineva *et al.*, 2022; Svartsjaern *et al.* 2022; Mawson *et al.*, 2022). The Swedish National Seismic Network (SNSN) recorded it as a moment magnitude M_W 4.2 seismic event, which is considerably larger than any seismic event previously experienced at Kiruna and was felt several thousand kilometres away. A total of 20 000 aftershock events were recorded within 24 hours, by the mine seismic network. The largest of the aftershocks was local magnitude M_L 1.4. Importantly, no-one was exposed in the area at the time of the M_W 4.2 seismic event and re-entry was only permitted after the seismicity returned to normal levels. Details of the M_W 4.2 seismic event, aftershocks, detailed analyses and damage, and rehabilitation strategies have been published at RASIM10 (Boskovic 2022; Dineva *et al.*, 2022) and CAVING2022 (Svartsjaern *et al.*, 2022; Mawson et al., 2022), and a workshop on the incident was held at CAVING2022. All the information in this section has been drawn from these publications.

Background

Kiruna is the largest underground iron ore mine in the world, typically producing 27 Mt/a (75 000 t/d). The orebody dips at 55° to 60° and is typically 80 m wide (0–160 m) with a strike length of approximately 4000 m. It started as an open pit mine in 1898 and went underground in 1962. The ore is extracted using sublevel caving, which is a top-down mass mining method that results in hangingwall caving and subsidence on the surface. Figure 10 illustrates the current mining layout below 1045 level. The infrastructure is already developed to 1365 level. Level numbers represent depth below the top of the former Kiirunavaara hill, which has been mined out, and the depth below the typical ground surface is approximately 230 m less than the level number. Kiruna has 11 mining blocks, defined by the orepass grouping. The seismic events and damage occurred in block 22.

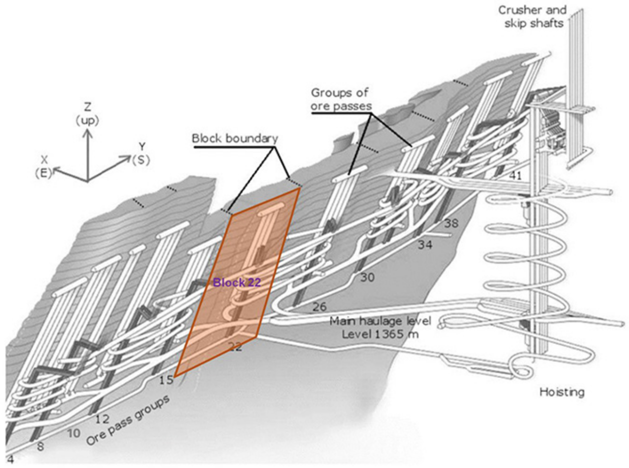

Figure 10—Schematic of the active portion of the Kiruna mine below 1045 m level, showing the location of block 22 (modified from Mawson *et al.*, 2022)

The orebody shape and mining method result in stress concentrations on the horizontal mining face (abutment), extending deeper as mining continues. The rock strengths (hangingwall, orebody, and footwall) range between 180 MPa and 225 MPa and the footwall rocks tends to be brittle. Due to the high rock strength, very little stress damage and seismicity was experienced above 907 level (677 m below surface). Below 907 level, the stress concentrations on footwall drives and orepasses due to the advancing mining face began to exceed the strength of the footwall rocks, causing stress damage and strainbursts. The stress acting on the orepasses and footwall drives is partially relieved by the hangingwall caving, and ensuring an active cave is part of the stress management. Kiruna has a large state-of-the-art seismic network with more than 250 geophones (4.5 Hz and 14 Hz), which records approximately 5000 seismic events per day. The system reliably records seismic events a small as M_L –1.5 (small pops and cracks) with a location accuracy of 20 m.

Kiruna block 22

Figure 11 shows the mining layout in block 22 at the time of the M_W 4.2 seismic event. The orebody is narrower and more variable in block 22 and has not been mined at the same rate as the adjacent blocks. It is lagging blocks 15 and 26, which increases the stress concentration in block 22. The layout on 993 level is longitudinal, to minimize development in the narrow orebody, while on 1022 level, the more typical transverse layout was developed. The different layouts effectively increase stress concentrations and prevents connection to the cave on the level above, negating the stress relief offered by caving of the hangingwall.

