Deep Mining 2024 – P Andrieux & D Cumming-Potvin (eds)
© 2024 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-9-6
doi:10.36487/ACG_repo/2465_57

# Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic event: part 2 – the mitigation plan

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## Abstract

*A MN3.7 seismic event occurred on 30 October 2020, at Westwood mine. Following the event, the entire mine production was halted to focus on understanding the mechanism of the event and to identify areas with potentially similar conditions. The current paper presents the background information that was available prior to the event. Subsequently, investigations were carried out to understand the mechanism of the seismic event and included: geological, structural and geotechnical model updates, advanced seismic analyses, numerical stress modelling, integrated rockburst hazard assessment, as well as a complete review of the dynamic ground support standards of the mine. Finally, a very detailed risk register was prepared to identify ground control related hazards and to establish a mitigation measure plan process (i.e. risk identification, existing mitigation measures, current hazard levels, proposed mitigation measures as well as residual hazard levels).*

**Keywords:** *seismic risk, rockburst, stress modelling, rock mass characterisation, damage mapping, seismic Hazard Map*

*This paper is part of a larger paper, made of two papers. Paper 1 Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic events: part 1 – the investigation, addresses the investigation of rock mass behaviour characterisation. Paper 2 Geotechnical strategies to resume mining at Westwood mine following a MN3.7 seismic event: part 2 – the mitigation plan (this paper), addresses the implementation of a mitigation plan.*

## 1 Introduction

The occurrence of a major seismic event is very critical in the life of a mine. Usually, such an event can have serious consequences on its operations, as experienced at the Westwood mine, where a MN3.7 seismic event occurred on 30 October 2020. Following this significant event, all mine production was suspended, and the mine was put under care and maintenance, to focus on understanding the event's mechanism and identifying areas with potentially similar conditions.

To successfully carry out this campaign, a geotechnical strategy was implemented to better characterise the rock mass, including:

- investigations and updates to geological, structural, and geotechnical models
- advanced seismic analyses
- numerical stress modelling
- integrated rockburst hazard assessment
- a comprehensive review of the mine's dynamic ground support standards.

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Additionally, a detailed risk register was created to identify ground control related hazards and establish a mitigation plan, covering risk identification, existing mitigation measures, current hazard levels, proposed mitigation measures, and residual hazard levels.

The following parameters were analysed:

- alteration
- disking
- mechanical properties
- geochemistry
- Rock quality designation (RQD) and geological strength index (GSI) with regards to the historical major seismic events

This analysis allowed the identification of seismic domains.

Furthermore, ground assessment was performed doing a systematic damage mapping of all existing underground openings. An in-depth seismic analysis was conducted to understand the source mechanism of all major events occurring at the mine including the cluster of events that occurred close in time, as well as seismic hazard maps; which consist of identification of seismically active faults as well as the probability of occurrence from past seismic events.

Finally, stress modelling based on re-run numerical stress models with Beck Engineering and updates of lithology and structures models to understand the impact of the mine sequence on mine opening stability and seismic potential were performed.

All of this information helps to determine strategic and tactical measures to reduce the seismic risk at Westwood. These measures include:

- the design of an adequate ground support system
- using a machine-learning algorithm (Hazmap), identifying variables that affect rockburst potential
- enhancing the precision of the seismic analysis.

The current and residual risk of personnel exposure has been assessed using a risk management process (risk register with mitigation measures). A detailed plan has been established to deploy the mitigation measures, then, a strategy was developed to thoroughly investigate the mines' seismic and geotechnical behaviours and develop mitigation to safely reopen the mine.

This paper provides detailed insight into the methodology of conducting studies and the development of strategic and tactical measures implemented. This paper presents all mitigation plans implemented to reduce seismic risk, including strategic measures to monitor seismicity and tactical measures such as the design of ground support systems, establishment of practical seismic monitoring methods, adaptation of equipment to risk conditions and personnel training.

# 2 Investigation results summary

The geotechnical risks identified at the Westwood mine include large seismic events, often resulting in fault slips that lead to rock ejection and ground falls due to seismic energy release. Risks also include smaller seismic strain bursts, which can also cause rock ejections. These risks have the potential to result in either complete or partial closure of mining openings.

Westwood mine has a complex geologic setting. It is comprised of three mining areas, the East, Central and West mines. Historically the areas have a range of ground conditions from seismically active to squeezing.

The larger bursts have resulted in ground support stressing and localised shake down damage. On 30 October 2020 an atypical large seismic event Nuttli magnitude (MN) 3.7 occurred, causing significant damage and entrapping a miner. The miner was safely rescued but the event resulted in a decision to close the mine for reassessment.

From this investigation, a new approach and methodology for mining in seismic environments was developed, known as the new geotechnical algorithm. Following a comprehensive evaluation of the algorithm, and the mine now employs a robust approach to address seismicity. Since 30 October 2020, the time of the large seismic event, the mine has gained insights into mine seismic and geotechnical behaviour and has devised strategies and tactical mitigations to reduce high risks to manageable seismic levels.

Furthermore, the development of a new algorithm necessitates both a cultural and technical shift, leading to an improved, systematic approach to mining operations at Westwood (taken from an internal report 2020).

## 2.1 The driving factors of the 30 October 2020 event

The understanding of the MN3.7 seismic event was a fundamental matter to the investigation team. The understanding of the cause of the event will help the investigation team implement a mitigation plans for future events (taken from internal report 2020).

Throughout the investigation and different types of analysis, it was possible to identify the following evolution of understanding of the mechanism of the event (Figure 1).

