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Ground support evolution through success and failure

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Abstract

Advances in the science and technology of ground support have provided a greater understanding of how the various ground support elements function individually, and as an interlinked system, to transfer loads and help control rock mass damage and failure. The development of new reinforcement and surface support elements and the advent of sophisticated equipment have all contributed to making the installation of ground support a much safer activity in mechanised underground mines, and to safer mines, in general. Meanwhile, the cost pressures from mining generally lower grade ores at greater depths in addition to rising material, labour and equipment costs are pushing for higher ore extraction rates. This in turn requires larger mining equipment leading to increases in excavation size and development costs (higher capex) in return for greater mining efficiency (lower or stable opex). Higher extraction rates also represent an increase in the rate of change in stress conditions per unit of time that generally require enhanced control measures. This paper presents an overview of technological and scientific advancements witnessed over the last 40 years, highlighting the safety and productivity benefits observed during this period. Successful applications of ground support under a range of conditions in underground mines serve to illustrate some of the advancements realised through the collaborations between industry, academia, service providers, equipment manufacturers and suppliers of ground support elements. Future developments and optimisation efforts are expected to focus on measuring and monitoring the interaction between the ground support system and the rock mass, increased automation and robotisation of at least some parts of the mining cycle to further reduce human exposure. The identification of rock mass failure mechanisms and rock mass behaviour are required for any advanced numerical modelling and analyses of the rock–support interaction. Leveraging new and emerging technological tools to develop fit-for-purpose geotechnical models will enable us to mine safely and productively under increasingly challenging conditions.

Keywords: *safety, ground support, equipment, support elements, costs, efficiency*

1 Introduction

In addition to ensuring environmental excellence and maintaining social acceptance, successful mining projects rely on 3 interconnected pillars: maintaining a safe working environment, controlled and well-managed costs, and uninterrupted production at the required mining rate and ore grade. Rock engineering is a key contributor to these 3 aspects from the earliest stages of exploration into project construction to commercial production and eventually to mine closure. From geotechnical characterisation to excavation design, mine sequencing, ground support and backfilling, rock engineering principles lay the foundation for successful mining and getting it wrong can have costly consequences.

Key business drivers of mining operations can be most simply described as safety, production and costs, as depicted in Figure 1. Successful operations are first and foremost safe, environmentally and socially sustainable, and ore delivery and mine production costs are aligned with the mine plan expectations. The geotechnical risk management process is a key contributor to ensuring safe, reliable and economic ore extraction. Simply said, our goal is to protect the people and protect the mineral reserves. Potential consequences of ground failure

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are summarised in Table 1, with severity ratings ranging from negligible to severe in terms of material impacts on people and the business.

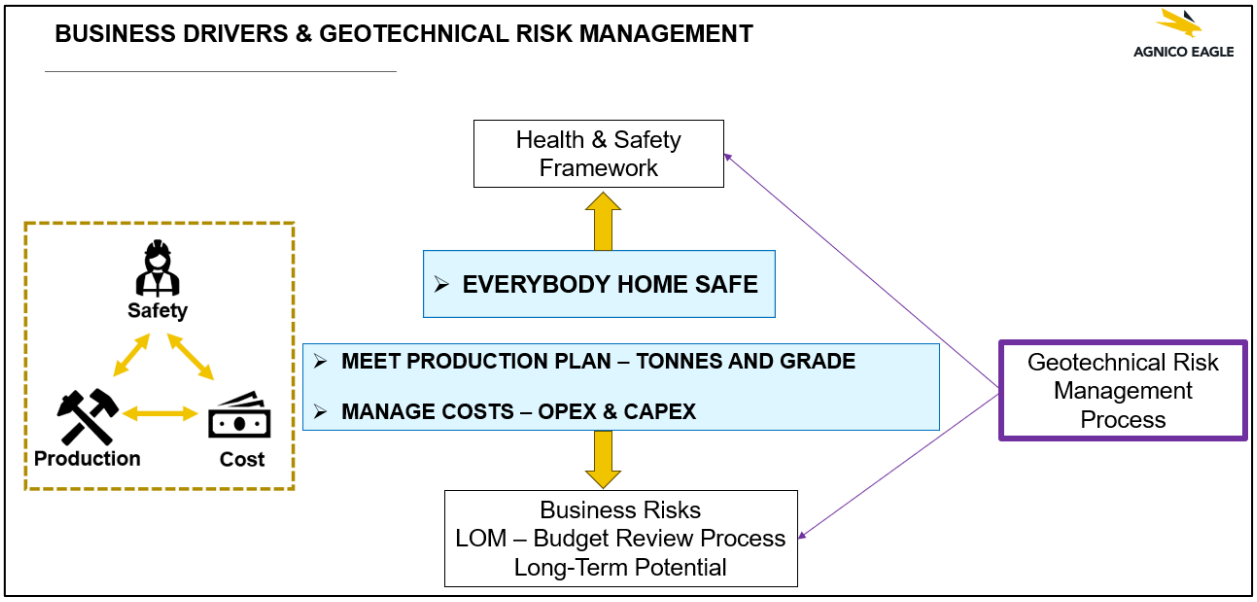


Figure 1 Impact of geotechnical risk management process on key mining business drivers. LOM = life of mine

Table 1 Potential consequences of ground failure

Rating	Health and safety	Reputational impact/public perception	Economic	Technical
Negligible to severe	Direct impact on people's life or health	Support of public, community, shareholders and workforce	Direct economic impact	Impact on a critical system, asset or performance goals
	Physical	Surface vibrations/damage from mine seismicity	Equipment damage	Rehabilitation needed
	Psychological	Impact on public infrastructures	Production loss or interruption	Production rate, reserve recovery
	Trust	Premature mine closure	Project delays Cost overrun	Main mine infrastructure and operating systems

Extracting rock from its original stable state within the earth's crust inherently alters the equilibrium of forces and can result in failure of the rock mass at various scales (drift to stope to zone/mine in underground, bench to multi-bench to overall slope in open pit) depending on the geological context, initial stress state, mining methods and extraction rate. Anticipating, recognising and managing rock mass failure at the scale of interest requires a multi-layer risk management system, as depicted in Figure 2. This process starts with developing an understanding of expected in situ stress and strength conditions as described in a geotechnical model depicted in the top righthand corner of Figure 2. The components and sources of data for developing a geotechnical model are described in Figure 3.

