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Integrating Smart Bolt technology in critical excavations

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Abstract

MMG Rosebery underground mine has been in continuous operation for over 90 years. Much of the legacy infrastructure was established at a time when the ore reserve was smaller than it is today. Expansion of the mineable resource has resulted in some critical infrastructure being located closer to stoping panels than originally intended.

Targeted numerical modelling was undertaken to better understand changes in and around key infrastructure associated with additional stoping. This was used to inform strategies to manage the changing geotechnical environment.

Modelling indicated modest closure and capacity degradation of the installed ground support. The predicted closure remained within the ground support design limits; however, given the continuous utilisation of the infrastructure and significant disruption associated with reactive rehabilitation, a risk-based strategy was adopted. This involved phased installation of supplementary support alongside enhanced monitoring to enable early detection of change.

The paper presents a case study of the implementation of a novel ground support monitoring technology developed by ThingWave™ and deployed using Jennmar's Smart Bolt system.

The instrument is designed to be compatible with common mechanised support installation methods and is integrated within the ground support element.

Smart Bolts provide real-time data on rock mass behaviour and support response without the need for manual collection. The system delivers high-resolution monitoring of deformation and deformation rates, enabling increased understanding of rock mass response and support performance. Sudden step changes in deformation can be attributed to specific triggers (e.g. blasting or seismic events) through continuous time-stamped data recording.

The system enables engineers to estimate residual ground support capacity and assess whether sufficient capacity remains to withstand expected future demand. This provides a basis to anticipate support failure and plan upgrades proactively.

The paper explores further applications, including the use of monitoring data for numerical model inputs and validation, and the use of high-density continuous monitoring data over mine areas to optimise ground support design and application.

Keywords: *smart monitoring, support capacity, residual capacity, model validation*

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1 Introduction: case study area

Rosebery's underground workshop is situated approximately 1,300 m below surface and is offset approximately 150 m into the footwall from the main ore lode. The workshop was developed during 2012–2013 to provide permanent underground servicing facilities for heavy mobile equipment. At the time of construction, the workshop occupied a position considered sufficiently removed from planned extraction to provide a stable long-term facility.

Figure 1 shows the location of the workshop relative to the ore lens' at the time of its development.

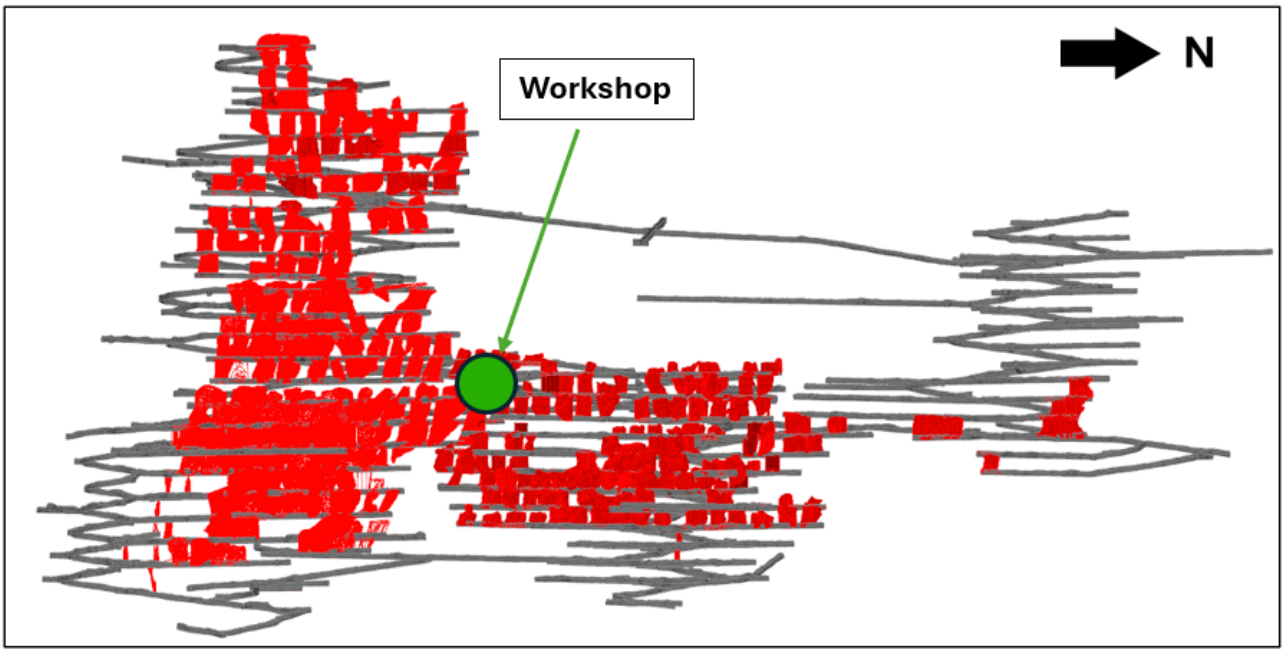
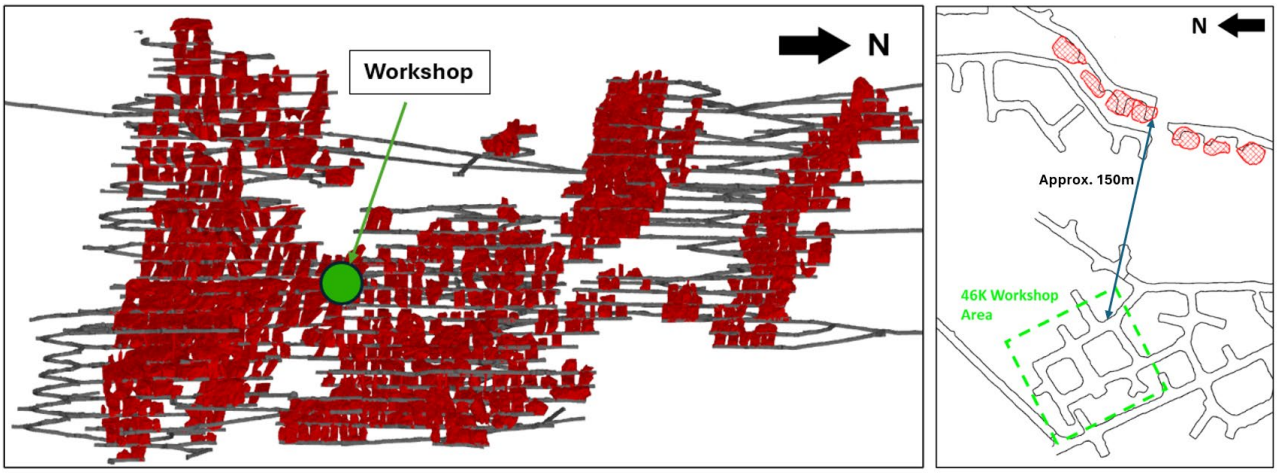