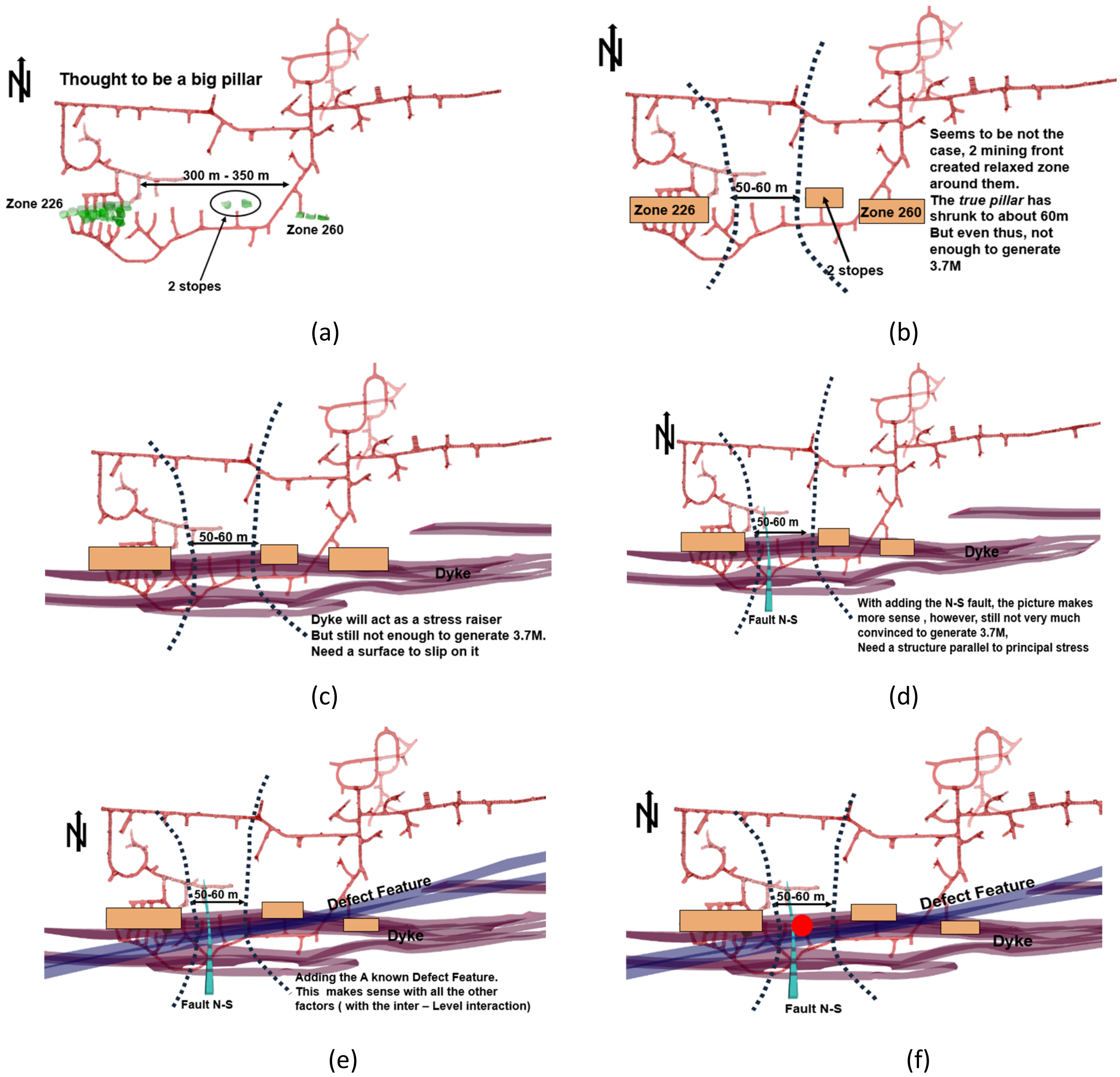



**Figure 1 Seismic mechanisms of the 30 October 2020 event**

- The understanding was that the event occurred in a considerable size pillar at reasonable distance from any mining activities (about 200 m from any mining activities).
- Then throughout analysing of the history of the area, it was found that there were mining activities; mining two primary stopes. Mining these stopes, created relaxed zone surroundings, which diminished the originally thought pillar from 350 m width to about 50–60 m pillar (Figure 1b). This created a stress concentration within the secondary pillar.
- The thorough geology and structural analysis was able to find the existence of an east–west dyke that acted as a stress raise, where the dyke act as an abutment which built and concentrated stress.
- The structural analysis identified a north–south fault, and east–north-south–west geology defect.
- The conclusion of the source mechanism of the event to be a fault slip event.

The MN3.7 occurred in the small pillar, with the existence of a very stiff east–west dyke, and on the intersection of the fault and the geology defect. The fundamental cause identified is a combination of a high-stress corridor, complex interactions between geological features, and an abnormal, unknown north/south fault (Figure 1). The event is considered a fault slip event.

# 3 Development of a seismic risk algorithm

Throughout the investigation process (that lasted for a few months) it has been recognised that the seismic challenges at Westwood mine are extremely complex, and none of the geotechnical tools can explain and tackle the problem alone. The general ground control approach moving forward is based on a comprehensive set of mitigating measures that address a variety of issues. Each individual control measure has its own uncertainties and limitations. Therefore, it is preferable to combine multiple procedures to create a robust risk management strategy. In other words, the adopted approach to tackle seismic risk is multi-faceted and does not rely on a single method or tool. This multi-pronged approach is also dynamic; inputs can evolve by adding, eliminating, and/or combining certain measures and the criteria and weighting associated with each can be adjusted as more data is collected and back-analyses are completed. Looking ahead, existing drifts, new stopes, and development in high-risk zones will follow this algorithm. Figure 2 presents this general multi-pronged approach which was followed to manage geotechnical risk at the Westwood mine.

The risk assessment algorithm aims to identify hazards related to ground control and to either eliminate or mitigate these hazards by reducing the level of risk through the implementation of control measures as necessary. This contributes to creating a safer and healthier workplace. The objectives of the risk assessment address the following questions:

- What potential events can occur and under what circumstances?
- What are the potential consequences of these events?
- How likely are these consequences to occur?
- What control measures are currently in place? Are they effectively controlling the risk, or is further action required?

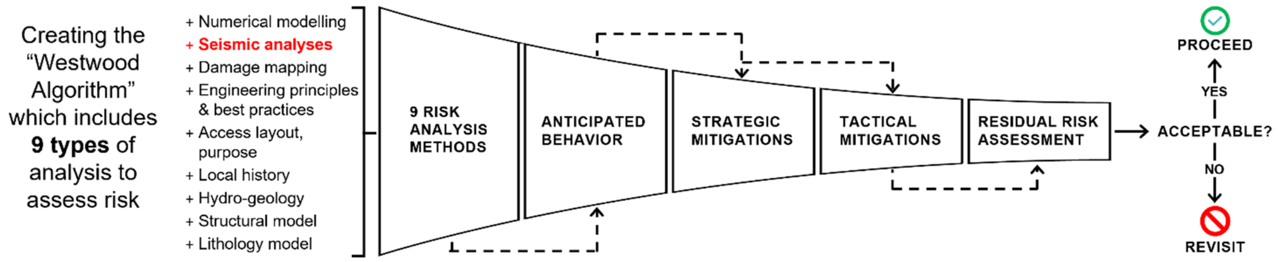



**Figure 2 General multi-pronged approach followed to manage geotechnical risk at Westwood mine**

To answer these questions, as illustrated in Figure 2, different aspects concerning geotechnical risk are evaluated chronologically as follows:

- Ground control risk identification – identify hazards related to ground control and factors that could potentially cause harm to personnel or damage to mine equipment, ground support systems, and/or infrastructure.
- Hazard analysis and evaluation – analyse and evaluate the consequences and likelihood associated with ground control risks to determine their severity and establish a hazard ranking.
- Risk control – determine appropriate mitigation measures to eliminate or reduce ground control hazards and risk factors. If elimination is not feasible, select mitigation measures to reduce the risk.
- Risk management and documentation – monitor and assess the effectiveness of implemented controls for ground control hazards. Keep records of the assessment process and control actions taken in a risk register.