Key outputs of a fit-for-purpose geotechnical model are the:

- recognition of rock mass failure mechanisms as described in several publications (Hoek et al. 1995; Martin et al. 1999; Kaiser et al. 2000; Potvin & Hadjigeorgiou 2024)
- estimation of rock mass strength parameters including post-peak behaviour (note that the rock mass term used in this context represents the rock at all scales from intact to rock fabric [jointing] and intermediate to large-scale geological structures)
- identification of external conditions that are likely to impact rock mass and ground support capacity over time (e.g. static and dynamic deformation, ground and surface water quantity and quality, rock, air and water temperature and corrosion potential).

From the anticipation and recognition of expected rock mass failure mechanisms, mine design parameters including ground support requirements are developed, as depicted in the first 2 slices starting from the top right corner of the multi-layer system in Figure 2. The control measures for managing rock mass failure risks that are related to mine design are labelled strategic because they are typically implemented early in the development of an underground mine. These higher order control measures (elimination and substitution as defined in NIOSH [2023]) are not easily modified if conditions differ from expectations. Once mining starts, monitoring for design conformance and performance provides essential data to revise initial estimates and expectations based on back-analysis, and to develop trigger action response plans. The third slice of the multi-layer system represents the tactical ground control measures that are implemented during production to reduce the consequences of the expected hazards and provide safety assurance to operations. These tactical measures are nimble and can be adapted over time as knowledge and understanding of rock mass behaviour increases. In underground mines, when rock mass failure occurs in the presence of personnel, the last line of defence is the ground support in place; the fourth and last slice on Figure 2. The analysis of rock mass and ground support behaviour during failure events provides opportunities for improving the tactical and strategic control measures, assessing gaps in the geotechnical model and defining additional investigations or studies. Some highlights of the evolution of ground support practices are discussed in the next section.

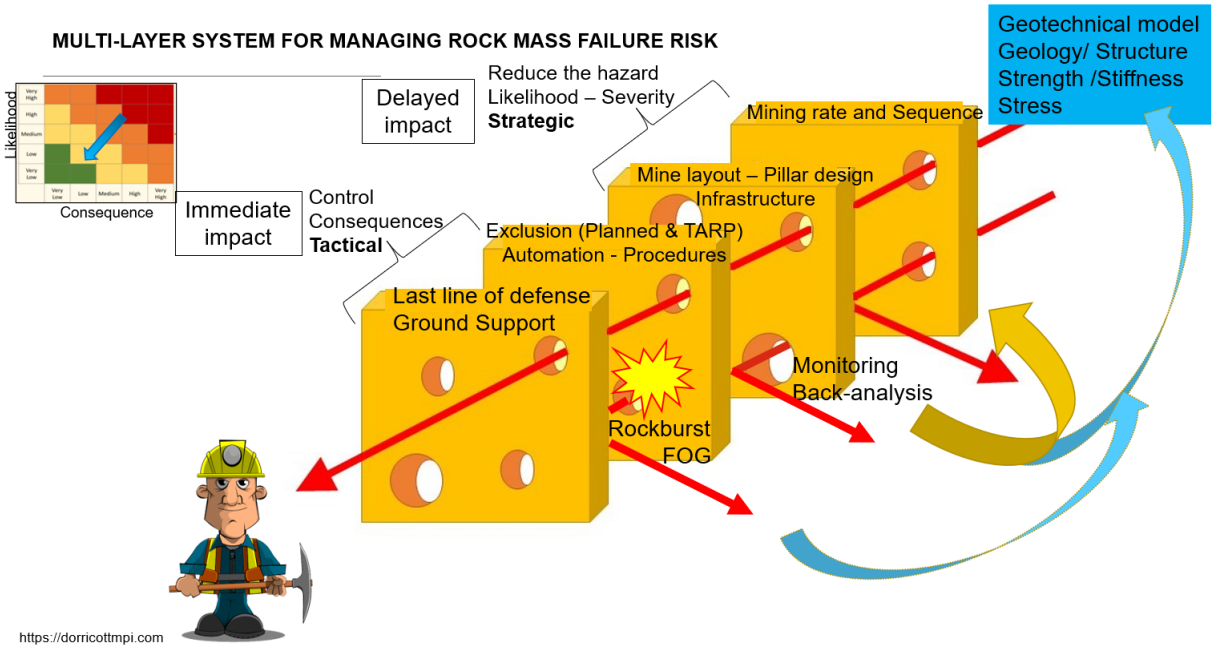


Figure 2 Strategic and tactical, multi-layer process for managing rock mass failure risk. FOG = fall of ground; TARP = trigger action response plan