Figure 1 2013 mine void at time of workshop development

During the subsequent decade, improved geological understanding and favourable economic conditions significantly expanded the economic resource. Progressive extraction and extension of the ore lens fundamentally altered the surrounding mining geometry, progressively reducing the separation between active stoping fronts and the workshop (Figure 2).



(a) (b)

Figure 2 (a) Long section of current mine void; (b) Plan section offset of workshop from orebody

As mining advanced, the workshop exhibited a gradual evolution in rock mass behaviour. Shortly after construction, localised stress damage was recorded and was associated with relaxation of the rock mass into the large spans. This was primarily in the sidewalls and pillar corners. Damage manifested as cracking of the fibrecrete surface support and localised loading and failure of fully encapsulated resin bolts in the collar region. This observation prompted a support upgrade to improve the deformation capacity of the support system. Minor seismic-induced damage was observed in 2014, providing an early indication that the workshop was beginning to experience the effects of stress redistribution beyond that anticipated during its original design. Following these early observations, the excavation remained largely stable for almost a decade despite continued mining in the surrounding orebodies.

This period of stability ended in 2025 when renewed stress-related deterioration and a large outlier seismic event occurred within the workshop. The recurrence of seismic damage after an extended period of relatively benign behaviour suggested that a changing stress regime around the workshop was being governed by mine-scale stress redistribution associated with long-term ore extraction. This prompted a detailed geotechnical investigation to establish the mechanisms driving the observed behaviour and to assess the risk to the workshop in the future.

2 Modelling

Numerical modelling was undertaken to assess the influence of ongoing and planned mining on the workshop. Historical mining steps were modelled to understand progressive stress changes on the workshop over time before the future mining sequence was incorporated.

A key outcome of the assessment was the identification of a progressive reduction in major principal stress around the workshop over time and as mining advanced. The workshop is positioned in the footwall of the extracted mine void, and continued stoping was predicted to generate a stress-shadowing effect in the area. The largest changes were associated with the extraction and closure of a regional pillar during the middle stages of the mining sequence (Figure 3).

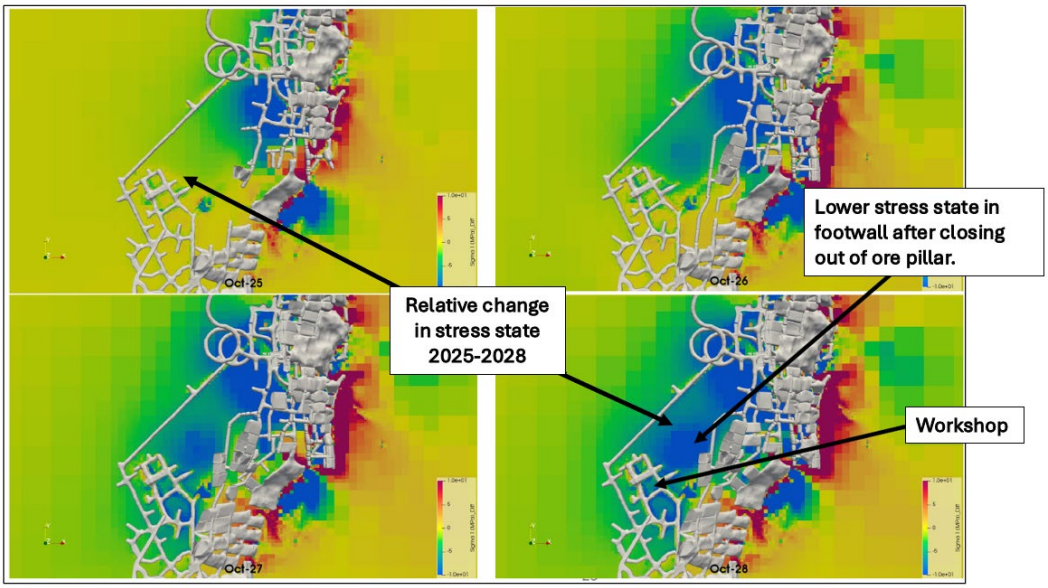


Figure 3 Reduction in principle stress in footwall of orebody causing a stress-shadowing effect