A risk assessment of ground control hazards involves a thorough examination of the workplace to identify conditions, situations, processes, etc., that may pose harm (particularly to people). After identification, the likelihood and severity of the risk are analysed and evaluated. Once hazards are identified, measures should be investigated and implemented to effectively eliminate or control potential harm.

# 4 Strategic and tactical mitigation plans

As found previously, the approach adopted to tackle seismic risk is multi-dimensional and does not rely on a single method or tool. Importantly, this multi-pronged approach is a dynamic process: both the types of inputs can evolve (by adding, eliminating, and/or combining some), and the criteria and weighting associated with each can be adjusted as more data is collected and more back-analyses are completed. Some aspects, such as seismic monitoring and damage mapping, are continuous/constant, while others, such as numerical models and updates to geological models, are campaign focused. It is necessary to regularly review, adjust, and improve the process and its components.

The geotechnical analysis that is currently being implemented comprises several key components (Figure 2). This strategy aimed to evaluate all geotechnical aspects related the rock mass zones, including:

- Geology – enhanced understanding and updating structural and lithology model.
- Seismic analysis – developed the best practical understanding of past seismic events.
- Stress modelling – gained insights into the impact of the mine sequence on mine opening stability using numerical modelling. Several sequences were evaluated to select the safest and most profitable option for the mine.
- Seismic hazard management plan – back-analyses was conducted to classify all areas of the mine according to their seismic potential and current seismicity level. A suite of the seismic analysis methods was implemented to monitor the seismic response to mining activities such as seismic hazard calculation, and seismic response analysis to blasting (re-entry protocol).
- Hazard model – a four-dimensional seismic Hazard Map (HazMap) model, which incorporates both space and time was developed to monitor the rockburst hazard. This model aids daily decision-making by evaluating the daily evolution of seismic activities, changes in surrounding underground conditions (for specific areas), and the impact of working near certain geological structures. The model uses a colour coding system (green = low risk, yellow = medium risk, and red = high risk) for underground openings, based on the evaluated risk.

Based on the results of this characterisation of different aspects of the rock mass, the mitigation plans were developed, tested and implemented to monitor the geotechnical risk at the Westwood mine. This mitigation plan is divided into two parts, including:

- Strategic measures – these are applied during the mine design process (engineered measures):
  - Mining rate controls – implemented to allow the rock mass to dissipate energy released after mining blasts.
  - Mining sequence – optimised to enhance safety, production, and profitability, assessed using advanced numerical modelling. It was found that for complexity of Westwood mine that having a pillarless mining is more favourable rather than having a primary–secondary mining sequence.
  - Escapeways – constructing multiple escapeways to facilitate quick rescue of personnel in case of entrapment due to ground conditions.
  - Mine design – the new mine infrastructures (such as the lateral development) were developed in more favourable orientation as well as in more favourable lithologies where and when possible.
- Tactical measures – these involve design and operational changes, providing practical solutions:
  - Dynamic rock support evaluations – ensures areas remain open and accessible after a seismic event. Assessments are based on industry benchmarks, stress modelling results, structural modelling, seismic analysis of previous events, and the Canadian Rockburst Research Program (Mottahed & Vance 1998).
  - Seismic monitoring – advanced seismic analysis has been conducted to establish hazard classifications for different faults. This analysis allows for:
    - cool down periods following a blast
    - early warning/evacuations if needed
    - blast rate and exclusion zones following significant events.
  - Exposure management – worker exposure to hazards has been reduced through enhanced reinforced equipment cabins for mobile equipment and the use of tele-operated scoops (AutoMine) when necessary.
  - Establish pre-development review process to allows traceability and auditability for the geotechnical analysis. Additional details of the process will be explained in Section 4.1.2.5.

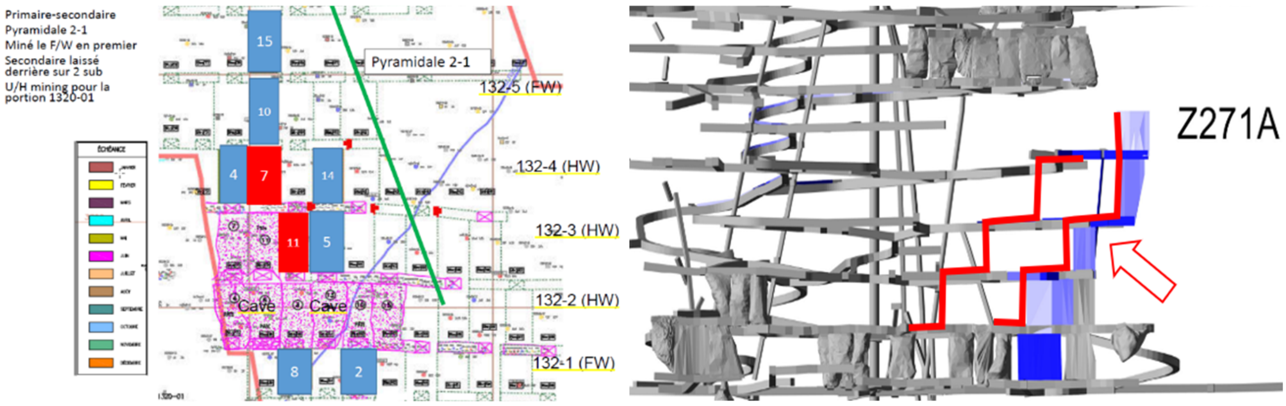
These measures are applied during the mine design process (technical measures). These measures encompass the following elements: mitigation plan in seismic zones, appropriate seismic mining sequence, escapeway, and de-stress blasting in stressed areas.

For each seismic zone, a comprehensive geotechnical risk assessment is conducted before the commencement of mining activities. A standard analysis report, known as the pre-development review (PDR), has been established for this purpose. All mining activities in seismic zones will follow the PDR process. This PDR incorporates newly developed mitigation strategies and tactics to safely operate in any seismic zone at Westwood mine. Derived from the algorithm used during investigations to assess geotechnical risk (Figure 2), this process includes data derivation and assessments, planning both strategic and tactical mitigations, evaluating residual risks (those expected to remain after mitigations are implemented), and deciding whether to accept the risk and proceed with mining or cycle back for further assessments and mitigation development. Seismic monitoring, the mine design, and the zone PDR are fundamental to ensuring safe mining at Westwood.