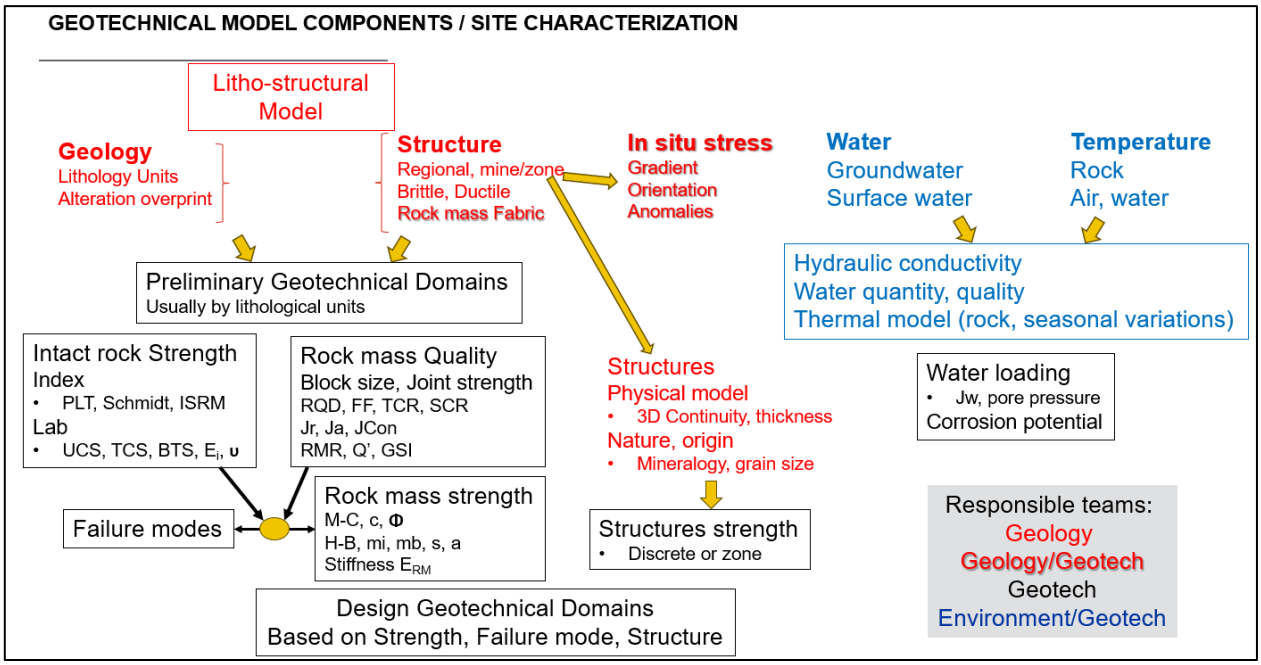


Figure 3 Geotechnical model components and sources of data. Responsibilities may vary between sites

2 Ground support evolution over the last 40 years

2.1 Safety improvements

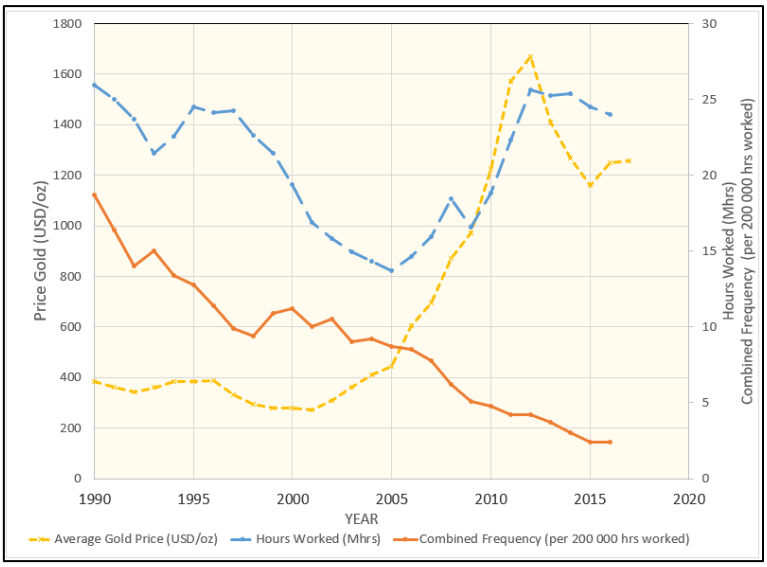
In 1980, the author was installing end-anchored mechanical rockbolts from a scissor deck with a stoper (handheld airleg). The ground support was being installed so far behind the active development face that the latter was not visible. This operational practice was deemed acceptable at the time. However, in 2026, it would not be allowed in many jurisdictions. During the 1980s, a typical drift size in Canadian mechanised mines was ~4.5 mW × 3.7–4.2 mH and a production scoop tram carried an 8 tonne payload. A high-grade copper mine at 1,200 m depth could be developed for CAD 85 million and operated successfully at a milling rate of 1,200 tonnes per day (tpd) (Desrosiers et al. 1990). Some large mines in Canada (e.g. Brunswick, Kidd Creek, and some Sudbury mines) were moving on the order of 6,000–10,000 tpd during that period but on average, drifts and mining equipment were smaller and mining rates were lower. In 2026, a new underground non-caving mining project in a low-risk jurisdiction may require over CAD 2 billion investment and a mining rate of the order of 20,000 tpd to be economic. Smaller, higher grade mining projects are still being found but they are becoming rarer and more difficult to develop. The high mining and corresponding development rates are made possible by high productivity haulage, such as scoop trams with nearly 18 tonnes (t) payload and 65 t trucks, and efficient excavation and ground support equipment. Average design drift sizes are ~5.3 mW × 5.5 mH and main travel ways are even larger. This evolution has been made possible by advances in equipment technology but is driven by the need for increased productivity due to lower ore grades from greater depths, larger hauling distances and higher labour and material costs. Larger excavations and higher mining rates translate to a higher rate of disruption of the rock mass and energy release per unit of time. Two major advances in rock engineering have enabled these major changes, while maintaining and indeed significantly improving underground mine safety. These enablers are rapid back filling, driven primarily by the development of paste backfill, and the advances in ground support technology and operational practice.

Figure 4a shows the improvements in the safety record of Quebec mines expressed in combined frequency (number of injuries per 200,000 hours worked in the mining sector). The total number of hours worked and the average gold price per year, highlight the production slowdown during the 1995–2005 period and the sharp increase following the rise in the price of gold after 2002. It is noteworthy that the accident frequency continued to decrease even as mining activity increased (data from Association Paritaire pour la SST au travail du secteur minier). Figure 4b traces the history of injuries from falls of ground and rockbursts in Ontario