While the broader modelling indicated a reduction in stress levels around the excavation, detailed assessment of the large seismic event highlighted the importance of structural behaviour in controlling local hazard. The analysis indicated that the event was associated with slip on a pre-existing geological structure, driven by mining-induced stress redistribution and a reduction in confinement acting normal to the structure. Rather than being associated with increasing stress accumulation, the event appears to have occurred as changing stress conditions promoted localised structural slip.

The modelling identified a localised peak in slip tendency coincident with the occurrence of the large seismic event, providing good agreement between the interpreted failure mechanism and the observed response. In contrast, conventional energy-based and seismic event trend indicators showed limited correlation with the event, suggesting that slip tendency was a more appropriate metric for assessing hazard in this setting.

Forward analysis showed that elevated slip tendency persisted for a period following the event, particularly during the stage of mining associated with regional pillar extraction. However, no increasing trend in slip potential was identified beyond this interval, and no comparable peaks were predicted over the remainder of the assessed stope extraction plan. The modelling therefore indicated that the event was associated with a specific structural response to mining-induced stress redistribution rather than a broader increase in seismic hazard.

The modelling also predicted modest excavation deformation, characterised by gradual sidewall convergence over time. Forecast deformation levels remained within the expected performance range of the installed ground support system. The modelling indicated that future demand on the ground support system would be dominated by progressive stress-driven deformation rather than sudden large-scale dynamic instability.

These findings formed the basis of the revised ground control strategy for the workshop. Although the modelling indicated that excavation performance would remain within acceptable limits, it also identified a period of changing stress conditions during which localised structural slip and progressive support mobilisation were most likely to occur. Consequently, localised support upgrades were undertaken to manage the potential consequences of structure-controlled seismicity while an enhanced monitoring program was developed to verify model predictions and provide early indication of any departure from the anticipated excavation response.

The predicted deformation was sufficiently modest such that it would be difficult to distinguish expected closure onset using the existing monitoring techniques employed in the workshop. Consequently, the primary engineering objective shifted from predicting excavation performance to verifying that the workshop continued to behave in accordance with the model as mining progressed. A monitoring system capable of detecting very small changes in support response was required.

3 Development of a monitoring strategy

The numerical modelling predicted relatively modest excavation deformation occurring progressively over several years. Detecting departures from this forecast behaviour therefore required a monitoring strategy capable of identifying subtle changes in excavation response. In addition, monitoring of the upgraded ground support system was required to quantify progressive support mobilisation and provide confidence that sufficient residual capacity remained available to accommodate a potentially damaging seismic event should one occur during the remaining life of the excavation.

Current practice at Rosebery, as is common at many operations, typically focuses on measuring deformation of the supported rock mass through visual inspections, extensometers, crack gauges, and – more recently – LiDAR scanning (Batkhuu et al. 2024; Bawden 2023; Patwardhan & Karim 2024; Saydam et al. 2021).

While these techniques provide valuable information on rock mass behaviour, they do not directly quantify the response of the installed ground support. Hales (2022) investigated instrumented cable anchors in squeezing ground conditions, monitoring cable elongation alongside visual observations, multi-point borehole extensometers (MPBX) and LiDAR scanning. Although some correlation was observed between MPBX displacement and cable elongation, the relationship was inconsistent, demonstrating that rock mass deformation is not always a reliable proxy for deformation of installed reinforcement.

While conventional monitoring provides an effective indication of excavation behaviour, it offers only limited insight into the degree of mobilisation or residual capacity of the installed ground support.

A further requirement of the monitoring strategy was that sensors could be installed throughout the excavation, including the high backs, sidewalls and pillars and that monitoring data could be retrieved remotely from all sensors.

4 Incorporation of Smart Bolt technology

To address these monitoring requirements, MMG Rosebery partnered with Jennmar to deploy the ThingWave™ Smart Bolt monitoring system within the workshop as an enhancement to the existing monitoring program. Trials at other underground mining operations had already demonstrated the capability of the technology and its suitability for addressing the monitoring requirements identified at Rosebery.

Figure 4 presents monitoring data from a Smart Bolt installation at Boliden's Kristineberg mine in northern Sweden, (Bondarchuk, pers. comm., 27 May 2026). The deformation history illustrates the system's ability to record both gradual squeezing ground conditions and discrete step changes associated with more rapid loading events. At Kristineberg, these step changes were attributed to nearby blasting activities. The total measured elongation over the monitoring period was 15 mm. The continuous high-resolution dataset demonstrates the ability of the system to identify the timing, magnitude and rate of individual deformation events that would be difficult to assess and correctly interpret using conventional periodic monitoring techniques.