Figure 12 shows vertical movement measured on surface due to hangingwall caving and subsidence. It is apparent that the downward movement of the cave material above block 22 is negligible compared with the 5 m of downward movement in the adjacent blocks. This provides evidence that the cave has stalled above block 22 and is a direct consequence of mining practice in block 22. This phenomenon had not been observed previously.

Underground damage

Figures 13 and 14 indicate the extent of damage mapped underground after the M_W 4.2 seismic event. The damage occurred over multiple levels and was most severe within or adjacent to block 22. Footwall drives were affected more than crosscuts because the stress orientation is perpendicular to the footwall drives. Damage

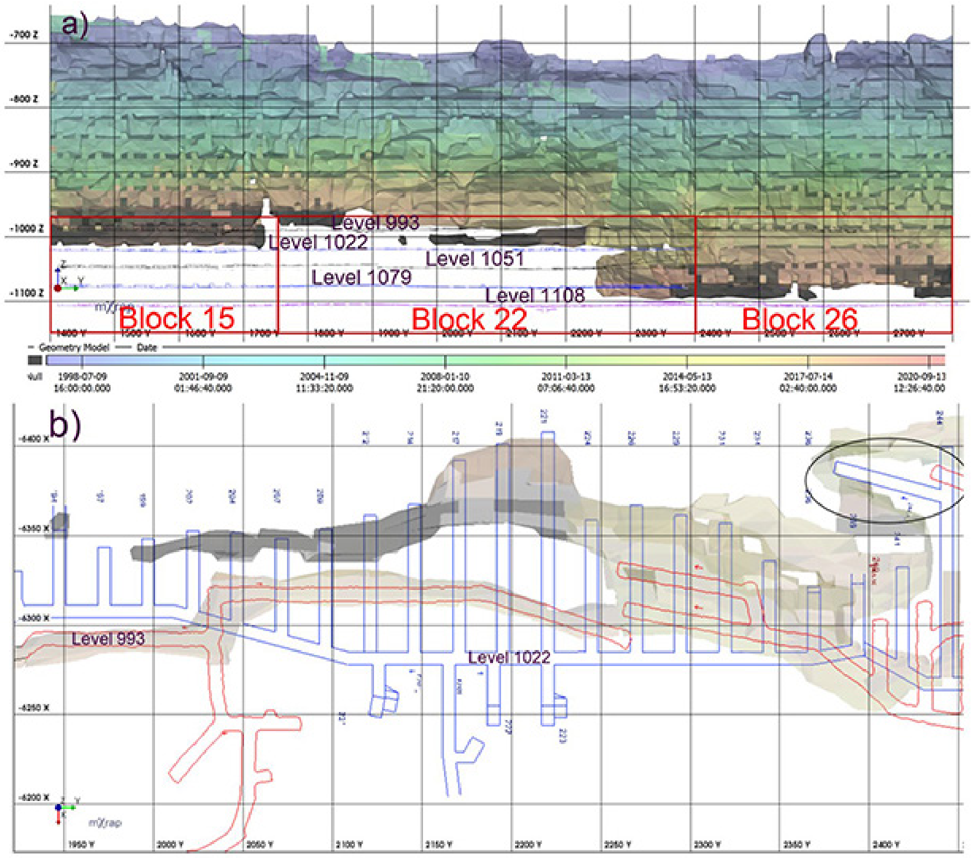

Figure 11—Mining layout of block 22 at the time of the M_W 4.2 seismic event. (a) Longitudinal section, (b) plan view of levels 993 and 1022 (after Boskovic, 2022)

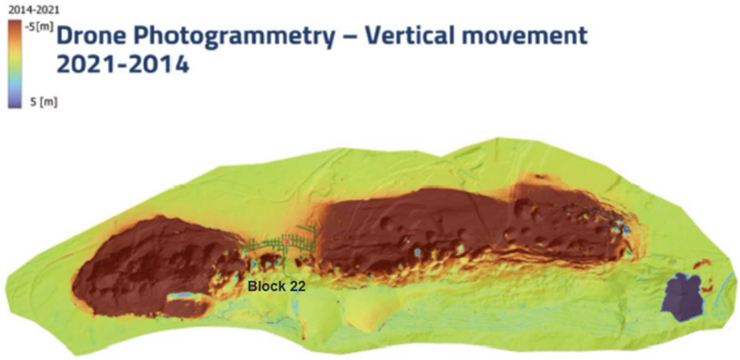

Figure 12—Vertical movement on surface due to hangingwall caving and subsidence (Mawson *et al.*, 2022)