### *4.1.1 Strategic measures*

#### *4.1.1.1 Mining sequence*

The previous mining sequence was designed as pyramids (primary–secondary) (Figure 3a). However, stress modelling during the investigation revealed a significant increase in the stress field across the area, particularly around ramp 132-05 and access points to mining areas such as (primary–secondary). As a result, the mining plan was modified to monitor the increase and migration of stress within the infrastructure. The newly adopted mining sequence is the pillarless mining method (Figure 3b). This sequence helps to redirect the stress towards the west of the zone, creating a buffer zone between the mining face and the ramp by leaving some stopes unexploited until the end of the mine's lifespan. Additionally, this approach helps to control mining extraction rates, allowing the rock mass to dissipate the energy released after a mining blast.




(a) (b)

**Figure 3 Mining method and mining sequence. (a) Primary–secondary method; (b) Pillarless mining method (looking north)**

### *4.1.1.2 Emergency exit*

The construction of multiple escape routes ensures the rescue of personnel in the event of entrapment due to ground failure, providing additional vertical access routes as supplementary exits beyond the existing lateral ones (Figure 4). These emergency exits are strategically planned with consideration of geological domains that have high seismic potential. The level has an exit on both sides of the seismic domains, such as ramps and access levels before entering the seismic domains, with emergency exits positioned after traversing these areas. Additionally, all levels are interconnected by at least one emergency exit.

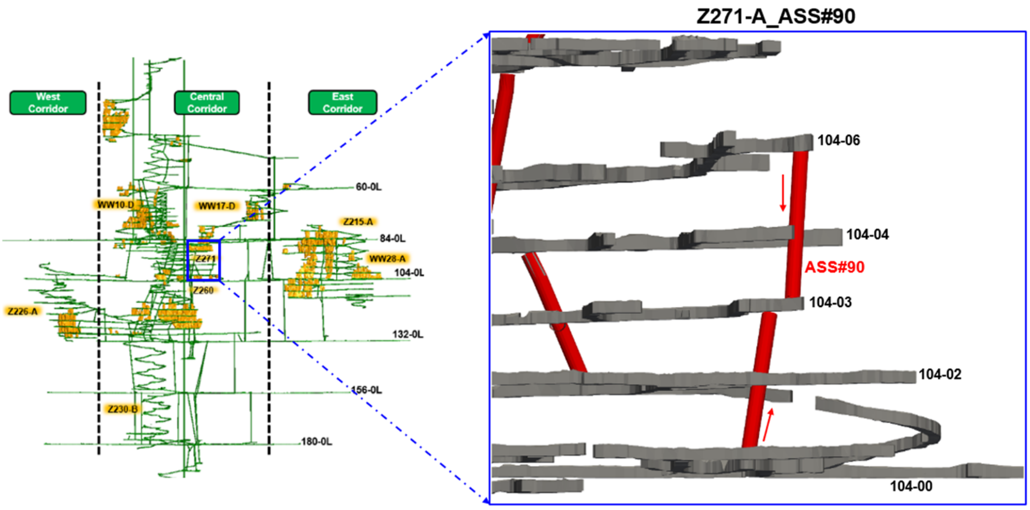



**Figure 4 Long section of the mine show an example of the new emergency exit between levels (looking north)**

## *4.1.2 Tactical measures*

These measures entail operational adjustments through the adoption of practical solutions aimed at mitigating risks. These mitigation measures include the design of a dynamic support system, seismic monitoring, and the management of worker exposure to geotechnical risks. Dynamic ground support enables areas to remain open and accessible during seismic events by increasing yield strength, thus averting total failure. These support systems are conceived based on industry standards, stress modelling outcomes, structural assessments, seismic analyses of past incidents, and insights from the Canadian Rockburst Research Program (Mottahed & Vance 1998).

Regarding seismic monitoring, it tracks the rock mass response to mining activities, establishes hazard classifications for various faults in the mine, and reduces employee exposure by implementing an exclusion protocol. Given the significant role of worker exposure, this aspect has been strengthened through the creation of reinforced cabins for various mobile equipment. Additionally, the deployment of new technologies like tele-remote scoops (AutoMine) and wireless explosives serves to minimise worker exposure to deteriorating ground conditions. These mitigation measures are further elaborated in the subsequent sections.

#### *4.1.2.1 Dynamic ground support design*

Dynamic ground support stands as a pivotal enhancement from the mine's prior state, i.e. before the 30 October 2020 event when dynamic support capabilities were minimal to non-existent. Subsequently, a project was initiated to establish dynamic ground support standards at Westwood. To formulate a standard for dynamic (burst-prone) ground support at Westwood, a three-phase project was launched. These phases entail comprehending the mechanisms of past damaging events through back-analyses, designing the dynamic ground support standard benchmarking designs with existing seismically-active mines nationally and internationally and furnishing detailed engineering and deliverables.

##### *4.1.2.1.1 Understand the mechanisms of previous damaging events (back-analyses)*

Initially, an extensive review of literature was undertaken to gain a thorough understanding of the latest and widely accepted methodologies concerning dynamic support design. It is essential to comprehend the origins and mechanisms of damage resulting from previous seismic events in order to appropriately select suitable mitigation measures, such as dynamic ground support.

Subsequently, a back-analysis process was conducted for several seismic events that led to underground damage incidents. A total of eight case studies were meticulously examined based on available information. As seismic activity increased at Westwood over time the details recorded by site personnel became more comprehensive and of higher quality, facilitating the interpretation of source and damage mechanisms. Each case study included background information such as location, mining activities during the event, and geological settings. Available numerical stress modelling results and seismic analyses (including magnitude-time charts, event sequences, source plots [moment tensor], etc.), as well as data on rockburst damage location, intensity, and rock fragmentation, were also reviewed.