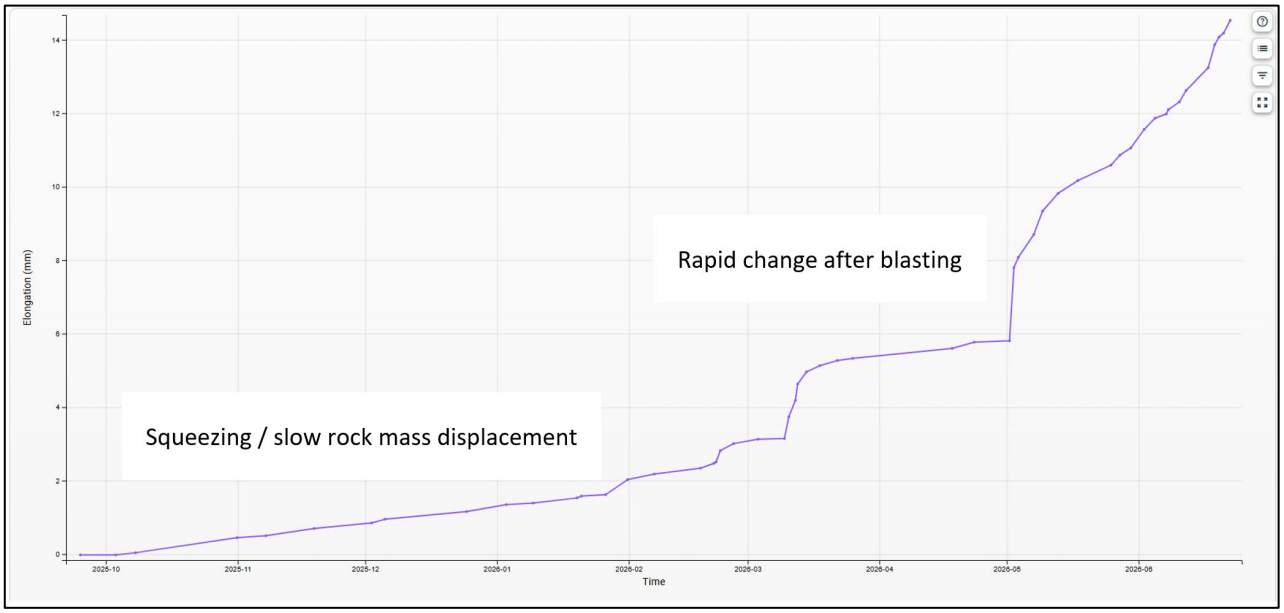


Figure 4 Smart Bolt monitoring data, courtesy of Boliden's Kristineberg mine, published with permission

A major advantage of the ThingWave™ Smart Bolt system is its cloud-based connectivity, enabling near real-time access to monitoring data without the need for manual collection. Individual Smart Bolts communicate through a self-forming wireless mesh network, automatically transmitting deformation measurements at user-defined intervals to a cloud platform. This allows engineers to review ground support behaviour over any selected time period or immediately following blasting, seismic events and other operational activities. Figure 5 illustrates the Smart Bolt cloud system setup.

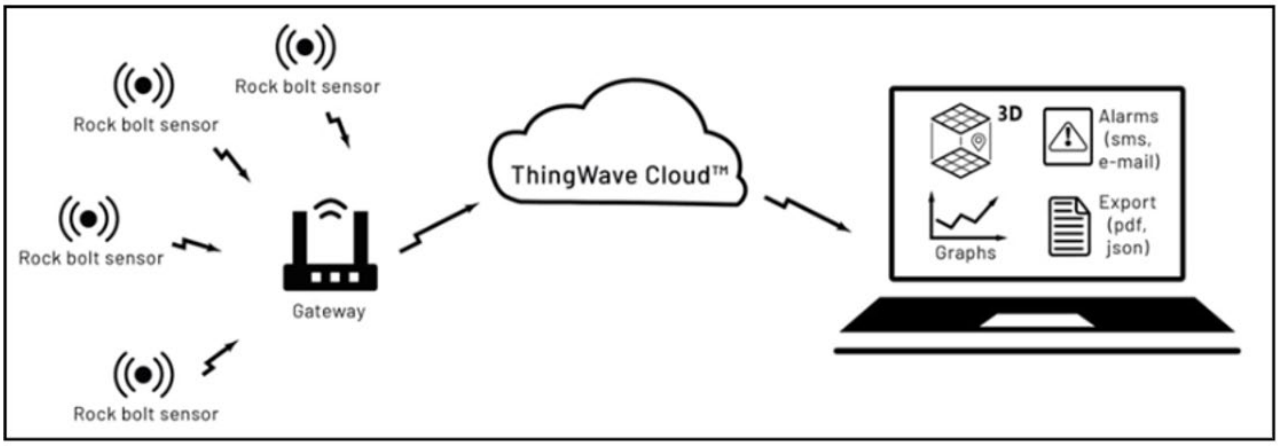


Figure 5 ThingWave Smart Bolt data collection and reporting platform

The Smart Bolts are integrated within the installed ground support system and measure deformation of the reinforcement tendon itself. The instrumented bolts are based on a J-Tech deboned resin bolt. A sensor wire extending to the toe of the bolt is connected to a displacement transducer housed within the bolt head assembly. Figure 6 shows the features of the Jennmar, ThingWave™ Smart Bolt sensor.