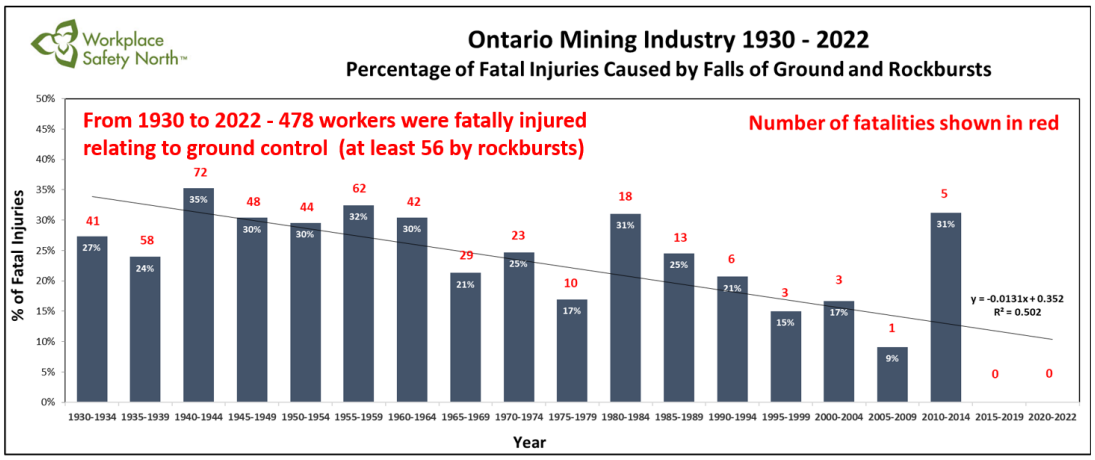
mines since the 1930s (Workplace Safety North 2022). The trend towards a safer mining environment is clear and reflects regulatory and societal evolution. In addition to the change in mindset, the improvements in the safety record are attributed to contributions from:

- safer excavation and ground support methods, mechanisation and equipment technology
- better understanding of rock mass characteristics, rock mass behaviour and failure mechanisms to improve design concepts through research, laboratory and in situ testing and advanced analyses using numerical modelling tools and monitoring
- rapid backfilling
- integrator tools to facilitate analyses.

Ground support installation has historically been one of the mining activities with the highest potential for physical harm to workers. The advent of mechanised scaling and bolting, in-cycle shotcrete and, in some cases, de-stress blasting, have contributed to significantly improving the safety of workers during this critical phase of the drift excavation cycle.



(a)



(b)

Figure 4 Safety improvements are evidenced by injury statistics from mines in the provinces of (a) Quebec and (b) Ontario

While the safety and technological improvements are remarkable and merit mention, some aspects should be acknowledged. Firstly, the increase in cost. In a similar rock mass, increasing mining depth by 2-fold (e.g. from 600 to 1,200 to 2,400 m) results in more than doubling the cost per meter of development at every step. At moderate depths, the onset of seismic conditions can result in a 5–12% cost increase. Proportions vary depending on individual mines but all in all, ground support operations (labour, materials) represent a third to nearly half of the total development cost while equipment maintenance varies from 10% to nearly 20% depending on the equipment used. Underground development is typically one of the largest big-ticket items on the capex list of a new project; hence, there is often pressure on the technical teams to 'optimise' quantities and costs early in project/mine life. Obtaining sufficient geotechnical data to correctly evaluate anticipated ground conditions and how they will evolve over time can be challenging.

There have been discussions around the need to reduce drift sizes (and hence equipment sizes) to promote stability and increase advance rates. The author is of the opinion that, although this might be desirable in theory, it is unlikely to be economically realistic and more benefit can be derived from designing and supporting operationally feasible excavations, controlling overbreak and avoiding damage to ground support through worker education, support protection and automation.

Secondly, reporting and analysing the safety performance based solely on accidents causing injuries can be misleading as it does not consider incidents occurring in areas under access restriction protocols. These near-misses or high potential incidents (HPI) must be reported and investigated with the same scrutiny as actual accidents. Incident cause analysis method investigations are conducted to investigate HPIs within most mining companies and are a legal requirement in some jurisdictions. In seismically-active mines, ground control teams have developed tools to routinely track and demonstrate the effectiveness of control measures. These may take the form of matrices relating the severity of damage (e.g. rated as the amount of displaced material) against worker exposure and ground support performance. These tools provide a more accurate overview of the level and evolution of ground failure risk and complement the more traditional safety statistics.

2.2 Ground support technology and practice

Considering the safety performance under increasingly challenging conditions, it is fair to qualify the advancements in ground support materials, design and installation as a revolution. Ground support systems consist of 3 main components: rock mass reinforcement provided by bolts of various lengths and areal/surficial support that is connected to the bolts via plates. Since the early pioneering work in South Africa with yielding bolts, cable lacing and testing machines, the mining industry has benefited from a tremendous body of research leading to the development of several new reinforcement (various versions of cement and resin grouted yielding bolts, modified geometry cable bolts, hybrid bolts, combined friction and end-anchored bolts), and areal/surficial support (thicker gauge welded mesh, various types of mesh straps, plain and fibre-reinforced shotcrete, high tensile rolled mesh) elements and an enhanced understanding of the capacity and limitations of ground support systems (Hoek et al. 1995; Kaiser et al. 1996; Hutchinson & Diederichs 1996; Villaescusa et al. 2023; Potvin & Hadjigeorgiou 2024; Kaiser & Cai 2018; and many others). On the equipment front, regardless of differences in ground support operating practices (e.g. Australian jumbo bolting and Canadian specialised equipment), the focus has been to reduce exposure by removing workers from the highest risk areas at the face. The introduction of fully mechanised bolting with protected cabins and safe working distances from the face allows the development to advance safely in potentially seismically active areas. Until recently, it was only possible to install cement grouted or friction bolts with these units. This led one mine to modify existing equipment and develop its own resin grouted rebar and paddle bolt installation system out of necessity. Since that time resin grouted hollow bolts can be installed efficiently with a mechanised bolter; however, it is still early to assess the performance of these bolts under seismic loading.

With the increase in excavation size, cable bolts have become an essential element in the toolbox for ground support design of stopes and drifts in both static and dynamic conditions. The installation of cable bolts has also greatly benefited from mechanisation with the development of cable bolters that can drill, install and grout plain strand cable bolts efficiently and safely. The only caveat has been the inability to install modified

geometry cables without altering their geometry and function. The bulges get squeezed upon insertion, thereby modifying the cable-grout interaction mechanism from crushing grout within the bulges to slip negating the advantage of their modified geometry. The development of bulge or modified geometry cables was a significant breakthrough for hanging wall dilution control and it is unfortunate to have lost this capability. One hopes that equipment manufacturers and researchers will recognise this limitation and propose solutions.