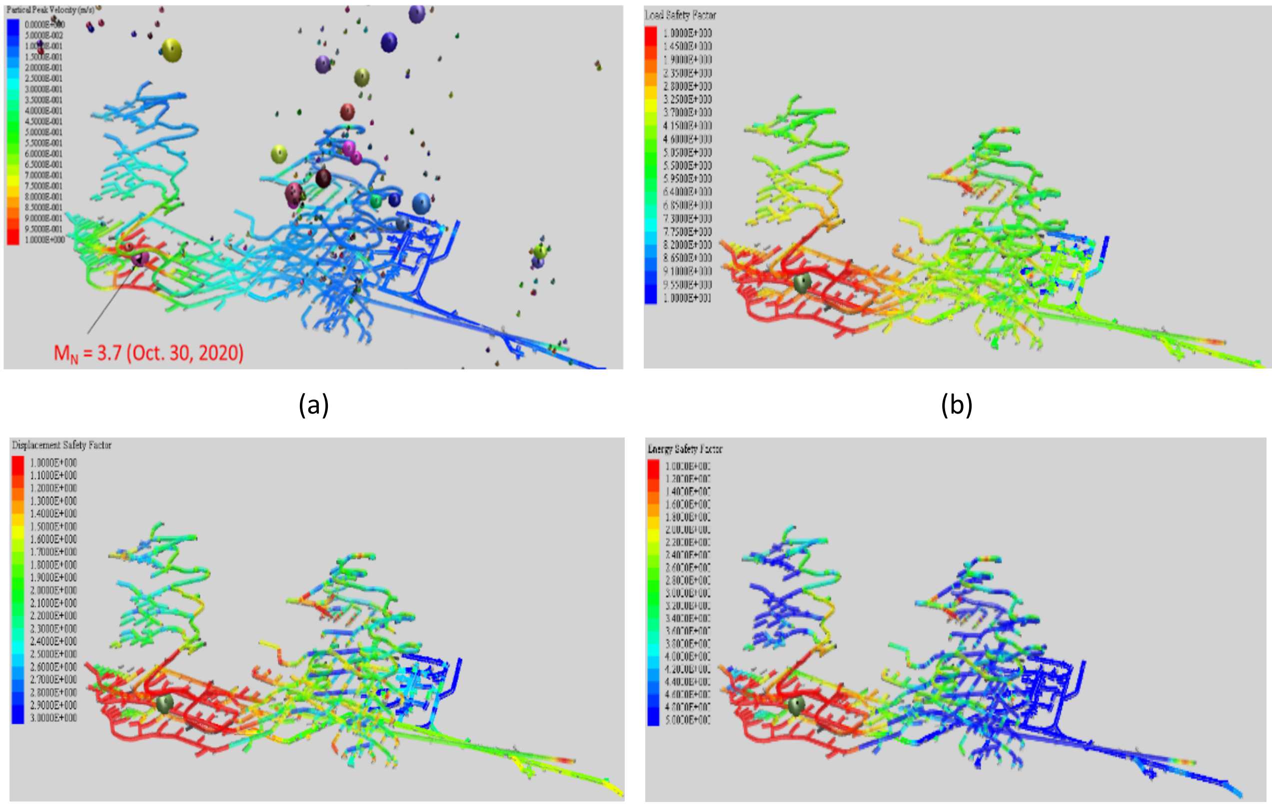
The analyses of these case studies revealed that most source and damage mechanisms were associated with strain bursts, including the larger seismic events; however, the trigger of these strainburst might be pillar burst or fault slip event. Dynamic ground support, along with re-entry protocols to some extent, can significantly mitigate the hazards associated with most of these occurrences.

These case studies serve as a template for mine personnel to analyse future damaging events, providing guidance on data collection, seismic analyses, damage, and support mapping, etc. Standardisation is an essential step towards a systematic approach to burst analysis.

##### *4.1.2.1.2 Design the dynamic ground support standard*

The initiation of the dynamic ground support design process involved evaluating the effectiveness of the existing ground support standard, typically consisting of 1.8 m long #6 rebars and #6 welded wire mesh (WWM), in light of the damage outlined in the eight case studies. BurstSupport software (MIRARCO Mining Innovation 2020) was employed to compute load, displacement, and energy safety factors across all drifts surrounding past seismic events. This software is founded on the principles outlined in the Canadian Rockburst Handbook (Kaiser et al. 1996). The mine was partitioned into various sub-models such as: west, WW17, Z226, upper east, and the BurstSupport outcomes from these sub-models were cross-referenced with the case study reports to ensure alignment with observed underground damage.

Overall, these analyses suggested that the models were generally satisfactory. However, notably, they highlighted that the existing ground support standard was inadequate to meet the requirements in most areas where historical event locations and magnitudes were simulated (Figure 5).




(c) (d)

**Figure 5 Burst support software simulation considering the MN3.7 seismic event. (a) Locations of the MN3.7 seismic event and other seismic events and ppv distribution in the drifts are shown; (b) Load safety factors for the 132 levels; (c) Displacement safety factors for the 132 levels; (d) Energy safety factors for the 132 levels**

Various enhancements, including ground support tendons with high energy absorption capacity, were modelled using the software until adequate safety factors were achieved. The ground support elements analysed in the study were comprised of 22 mm rebars, Hybrid Bolts, 22 mm D-Bolts®, Nevada Bolts, 22 mm VersaBolts®, Vulcan Bolts, and Spin cables. Although Par-1® bolts were not explicitly included in the software, their characteristics closely resemble those of D-Bolts and VersaBolts suggesting similar behaviour. Surface support was not considered in the current version of BurstSupport, which introduces a conservative element to the results. Additionally, it's noteworthy that most ground support tendons were limited to a capacity of 20 kJ/m² to mitigate extremely high energetic values, such as 50 kJ/m², often provided by some suppliers.

Given the complex in situ behaviour and loading conditions of bolts compared to laboratory drop test conditions, this approach is deemed more realistic. Some tendons also exhibit favourable energetic performance as they can deform significantly beyond practical and acceptable limits. The enhanced tendons were then evaluated against potential future seismic events, typically ranging from ML1.5 to 2.3 (MN~1.8 to 2.6), situated approximately 5 and/or 10 m from existing drifts in geotechnical domains prone to such seismic activity (e.g. U3-U4 contact, dykes, etc.). The 30 October 2020 MN3.7 event was also simulated using BurstSupport, revealing that most drifts had adequate capacity with the enhanced support systems (Figure 6).

This analysis aided in identifying the appropriate type of support to use and led to the establishment of ground support standards outlined in Table 1. The dynamic ground support design guidelines have been categorised into four different classes based on required intensity/robustness.