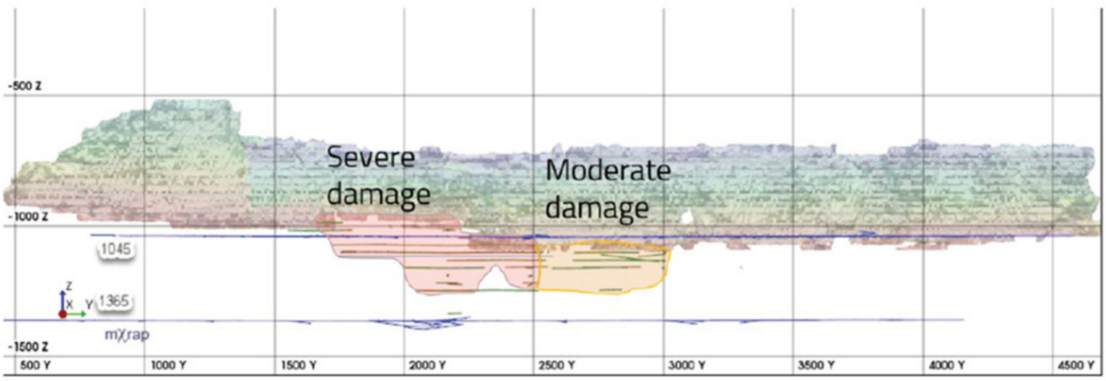

Figure 13—Longitudinal section through the mine showing the extent of damage mapped underground after the M_W 4.2 seismic event (Svartsjaern *et al.*, 2022)

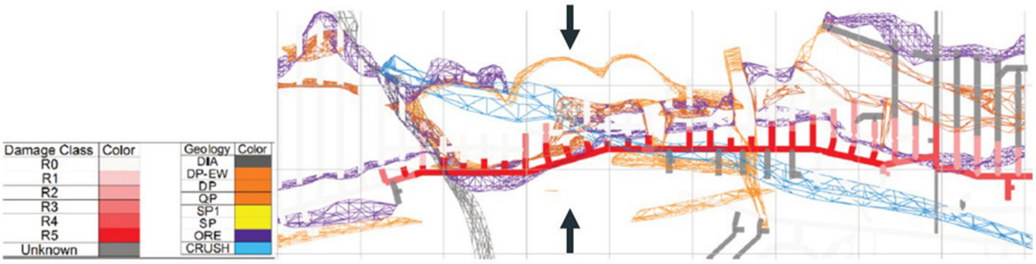

Figure 14—Plan view of 1079 level showing the extent of damage mapped underground after the M_W 4.2 seismic event (Svartsjaern *et al.*, 2022)

Figure 15—Photographs of rockburst damage on 1079 level

also extended from the intersections, which are larger, into the crosscuts. Figure 15 shows some of the intense damage in tunnels on 1079 level.

The source mechanism of the M_W 4.2 seismic event could not be analysed seismically through moment tensor inversion because the waveform was too complex. The Institute of Mine Seismology analysed the source mechanisms of the aftershocks (Dineva *et al.*, 2022; Boskovic, 2022). Figure 16 represents a model of the source mechanism of the aftershocks within block 22 (severe damage in Figure 13). The mechanism is sudden bulking of stress-fractured ground, as opposed to fault slip mechanisms, which occurred elsewhere. This highlights that the damage in the floor and roof of the tunnels occurred due to stress loading of the brittle footwall rocks. It is also likely that much of the damage occurred during the aftershocks.

Cause of the event and learnings

The detailed and comprehensive investigations into this complex, unforeseen event, and many discussions, have yielded a commonly accepted interpretation of the cause of the event. It is postulated that the hangingwall in block 22 suddenly caved, giving rise to the M_W 4.2 seismic event, which in turn resulted in a dynamic stress wave through block 22, overloading tunnels sited in a brittle rock mass.