Notwithstanding the tremendous achievements and improvements in ground support technology and operational practices briefly described above, ground support failures under dynamic loading still occur as presented in Caron et al. (2025) and can be challenging to manage tactically. The sudden and violent nature of dynamic rock mass failure has rightfully attracted much attention; however, important lessons can also be learned from falls of ground in non-seismic conditions.

3 Learnings from falls of ground under non-seismic conditions

Ground support systems are designed to control rock mass conditions around the periphery of excavations based on our best knowledge of rock mass conditions and expected failure mechanisms (known knowns, Elmo et al. 2022) and an anticipation of factors that are likely to impact stability in the future (known unknowns). Potvin & Hadjigeorgiou (2024) describe the factors that can cause the ground support to be degraded over time. These factors include changes in stress, rock mass degradation, increase in excavation dimensions, mine-induced seismicity and static and dynamic loading. In 2 cases of falls of ground that occurred in non-restricted areas (i.e. HPI), several of these factors were identified as primary causes. In Falmagne & St-Onge (2019), ice jacking – resulting from water inflow with a sudden sharp drop in air temperature – caused ice build-up within a joint leading to localised straining and premature failure of the inflatable bolts. In the second case, extensive mining around the area of interest, resulting in rock mass dilation and loss of confinement, is suspected to have caused localised straining of the installed ground support. Rock mass dilation also increases fracture connectivity thereby promoting the infiltration of/contact with high-salinity groundwater and localised corrosion of the resin encapsulated rebar and cement grouted cable bolts. An increase in excavation dimension due to equipment damage contributed to increasing the load on the already compromised ground support precipitating the fall of ground. In both cases, visual inspections could not detect significant changes at the surface of the excavation prior to the failures that would have indicated the consumption of support capacity and led to proactively closing the area. It is doubtful that a LiDAR scan of the excavation surface would have detected the small deformations that were affecting the ground support 1–3 m within the rock mass.

Fully encapsulated resin grouted rebar or cement grouted cable bolts are typically considered to provide good protection insurance against corrosion, in comparison to non-grouted bolts. Mapping of surface corrosion is a recommended best practice to assess the potential for corrosion. As the above incidents illustrate, these best practices -although good and necessary – may not be completely sufficient under some circumstances. Localised straining of ground support at a joint interface inside the rock mass may be difficult to detect from surface inspections alone. Fully grouted rebar and cable bolts that have experienced localised strain and cracking of the grout or resin can be susceptible to water infiltration and corrosion leading to potentially undetected capacity loss. Under non-seismic conditions, the reduced life expectancy of friction and inflatable bolts is well documented and reconditioning programs based on the age of the ground support are well established. It should be recognised that the protection insurance from fully encapsulated bolts also has a time limit under certain conditions.

The situations described above are difficult to manage effectively in a reactive manner in a mine with several kilometres of development and constantly changing stress conditions. A proactive approach of ground support replacement and targeted instrumentation is necessary and can take the form of a hazard map with multiple overlays for each causal factor such as accumulated strain, depth of deconfinement from numerical modelling, groundwater infiltrations from water mapping (location and estimate of quantity), excavation dimensions (these need to be regularly updated when changes are noted), rock type, ground support type and age. As LiDAR detection limits and change detection software continue to improve, it may be possible to

detect and set up alarms from subtle changes at the surface of excavations to further reduce risks and manage the ground support replacement more effectively. The proactive approach of capacity replacement is similar to the practice of preventive support maintenance being promoted for seismic mines (Kaiser & Moss 2022).

4 Learnings from advanced analyses and site investigations

As described in Section 1, formulating a conceptual geotechnical model for rock mass behaviour and failure mechanisms based on rigorous observations and data collection, is essential for excavation and ground support design. Kaiser & Kim (2008) emphasise this point as shown in Figure 5.

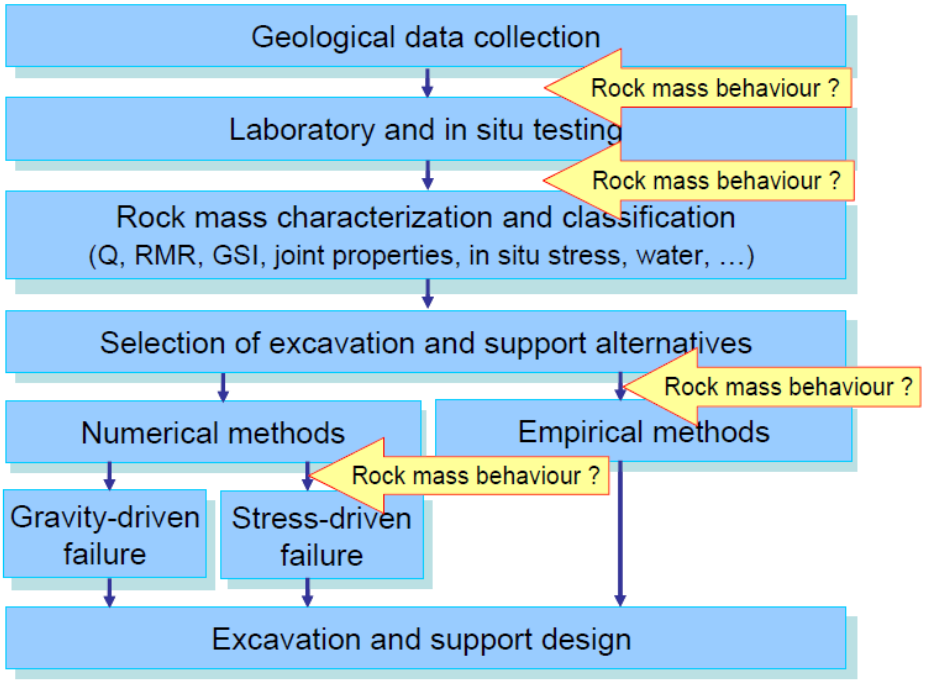
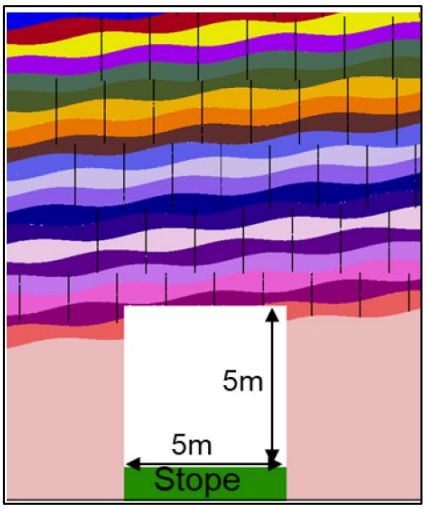