**Table 1 Summary of the proposed dynamic ground support standard for Westwood (taken from an internal document)**

| Class | Walls and back (staggered 1.2 × 1.2 m pattern) | Screen | Fibercrete (cm) | Debonded cables (m) | Mesh straps |
|---|---|---|---|---|---|
| 0 | Dynamic bolt 22 mm 2.1 m (secondary support) | | | | |
| I | Dynamic bolt 22 mm 2.1 m | #4 | – | – | – |
| II | Dynamic bolt 22 mm 2.1 m | #4 | – | – | #0–1 D |
| III | Dynamic bolt 22 mm 2.1 m | #4 | – | –5 | #0–2D |
| IV | Dynamic bolt 22 mm 2.1 m | #4 | 7.5 | –5 | #0–2D |

**Notes:**

1. Cables are required to be debonded by 1.5 m. Use staggered 1.5 × 1.5 m pattern.
2. 1 D corresponds to 0-gauge mesh straps installed parallel to drift orientation. 2D corresponds to 0-gauge mesh straps in both directions (i.e. parallel and perpendicular) to drift axis. The latter will form a ‘checkerboard’.

*4.1.2.1.3 Benchmark Designs with existing seismically-active mines nationally and internationally*

To validate the Dynamic Ground Support Standard, which includes selected bolts and patterns, a comparative analysis was conducted against tendons and surface support systems utilised in 12 other mining operations (nine Canadian mines and three international). This assessment revealed several key findings:

- Most benchmarked mines utilise a combination of 'standard' and 'yielding' tendons, typically installing the yielding support as a second pass.
- D-Bolts and VersaBolts, including Par-1s which function more or less similarly, are considered in our design as equivalent bolts.
- The prevalent tendon size across operations is 22 mm (#7), both for rebars and D-Bolts (or equivalents).
- D-Bolts are commonly employed as yielding support, while Conebolts® are less frequently used, often due to challenges related to grout specifications and quality control.
- Split-Sets, Swellex® Mn24, Conebolts, MDBolts®, and VersaBolts are utilised to a lesser extent.
- Although capable of absorbing high energy levels, debonded cable bolts are not widely adopted.
- The energy capacity of Westwood's Class III support is comparatively high, although tendon capacities were capped at 20 kJ/m² to maintain practical deformation levels.

Regarding the Westwood standards (Classes 0, I, II, III and IV), the use of 22 mm D-Bolts or similar bolts aligns with common practices observed in many other operations.

A similar benchmarking exercise was conducted for proposed surface support systems, yielding the following observations:

- WWM #4 and #6 are commonly used, while Chainlink #9 sees limited application and HEA Mesh is not utilised.
- Many mines employ WWM (#4 or #6) in conjunction with WWM straps #0.
- Shotcrete with fibre reinforcement is frequently applied and is often combined with mesh straps.

Concerning the Westwood standards, the use of #4-gauge WWM, with or without shotcrete (depending on the class), aligns with practices seen in many other operations.

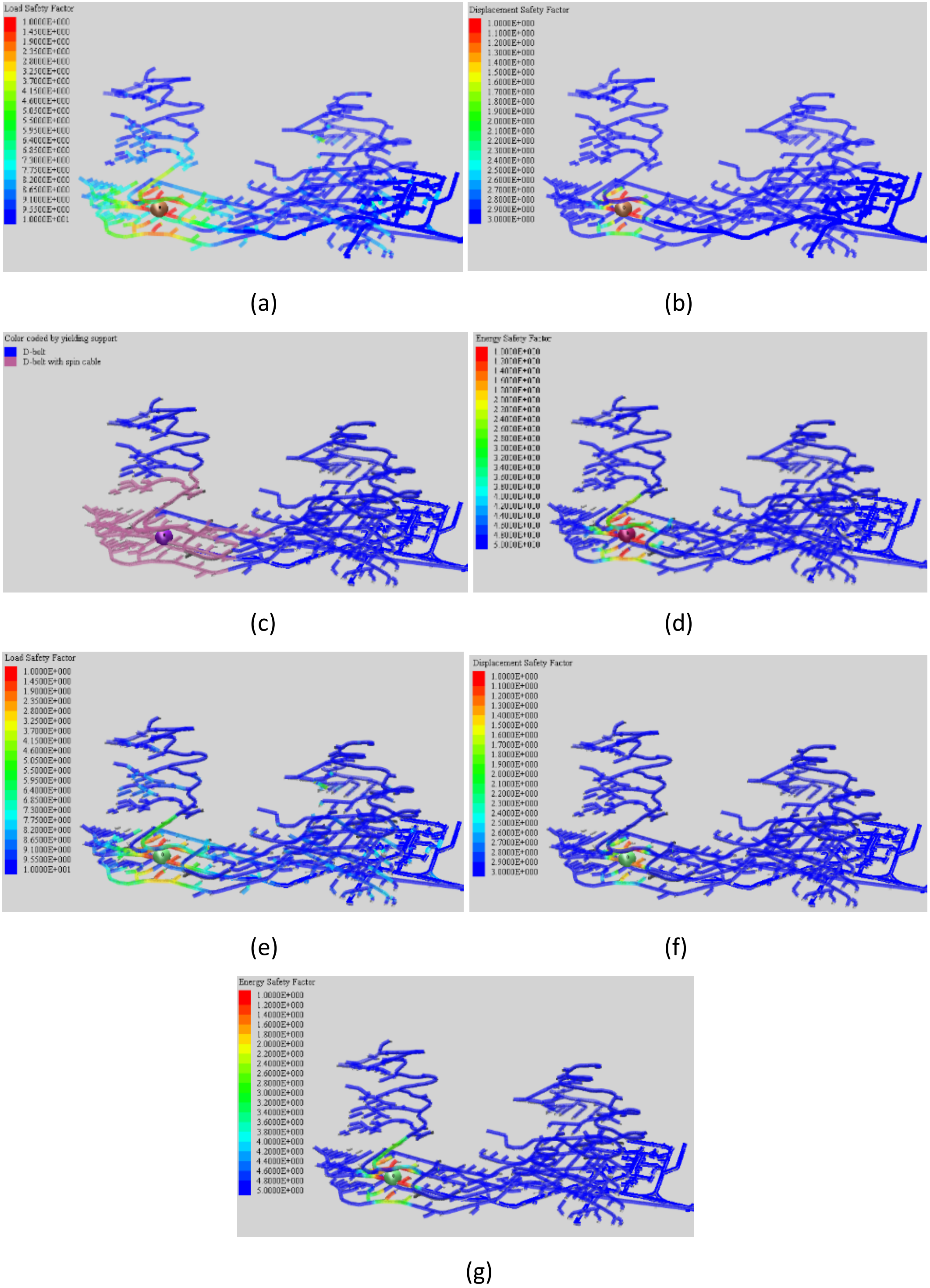



**Figure 6 BurstSupport software simulation considering the MN3.7 seismic event. (a) Load safety factors for the 132 levels considering enhanced support (D-bolt); (b) Displacement safety factors for the 132 levels considering the MN3.7 seismic event, enhanced support (D-bolt); (c) Energy safety factors for the 132 levels considering enhanced support (D-bolt); (d) Drift support in the 132 levels with enhanced support (D-bolt+Spin cable); (e) Load safety factors for the 132 levels considering enhanced support (D-bolt+Spin cable); (f) Displacement safety factors for the 132 levels considering enhanced support (D-bolt+Spin cable); (g) Energy safety factors for the 132 levels considering enhanced support (D-bolt+Spin cable)**