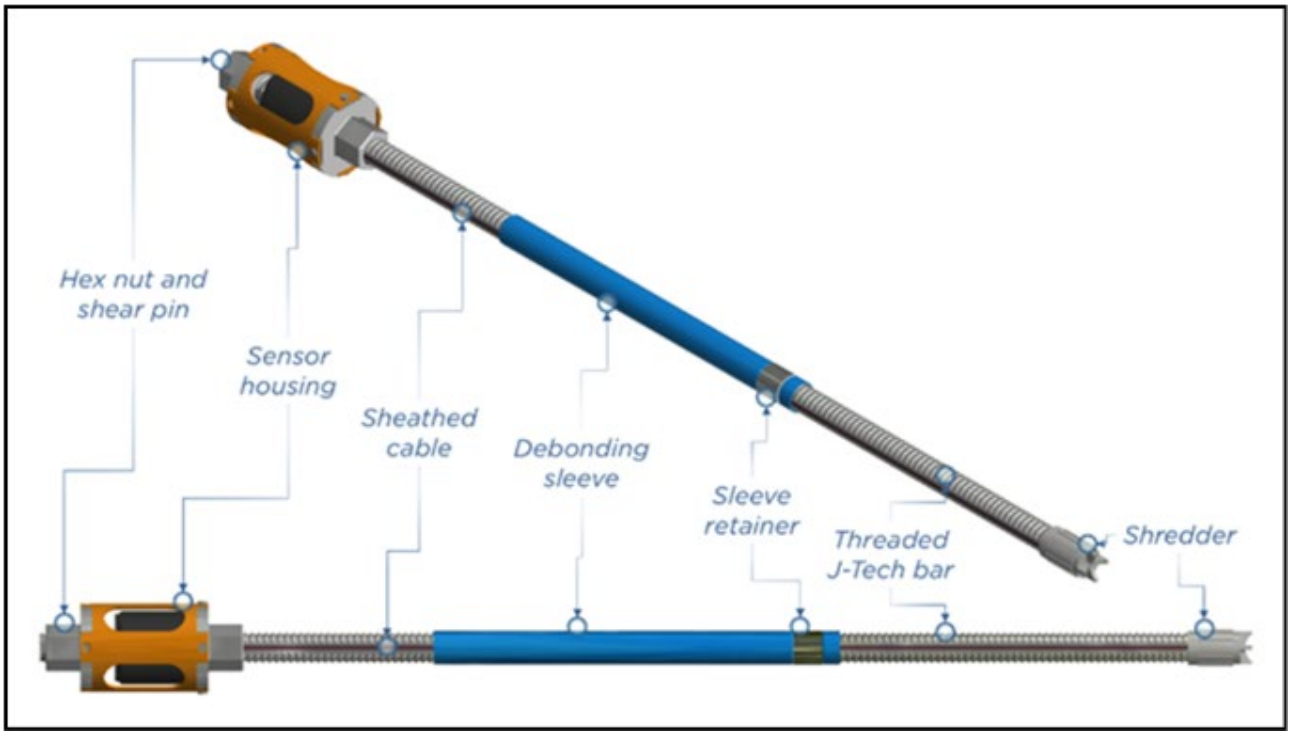


Figure 6 Smart Bolt components

The Smart Bolt was specifically developed for installation using conventional jumbo practices, enabling a single pass installation process for ground support and monitoring. The installation of Smart Bolts using a development jumbo in the workshop is shown in Figure 7.



Figure 7 Installation of Smart Bolt with standard development jumbo

The ability to accurately measure elongation of the actual element provides a direct measure of support mobilisation enabling engineers to assess how much of the available capacity has been consumed as excavation loading evolves. Figure 8 is a schematic illustration of the reduction in capacity of the support element from the deformation recorded on the same support element.