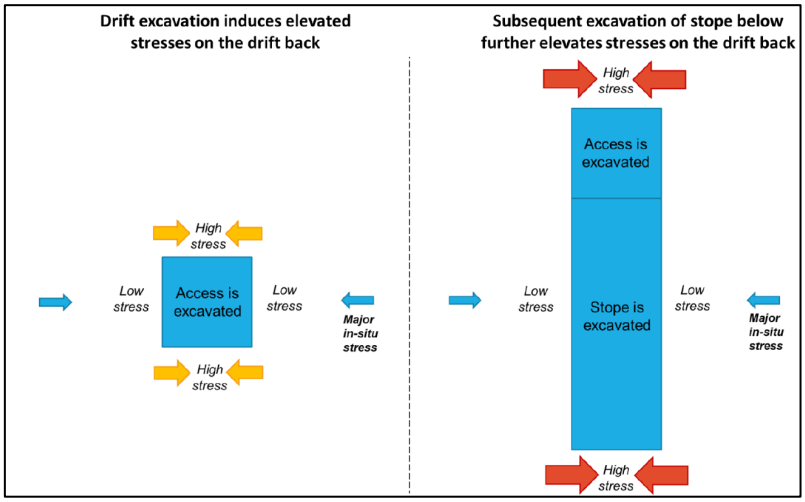
Figure 5 Site characterisation approach for standard geo-engineering projects; yellow arrows highlight where a sound understanding of rock mass behaviour is needed (from Kaiser & Kim 2008) (Q = Norwegian Geological Institute Rating for rock mass; RMR = rock mass rating; GSI = geological strength index)

This understanding is also required when conducting back-analyses of rock mass or ground support failure. Garza-Cruz et al. (2019) presented an example of using numerical modelling tools to describe observed ground support failures and assess the adequacy of alternative support systems. Figure 6 reproduces the results of the study showing the effect of rock mass deformation on the reinforcement elements. Used in this manner, numerical models are not intended to be perfect representations of complex geological and operational settings. However, it is necessary to capture the key components that control rock mass behaviour. In this case the undulating persistent sub-horizontal jointing with vertical cross joints.

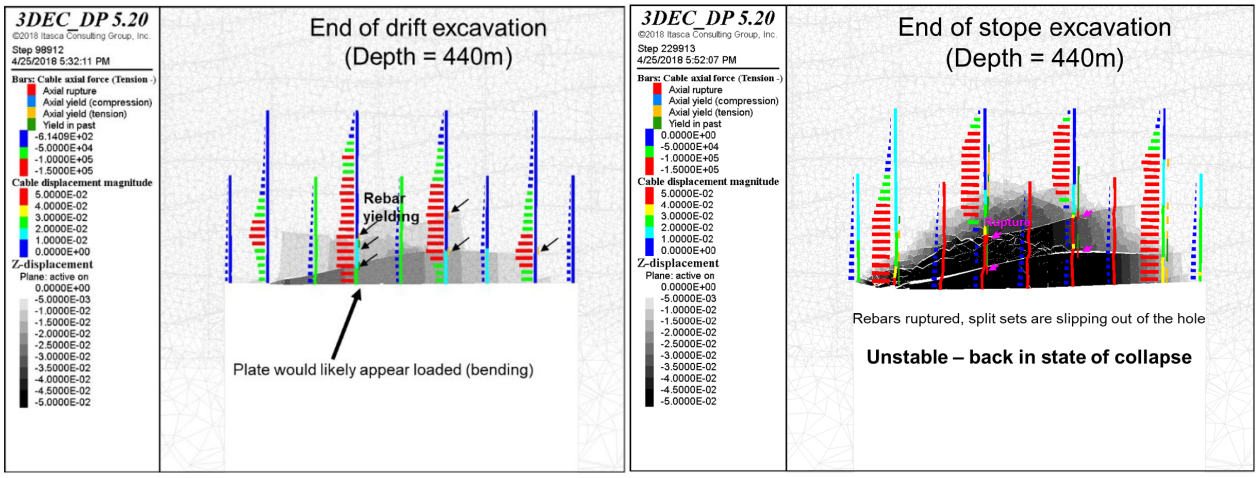
The work presented in Dehkhoda et al. (2023) simulates a ground support system within a discontinuous rock mass subjected to mining-induced stress and strain. In the model, the rock mass and bolts interact meaning that the effect of the bolts on the rock mass is simulated, as well as the effect of ground deformation on the bolts. An example of the model output showing the simulated strain accumulation on resin rebar is reproduced in Figure 7. Readers can refer to the papers for details of the work.