Several areas within the mine site, known as 'seismic domains,' have been identified based on site experience, including but not limited to the U3-U4 contact, the 'unconfined zone (ZDZC)' area (Central 104 Block), various dykes, and contact zones. These domains will inform the application of each support standard. Determining when and where to install enhanced dynamic support will require various tools, including numerical stress modelling, seismic analyses, and empirical knowledge developed at the mine. Numerical modelling, such as non-linear 3D stress modelling, will identify areas with higher seismic hazards, where large energy release rates are combined with significant deformations. These findings can then be integrated into the BurstSupport software to aid in selecting the appropriate support/class. In areas where rockburst-prone conditions are not anticipated, such as in squeezing or aseismic ground, dynamic ground support standards may not be necessary.

#### *4.1.2.2 Seismic monitoring*

In underground mines with seismic activity, seismic risk is often categorised as extreme, as the most severe consequences can lead to multiple fatalities and prolonged mine shutdowns, or even permanent closure in the worst-case scenario (Potvin et al. 2019). Proactive risk management is therefore essential for mines operating under seismic conditions, as is currently implemented at the Westwood mine. Understanding mine seismic hazards relies heavily on seismic analyses. Future seismicity in a mine is closely linked to past seismicity (Hudyma 2010), making systematic back-analyses and interpretation of seismic data crucial for anticipating seismic hazards. The more seismic analyses conducted, the better the understanding of the local seismic response to mining activities (Hudyma et al. 2004; Hudyma & Potvin 2004).

It is recommended that every mine should have a seismic risk management plan in place (Potvin et al. 2019). At the Westwood mine, the seismic risk management plan, known as the GeoSeismic Strategy, is based on the characterisation of geological and seismic data. This combined geomechanical characterisation and seismic response analysis help identify rock mass conditions that correlate with seismicity. With this knowledge, an in situ seismic risk Hazard Map (HazMap) has been developed on a mine-wide scale. This HazMap classifies different areas of the mine according to their potential to generate low seismic responses, high seismic responses with low magnitude, and susceptibility to significant seismic events.

Additionally, a suite of seismic analysis methods has been implemented to monitor seismic behaviour and anticipate associated risks (Harris & Wesseloo 2015). This strategy, dedicated entirely to seismic risk management, involves closely monitoring several aspects of seismicity. These include the quality of seismic events, identification of high seismic potential areas, calculation of seismic hazard, monitoring the seismic response of structures and abnormal seismicity, analysing the seismic response to blasting to define exclusion zones and times, and stress monitoring using seismic responses to blasts.

Figure 7 details the structure of this strategy, and this GeoSeismic Strategy is detailed in an article parallel to the present one.

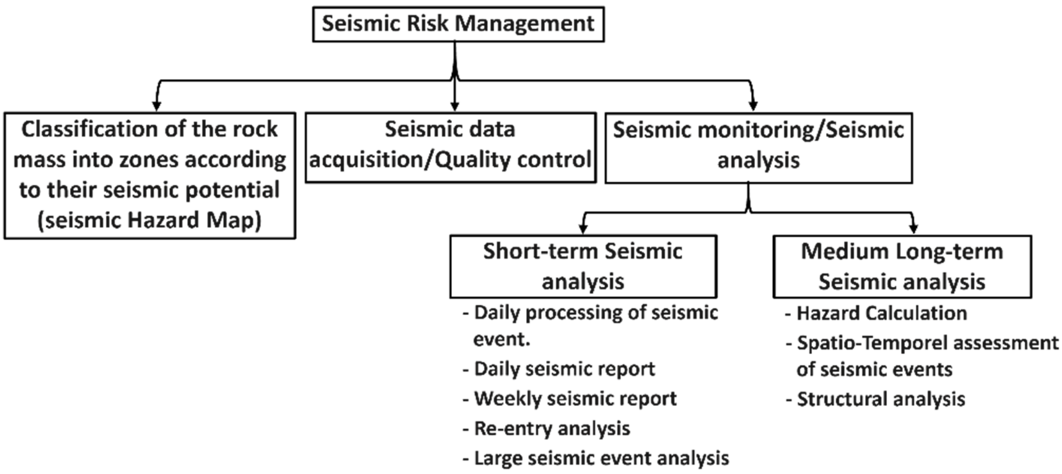



**Figure 7 Structure of the GeoSeismic Strategy at the Westwood mine**

#### *4.1.2.3 Equipment improvements*

Worker exposure to hazards has been improved by creating enhanced reinforced cabs for various mobile equipment and applying various technologies to reduce exposures (Figure 8).

- Fully mechanised bolting – Epiroc Boltec M units are being added to the fleet, which will improve the quality, efficiency and safety of bolting operations. The addition of these units began in 2021 and continued into 2022, along with the inclusion of injected resin.
- Reinforced driving compartments – cabins have been designed on the mobile equipment and are being installed to protect workers from large seismic events and rock projections.
- AutoMine – LHDs will be operated at a distance from the surface to limit operator exposure in high-risk areas.
- Orica wireless detonators (Webgens®) – longhole explosive loading practices are adapted for use with this technology to pre-load stopes and reduce worker exposure to deteriorating terrain once blasting has begun.

**Figure 8 Equipment improvements – reinforced cabinet by bulletproof glass; rock-deferred steel screen**

#### *4.1.2.4 Personnel training*

It was felt that the 'shift in the culture' being implemented at the mine could not be achieved without continuous communication with the workforce at different levels; either at the operation, engineering or at management level.

The goal of the personnel training was:

- to gain the confidence of the workers in the new mining philosophy
- keep workers informed of the new process change
- establish underground standards and operational policies to maintain a safe working environment
- manage compliance challenges to ensure that the culture change is applied consistently.

#### *4.1.2.5 Documentation and due diligence*

The PDR process that has been established following the investigation process, allows traceability and auditability for the geotechnical analysis (Figure 9).