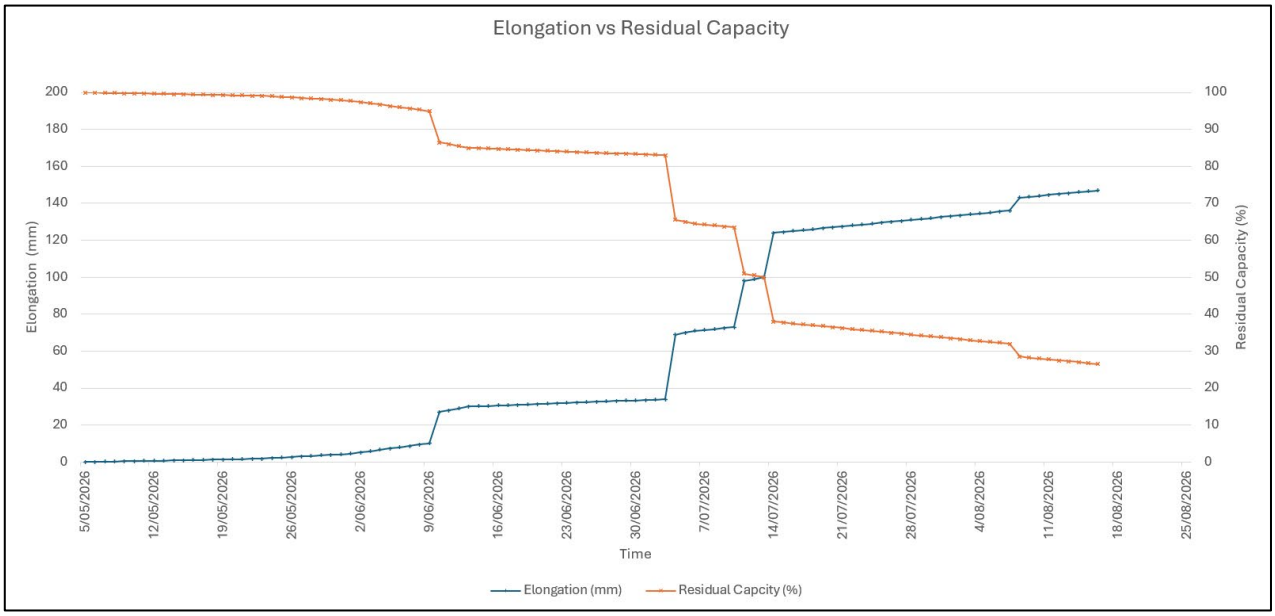


Figure 8 Illustration of the evaluation of residual capacity against measured displacement.

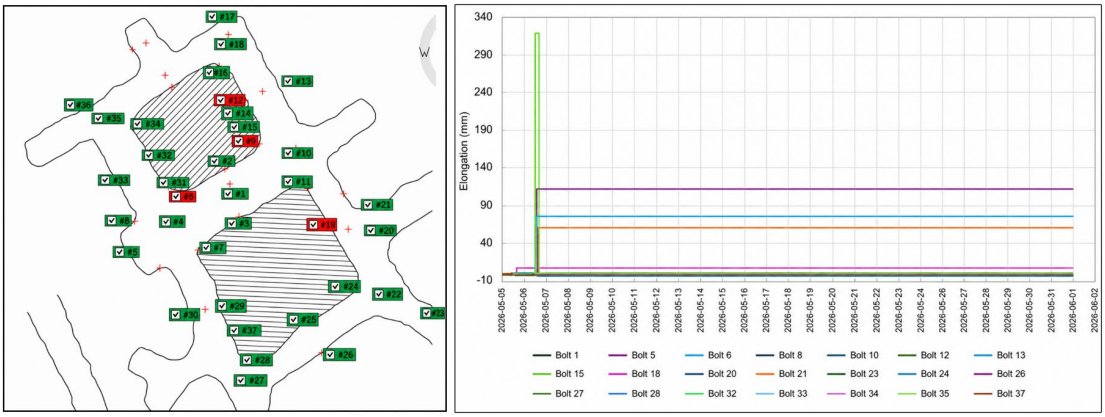
For the workshop, this represented an opportunity not only to monitor excavation behaviour, but also to validate the numerical modelling predictions by measuring the response of the installed ground support during specific stages of the mining sequence. The ability to make a direct estimation of the residual capacity of the installed ground support would provide confidence that sufficient deformation capacity remained to accommodate the peak periods of change forecast by the numerical modelling.

5 Initial results

A total of 37 instrumented Smart Bolts were installed throughout the workshop. Sensor locations were selected to provide coverage of the large-span intersections, critical pillars, the higher exposure areas around the known fault structure as well as areas identified in the numerical modelling expected to experience maximum closure.

Several monitoring bolts were damaged during installation due to failure of the sensor housing. The trial provided valuable feedback to the manufacturer, identifying the need for a more robust connection between the sensor housing and the bolt nut to prevent rotation of the internal electronics during bolt tensioning. The sensor housing design has since been refined to address this issue.

At the time of writing, the Smart Bolt array had been operating for approximately one month. Figure 9 shows the bolt array and recorded data.



(a) (b)

Figure 9 Smart Bolt monitoring (a) Smart Bolt array; (b) Recorded data to date

The initial spikes on the elongation axis represent the seating movement immediately after installation. Thereafter no notable deformation has been recorded at the scale of the plot shown in the Figure. To enable ease of longer-term analysis the bolt elongation graph will be zeroed at the point of installation.

Although no significant excavation deformation was expected during the initial monitoring period, several Smart Bolts recorded very small movements of <0.1 mm. While the magnitude of this movement may be considered insignificant and ordinarily dismissed, the same response was recorded across a cluster of adjacent Smart Bolts located closest to the orebody, suggesting a potential common source. Due to the continuous monitoring, it was possible to look for a causal event to investigate this small detection of movement.

The movement occurred within the same 5-minute recording interval as a production stope blast that generated a coincident M_L1.1 seismic event approximately 130 m from the installed bolts. Figure 10 shows the deformation histories from 3 of the Smart Bolts closest to the event, each recording the small displacement during the same monitoring interval.

It is noted that all Smart Bolts responding during this event recorded a negative displacement. Initial movement after installation can be greater in an oblique rather than axial direction relative to the installation angle (shear movement). The negative change is considered to reflect minor bending of the bolt. As the bolt deflects, one side experiences slight compression while the opposite side experiences slight extension. Because the sensing wire is located along one side of the bolt, the initial recorded displacement may be either positive or negative depending on its position on the bolt relative to the direction of movement. The important observation is therefore not the positive or negative direction of the recorded movement, but that several Smart Bolts responded simultaneously to the same distant mining event, demonstrating the sensitivity of the system to detect subtle change within the rock mass and ground support.