(a)



(b)



(c) (d)

Figure 6 **(a) Key controlling features in the conceptual geotechnical model; (b) Description of loading path; (c) and (d) Results showing the rock vertical displacement (greyscale), axial force on bolts (bar graph on bolt left side) and cable displacement (on bolt itself) (from Garza-Cruz et al. 2019)**

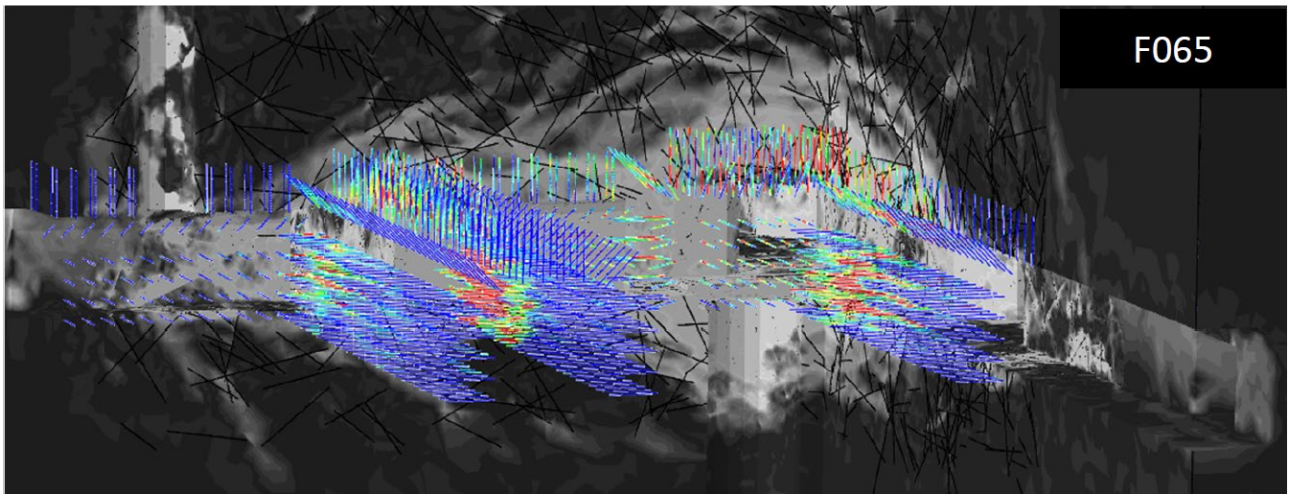
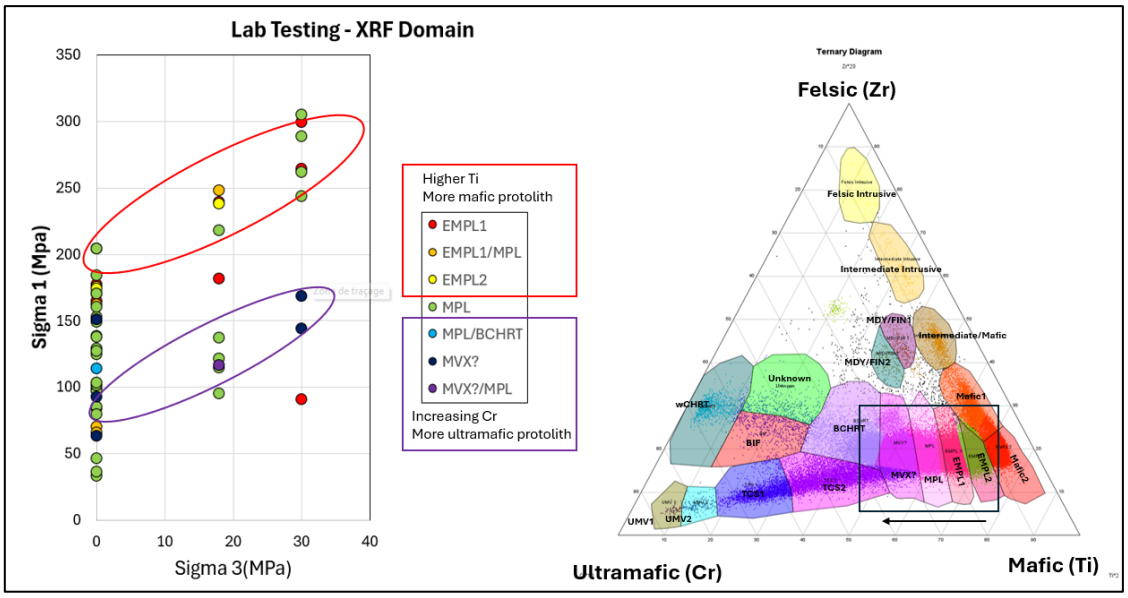


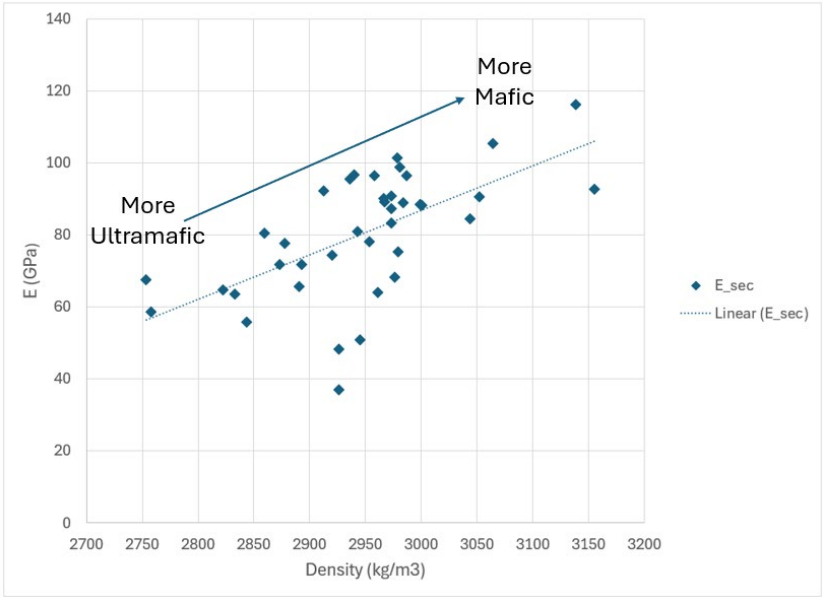
Figure 7 Results from numerical modelling showing displacement on bolts around an underground chamber (from Dehkohda et al. 2023)

These advanced models both integrate discrete structures to study the failure mechanisms. The case studies are particularly interesting as they consider both the effect of rock mass deformation on the bolts but also the reinforcing action of the bolts on the rock mass meaning that in effect, the rock mass is an integral part of the ground support 'system'. Future studies combining advanced numerical modelling and direct measurements of bolt deformation would be useful to continue to build on these learnings.