The learnings from this event are as follows.

- ➤ Footwall drives and orepasses became overstressed and damaged as mining progressed, because these excavations are within the high stress zone
- ➤ It is essential to ensure a cave connection between sublevels and monitor hangingwall caving
- ➤ Selective mining in the narrower parts of the orebody will result in stress concentrations.

Consequences

Due to the extensive damage in the footwall drives and crosscuts in block 22, it would be necessary to redevelop the access to the orebody. Several options for re-establishing block 22 were considered, but these involved skipping two or three levels and

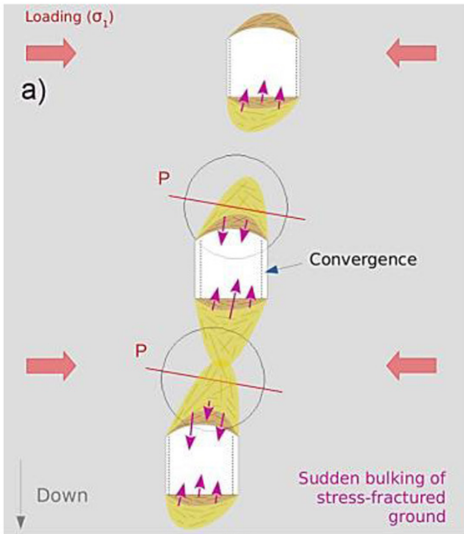

Figure 16—Source mechanism (Boskovic, 2022)

effectively forming a pillar. The hope was that the pillar would be small enough to yield in a ductile manner, and caving would propagate naturally. However, there is no reliable way of ensuring that the pillar would not fail dynamically, potentially repeating the same type of event.

Three-dimensional finite difference models (FLAC3D) were constructed to analyse the different options and to determine whether the pillar would yield. However, the current numerical modelling tools are not able to reliably simulate dynamic processes and cannot answer this question conclusively.

The risk of creating another major event is too high to consider mining in block 22 at this stage.

Management of seismic risk

The footwall infrastructure down to the main haulage level 1365 has already been developed. Stress damage and rockbursts can therefore be anticipated in the future in all mining blocks. Management of the risk requires multiple lines of attack:

- ➤ Developing and updating a litho-structural model of the orebody and footwall.
- ➤ Seismic monitoring and analysis, together with damage mapping, is essential to identify hazardous areas.
- ➤ The hazardous areas will need to be managed by installing more effective dynamic support, rehabilitation, and in some cases re-development with an improved layout.
- ➤ Mining will need to be carefully sequenced vertically and horizontally to avoid the formation of temporary pillars that create stress concentrations and unfavourable loading of geological structures.

- Cave connections between sublevels and monitoring of hangingwall caving will be essential.
- Seismic monitoring and exposure management (re-entry protocols) are essential to further mitigate the risk of injuries.

Concluding remarks

The challenges of managing geotechnical uncertainty in mines has been highlighted. Uncertainty and variability are inherent in geotechnical engineering.

Transparent investigations of unusual events with extreme consequences are essential and the findings should be published to enable them to be included in guidelines and future strategies.

Credible failure mechanisms should be analysed and described. The applicability and suitability of models should be determined. It is important to recognize that models do not provide definitive, reliable answers, but they can improve understanding by allowing trials and experiments to be conducted. Models should provide useful insights into the problem and help to find possible solutions.

High quality geotechnical data and geological understanding are important for making good decisions. It is important to check whether the sampling methods are appropriate and to ensure that all relevant data is collected. Recognizing what critical data may be missing is invariably more important than detailed analysis of the data that has been collected.

In the absence of important data, conservative assumptions should be applied in the initial design, taking cognisance of the potential consequences. A well-designed monitoring programme (visual and/or instrumented) can help to significantly reduce uncertainty. Designs should only be optimized when the relevant data is available.

Practical, flexible designs should be implemented where possible to enable optimization when it is feasible. The greater the confidence in the geotechnical data, analysis of failure mechanisms, and potential solutions, the more reliable the optimization.

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