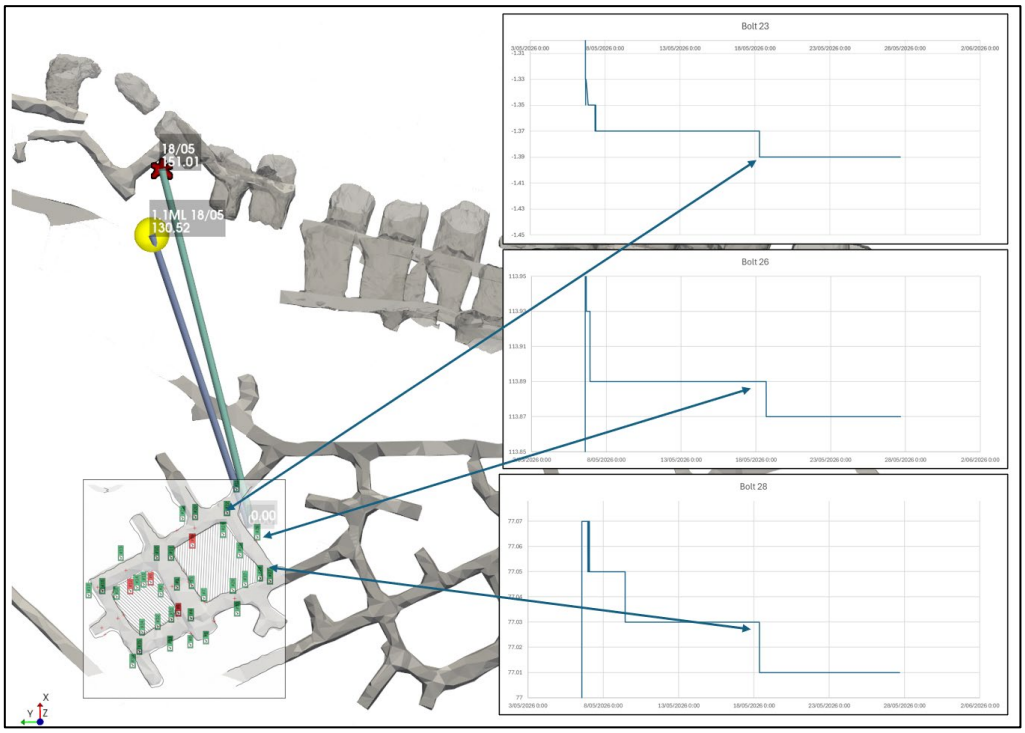


Figure 10 Movement detection on bolts coincidental with a stope blast and seismic event occurrence

At this stage, this represents a single observation and is not sufficient to conclude that the measured response was directly caused by the seismic event. However, the timing of the response across multiple Smart Bolts makes it an observation of interest. Continued monitoring during future blasting and any associated seismic activity will help determine whether this response is repeatable and whether a consistent relationship exists between distant discrete stope blasting or seismic events, the rock mass response and bolt movement in the workshop.

6 Smart Bolt data potential

The most immediate application is the ongoing validation of numerical modelling predictions. Rather than relying on periodic inspection or measurements of excavation closure, the bolt monitoring response can be compared directly with forecast rock mass behaviour. Continuous monitoring allows both cumulative deformation and the rate of support mobilisation to be quantified throughout the life of an excavation. Review of this relationship can provide confidence that excavation performance remains within modelling expectations, while departures from expected trends could provide an early indication that further investigation, model refinement or engineering intervention is required.

The direct measurement of deformation of an installed ground support element also enables better estimation of the residual capacity of the support system compared with indirect monitoring methods. By comparing measured elongation against the known deformation capacity of the bolt (and wider installed support), it becomes possible to quantify the proportion of capacity consumed and the capacity remaining.

A key opportunity for future work is the integration of Smart Bolt data with other data sets, such as seismic event frequency, magnitudes and blasting records.

The initial observations presented in this study have already demonstrated the sensitivity of the system to detect subtle reinforcement movement associated with a distant seismic event. As monitoring datasets grow, this approach offers the potential to distinguish between gradual stress-driven deformation, blast-induced loading and seismic event response. Correlating the response of the installed ground support element with individual and consecutive episodes of loading has the potential to improve understanding of the mechanisms driving excavation behaviour and support mobilisation.

Perhaps the greatest opportunity is to move beyond simply recording deformation towards predicting future support demand. Rather than assessing reinforcement condition at a single point in time, continuous monitoring enables deformation trends, and rates of support mobilisation to be tracked and linked to a mining activity or the rock mass response driving that change. Combined knowledge of measured deformation, residual support capacity, and the planned future mining sequence has the potential to indicate by extrapolation whether sufficient support capacity remains to accommodate the next stage of mining or anticipated loading event.

With further operational experience, these datasets could form the basis of trigger action response plans (TARPs). Figure 11 shows an illustration of how engineers might interpret the data from the Smart Bolts against the historical and forecast mining activities and expected seismic loading into a predictive tool enabling intervention before support failure occurs.