As illustrated in Figure 2 and emphasised by Kaiser & Kim (2008) (Figure 5), the development of a fit for purpose geotechnical model, from which rock mass failure modes and behaviour can be estimated, is the first and likely the most important step in the geotechnical risk management process. Site investigations and geotechnical mapping are expensive and often require time and collaboration that may be difficult to negotiate from exploration or geology teams with their own priorities. Much can be gained when priorities and physical resources can be aligned. This is an area where technological developments can bring significant benefits. Falmagne (2023) assessed that, on a typical project under development, geotechnical drilling represented only about 1% of all diamond drilling meters and laboratory strength testing was conducted on the equivalent of 0.1% of the number of assay samples. Mineral resource models are built following rigorous rules and grades are interpolated from a relatively regular array of sample results. Geotechnical models are built from a much-reduced dataset and typically rely on geological and structural interpretations developed primarily for mineral resource modelling. In some mines, this means that there is very little data from non-mineralised areas where critical mine infrastructure is located, and where litho-structural logging is frequently less detailed. Technological advances such as core scanning, borehole geophysics and analyses of core photography, combined with machine learning are starting to allow more reliable and useful data to be collected at limited extra cost. This means leveraging more value from the drillcore and drill holes that are already being drilled and can result in improved grouping of laboratory strength testing samples. This can have significant impact on the estimates of rock mass strength and stiffness parameters, as shown in Figure 8. Variations in lava flows that are not immediately obvious (nor relevant) from basic lithology logging are reflected in the mineral compositions and X-ray fluorescence (XRF) domains identified from the continuous core scanning logs. For example, recent work at one site has shown that as the XRF signature increases in Chromium (Cr) the rock transitions from a mafic protolith (higher Titanium [Ti]) to an increasingly more ultramafic protolith (higher Cr). A decrease in rock strength (Figure 8a), and lower stiffness (Figure 8b) are observed to the left of the Mafic Pillow Lava (MPL) XRF domain. Understanding the spatial distribution and structural context of these variations is key to mapping strength and stiffness contrasts and anticipating rock mass behaviour.



(a)



(b)

Figure 8 Correlation of core scanning X-ray fluorescence (XRF) data with laboratory testing results. (a) Uniaxial and triaxial testing results grouped by XRF domains; (b) Variations in stiffness (Young's modulus [E]) correlated to density show that lighter more ultramafic lavas are softer than their mafic, denser counterparts

5 Ongoing research for the future

Improving the quality and spatial distribution of reliable data for the construction of fit for purpose geotechnical models should continue to be a priority. In addition to the core scanning and borehole geophysics technologies mentioned above, geological/geotechnical drift mapping is still lagging in terms of efficiency and completeness. In high drifts it can be challenging to carry out inspections for conformance or to detect subtle changes that could trigger a detailed action. Continued improvements in LiDAR and drone technologies are desirable.

Understanding the interaction between the rock mass and reinforcing action of the ground support systems is a key avenue for future research. In situ, blast-induced dynamic testing of ground support systems holds promise for visualising the performance and interaction between the ground support system components and measuring the deformation capacity of the surface elements. These experiments are expected to enhance knowledge and understanding in addition to the laboratory-based static and dynamic testing (Ortlepp 1992; Gaudreau 2004; Doucet & Voizelles 2012; Villaescusa et al. 2023; Durham et al. 2024a, 2024b; Knox 2023; and several others).

In situ cable bolt deformation measurements have been around for several decades and have provided great insights into rock mass and ground support behaviour. Direct measurements of bolt (e.g. rebar, yielding bolts, etc.) deformation over time and during episodes of seismic activity have been attempted with varying degrees of success. The reasons for the slow uptake and integration of existing technologies are not clear, but the author is of the opinion that this would be an important avenue for ongoing research and technological development. In situ measurements of bolt deformation would provide useful validation for advanced numerical modelling work such as the examples presented in the previous section.

Deformation based ground support design (DBSD) implemented in the Rockburst Hazard Assessment (RBHA) design tool (Rigby et al. 2026b), provides a solid basis for proactive management and ground support design for strainbursting in hard brittle ground (Kaiser & Moss 2022). The ongoing research presented in Rigby et al. (2026a) recognising the effect of geological structures on the dynamic response of a tunnel is of particular interest. Using discontinuum modelling, the authors considered *"*different combinations of structure orientation and tunnel-structure distance to study how the structure influences the strainburst dynamics and the resulting demand on the ground support system*"* (Rigby et al. 2026a). Continuing to leverage advances in numerical modelling to build on the DBSD approach and include different modes of failure and rock mass behaviour (e.g. anisotropic rock masses) is expected to bring high value to the industry. From an operational perspective, controlling and managing the rock mass damage resulting from floor heave related to seismicity remains challenging. Some solutions inspired from earthquake building engineering have been applied to critical excavations, but more thoughts and experimentation are needed to incorporate solutions into drift designs.

6 Conclusion

As the last line of defence, ground support is one of the most effective control measures in our toolbox to isolate people from harm caused by unexpected rock mass failure. Hence, it has been and continues to be a major and vital focus of research and technological development for the mining industry.

This paper presented a non-exhaustive overview of technological and scientific advancements witnessed over the last forty years, highlighting the safety and productivity benefits observed during this period. The mining industry has achieved remarkable improvements in safety and productivity over the past 4 decades through advances in ground support technology, mechanisation, backfilling, geotechnical understanding, and numerical modelling. Successful applications of ground support under a range of conditions in underground mines illustrate the advancements realised through the collaborations between industry, academia, service providers, equipment manufacturers and suppliers of ground support elements. However, deeper mines, larger excavations, and higher production rates are creating increasingly challenging ground conditions. Future success will depend on developing higher-quality geotechnical models, improving monitoring of support system performance, better understanding rock-support interaction, and expanding automation and robotisation to further reduce worker exposure.

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