Additionally, the mine established an audit process that includes internal auditing and external auditing to be done in order to maintain reasonable due diligence for the process.

| a- General Information | | | |
|---|---|---|---|
| Date | | Reviewed by (Geotechnical engineer) | |
| Zone | | Approved by (Geotechnical manager) | |
| Location | | Approved by (Corporate Geotechnical manager) | |
| Approval Comments | | | |
| PDR to be signed by Mine General Manager, Operations Manager, and relevant departments. | | | |

| b- Hydrogeology | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Water inflow analysis of diamond drill holes (DDH) | ☐ | ☐ | |
| Reported inflow from other activities (e.g., development, stoping) | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| c- Structural Model | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| High Confidence in the structural model | ☐ | ☐ | |
| Presence of unfavorable lithology's | ☐ | ☐ | |
| Presence of unfavorable contacts: (i.e., 4.4.1r, 4.2, 3.3-4.3, 4.3-4.4.) | ☐ | ☐ | |
| Presence of unfavorable structures (e.g., faults) (i.e., F24, 31, Bousquet. F17, F13,) | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| d- Seismic Analyses | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Largest expected magnitude $M_{max}$ | ☐ | ☐ | |
| Expected seismic locations (e.g., seismically active structures or lithologies) | ☐ | ☐ | |
| Exclusion protocols required after development blasts | ☐ | ☐ | |
| Exclusion protocols required after production blasts | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| e- Numerical Modelling | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Hazards* in large-scale models (Beck Engineering) | ☒ | ☐ | |
| Hazards* in local-scale models (IAMGOLD) | ☒ | ☒ | |
| * *Hazards may include high RER, high increments of strain (IOS), excavation instability, unfavorable geometry such as sill or diminishing pillars, excessive stope dilution, large areas of deconfinement and/or high stress, unfavorable stress-to-strength ratios (stress/UCS), etc.* | | | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| f- Miscellaneous | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Corrosion assessment | ☐ | ☐ | |
| Historical instabilities | ☐ | ☐ | |
| Exceedance of support / rock mass "life expectancy" | ☐ | ☐ | |
| Other | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| g- *HazMap – TARP* | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Is the Hazmap applicable/done for this zone: | ☐ | ☐ | |
| TARP Result: Green (Ex: Type 1 support, limited cool down periods) | ☐ | ☐ | |
| TARP Result: Yellow (Ex: Type 2 or 3 support, extended cool down periods) | ☐ | ☐ | |
| TARP Result: Red (Ex: Type 4 support, Extended cool downs, full automation and re-enforced cabins, re-design of mine plan) | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| h- Strategic Mitigation Measures* | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Mine sequence assessment | ☐ | ☐ | |
| Escapeways | ☐ | ☐ | |
| Mining Rate | ☐ | ☐ | |
| Other | ☐ | ☐ | |
| Other | ☐ | ☐ | |
| Other | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| i- Tactical Mitigation Measures | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Dynamic Ground Support (DGS) | ☐ | ☐ | |
| Stope support – cablebolting | ☐ | ☐ | |
| Remote operations / equipment (e.g., *Boltec*, Armored Cabinet, *AutoMine*, *WebGen*): Use TARP from Hazmap | ☐ | ☐ | |
| Seismic TARPs<br>1. 6h to 12h cool down / Omori, Exclusion zone | ☐ | ☐ | |
| Other | ☐ | ☐ | |
| Other | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

| j- Acceptability of Residual Risks | Yes | No | If NO, Next level to comment and do a review |
|---|---|---|---|
| Residual Risk 1: ____________ | ☐ | ☐ | |
| Residual Risk 2: ____________ | ☐ | ☐ | |
| Residual Risk 3: ____________ | ☐ | ☐ | |
| Prepared by | | | |
| Reviewed by | | | |
| Date | Click or tap to enter a date. | | |
| Detailed investigation required | | | |
| | | | |

**Figure 9 The different types of geotechnical analysis are documented in the PDR document (information provided from an internal document)**

# 5 Summary of improvements since resuming mining activities

As mentioned before, following the MN3.7 event of 30 October 2020 that occurred in the access drift to the zone Z226, in the Western side of the mine, a decision was made to halt underground operations for about a year and half. This decision was driven by the need to have an understanding of the mechanism of the event, identify areas with (potentially) similar conditions, and put in place an action plan that consist of strategical and tactical mitigation plan.

For all seismic zones, the mining sequence, the mining method has changed to be pillarless, the mining rate has been reduced and escapeways were developed in needed locations.

As for the tactical adjustments/mitigation plan, Table 2 provides an overview of theses tactical adjustments.

**Table 2 Summary of improvements**

| Mitigation | Risk | Before | After |
|---|---|---|---|
| Ground support design | Fall of ground<br>Rockburst<br>Strain and faceburst | Combining static ground support with a hybrid bolt intended for mild seismicity | Four levels of dynamic support standard to tackle the various geotechnical conditions at Westwood<br>The improvement in QA/QC and compliance has increased from 65% to +90% |
| Fully mechanised bolting in high-risk areas | | Semi-mechanised roof bolters and handheld drills | Double boom Epiroc Boltec with injectable resin in applicable areas |
| Dynamic rehabilitation of existing drifts | | N/A | More than 250K of dynamic bolts were installed between July 2021 and May 2024 |
| Reinforced operator's cabs | Rockburst<br>Strainburst and faceburst | Non-existent | Fleet of Reinforced operator's cabs (bolters, scoops, jumbos, etc.) |
| Remote operation (AutoMine) | Fall of ground<br>Rockburst<br>Stope failure/dilution | Non-existent | In progress project for operation from surface |
| Pre-loading of longholes (Webgen) | | Non-existent | Most of the stopes are loaded with Webgen method |
| Seismic monitoring protocols | Fall of ground<br>Rockburst<br>Strainbrust and faceburst | Limited seismic analysis to be applied: Cooling periods, early warning / evacuation, exclusion zones | Advanced seismic analysis and seismic risk management plan to be applied:<br>Cooling periods<br>Early warning/evacuations<br>Extraction rates<br>Exclusion zones |
| Audit and peer review | | On annual basis | Audits and peer review process is established and done systemically |

# 6 Conclusion

Throughout this investigation, a good understanding of the rock mass at the Westwood mine has been obtained, revealing it to be extremely complex. A series of analytical methods have been implemented to characterise this rock mass, determine the potential geotechnical risks that could result from mining operations, and establish appropriate mitigation measures for these risks. These updates to the mitigation plans will be updated periodically, informed by field observations and data collected from diverse geotechnical systems, as well as corresponding mitigation plans.

## Acknowledgement

We would like to extend our gratitude to the management of the Westwood mine for allowing us to publish this study. We also thank the support of all the parties, that contributed to the geotechnical investigation.

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