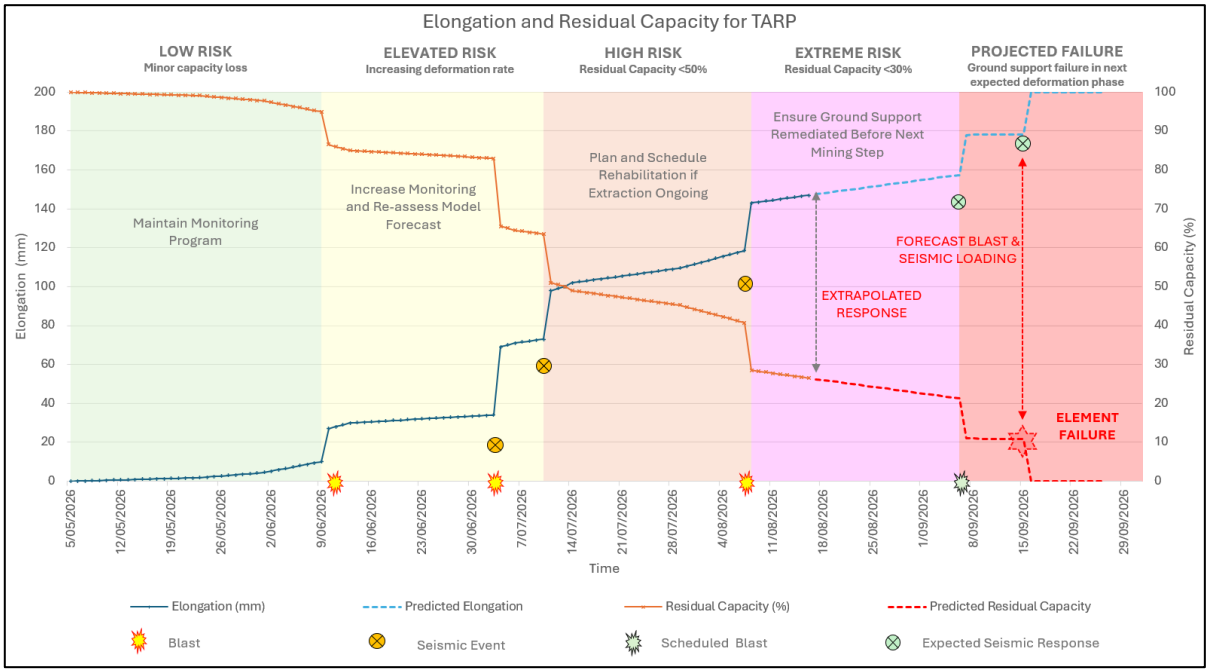


Figure 11 Correlating causes and rate of deformation to predict support response to future loading events

Trigger levels based on deformation magnitude, deformation rate, simultaneous response across multiple monitoring elements, or departures from expected model behaviour could provide objective criteria for an engineering review, increased monitoring, supplementary support installation, or changes to the mining sequence. Such an approach would represent a significant step from reactive condition monitoring towards predictive, risk-based management of ground control strategies.

A final goal of the trial at Rosebery is to extend the Smart Bolts's current capabilities of elongation monitoring to incorporate vibration sensing using the existing on-board accelerometer sensor. With a high sample rate of 2,000 samples per second it is possible to achieve a time resolution of better than 1 ms. Given the high accuracy shared time over the wireless mesh network of approximately 1–2 ms resolution, it would be possible to create a spatially distributed seismic sensor array as long as software-controlled scheduling can be reliably implemented. Running accelerometers at high sample rates continuously would drain the batteries of the Smart Bolts. During the next phase of the trial, it is intended to remote control each bolt and provide a schedule for activating the high-frequency vibration sensing. This input would typically come from the mine planners stoping schedule. By using the collective sensing performance of the full array of Smart Bolts with elongation and vibration sensors, the authors believe that energy release during blasts and simultaneous seismic events could be used to validate dynamic behaviour of the rock mass and thereby provide a real world comparison between ground motion and ground support loading, providing greater insights into support performance and inputs for dynamic ground support capacity design.

7 Conclusion

This case study has demonstrated the successful implementation of Smart Bolt technology within a critical underground excavation to directly monitor the response of installed ground support under changing mining-induced stress conditions. Numerical modelling identified a period of progressive stress redistribution and modest excavation closure, informing a proactive ground control strategy comprising targeted support upgrades and enhanced monitoring. The Smart Bolt system was subsequently deployed to verify these modelling predictions and provide continuous measurement of reinforcement response throughout the remaining mining sequence.

Although the monitoring period presented in this paper is relatively short, the initial results demonstrate the capability of the system to detect very small reinforcement movements and to identify simultaneous responses across multiple elements associated with a distant blasting and seismic event. While this single observation is insufficient to establish a causal relationship, it provides confidence in the sensitivity of the technology and highlights the value of continuous, time-stamped monitoring for investigating excavation behaviour that would be difficult to identify using conventional monitoring techniques.

Unlike conventional monitoring systems that infer ground support performance from measurements of rock mass deformation, Smart Bolts directly measure the deformation of the installed reinforcement itself. This provides engineers with a direct assessment of support mobilisation and estimation of the remaining capacity of the support system.

The broader significance of this technology extends beyond excavation monitoring. Integration of reinforcement response with numerical modelling, seismic monitoring and blasting records has the potential to improve understanding of the mechanisms driving excavation behaviour and support demand. As operational datasets mature, these measurements may support the development of quantitative TARPs, enabling a transition from reactive condition monitoring towards predictive, risk-based management of ground support. Future development of distributed deformation and vibration sensing within Smart Bolt arrays may further expand these capabilities, providing new opportunities to better understand dynamic loading on ground support, validate dynamic support behaviour and optimise dynamic ground support design methods.

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