Operational slope stability risk management for large open pits at the Mount Milligan Mine – a case study

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Abstract

Mount Milligan Mine is located in Central British Columbia, Canada. Mining of the copper-gold porphyry deposit commenced in 2013 with a projected 16-year mine life. The geotechnical model and pit slope design criteria were developed based on limited geomechanical data collected from the 2007 feasibility study, resulting in some uncertainties relating to large-scale structural features, rock mass structure, and porewater pressure distribution. Risk management became a challenging task for the mine's pit operations team.

3D laser scanning technology was applied to capture the orientations and frequencies of rock mass discontinuity planes after initial pit development. Geological structural mapping was also implemented to document the relationship between major structures and rock mass jointing patterns. The acquired data calibrated the structural model confirming the predominate kinematic failure mode was bench-scale wedge failures. Design adjustments were subsequently made for interim pit walls along with other remedial measures to reduce instability risks.

A real-time radar monitoring system was implemented once risk management became increasingly dependent upon slope monitoring and the implementation of appropriate operational protocols. Customized detection protocols and warning/alert thresholds were updated as the pit excavation advanced. The real-time slope monitoring identified risks of potential wall instabilities in advance and boosted the confidence of mining operations.

As mining progressed, increased knowledge of rock mass characteristics and slope performance factors led to an optimized slope design for the LOM pits. Mount Milligan Mine presents a good example of risk management for large open pits with limited geomechanical data at the onset of pit operations, where confidence in mine safety was gained over time through ongoing data gathering and interpretation, slope monitoring, targeted slope remediation, and slope optimization to achieve economic success throughout operations.

1 Introduction

Mount Milligan Mine is located in central-north British Columbia. The copper-gold porphyry deposit consists of two major mineralization zones, the main Magnetite Breccia (MBX) and the Southern Star (SS). It is mined using conventional truck-shovel open pit methods at 60,000 tpd. Production started in 2013, with an anticipated mine life is 16 years. The maximum depth of the MBX Pit is anticipated to be in the order of 350 m.

The open pit slope geotechnical model was developed based on limited geomechanical data collected from the 2007 feasibility study site investigation program. The open pit mine plan was developed with the understanding that some uncertainties and data gaps would exist relating to large-scale structural features, rock mass structure, and rock mass permeability and porewater pressure distribution.

Risk management became increasingly complex as pit development progressed, and adverse conditions were identified that were not predicted with the limited design dataset. Ongoing data collection and modelling enhancement were implemented throughout the open pit operations. This paper presents the progression of the industry leading structural data collection, slope monitoring, and mine risk management strategies utilized by the mine operators to develop proactive and reactive strategies for mitigating open pit slope stability issues.

2 Pit Slope Design

2.1 Project Overview

The Mount Milligan Mine has undergone numerous studies and economic evaluations since the discovery of the deposit in 1987. Terrane Metals acquired the property in 2006 and design and permitting activities were completed over the following six years. Terrane Metals was acquired by Thompson Creek Mining in 2010, were who subsequently acquired in 2016 by Centerra Gold Corp., the current mine operator.

Knight Piésold (KP) was involved in the early stages of the project development. Early site investigations for pre-feasibility level pit slope design were carried out throughout 1991 and 1995. KP completed an open pit slope design for the Mount Milligan feasibility study in 2008.

Overburden stripping of the MBX Pit commenced in early 2013, followed by full-scale production beginning in August 2013. The recommended pit slope design parameters from the feasibility study (KP 2008) served as the design criteria for the initial pit development. KP has been providing technical support to open pit operations since then. Ongoing pit operations have included the implementation of supplementary data collection, further refinement of the pit geotechnical model, and close monitoring of pit wall stability.

As of 2023, the floor of the MBX Pit has reached an elevation of 890 m, with the West Wall reaching a maximum height of 260 m. An overview photo of the 2023 MBX Pit West, North, and East Walls is shown in Figure 1.

Figure 1. 2023 MBX Pit West, North, and East Walls (view looking North).

2.2 Geological Setting

The Mount Milligan deposit is characterized by andesite Triassic flows and pyroclastics and early Jurassic intrusions of monzonite and diorite and later Jurassic to Cretaceous intrusions of trachyte dykes. Two major gold-copper porphyry deposits, including the main MBX and the SS, are associated with two large intrusive monzonite stocks that have intruded the Upper Triassic-Lower Jurassic Takla Group andesite and lactic volcaniclastic rocks.

- The lithological and structural setting at the Mount Milligan deposit can be simplified into three major lithology and structure systems as illustrated in Figure 2 (From Lefort, et al. 2011):
- Early easterly dipping volcanic formation, including the Andesite, Latite, Trachyte flow units, as well as some lithology contacts and major faults (e.g., Harris Fault in the MBX Pit, and SS NW Faults in the SS Pit).
- Sub vertical to slightly westerly dipping intrusions (Monzonite/Monzodiorite), including the MBX intrusion and SS intrusion).

- Late northeast to east trending extensional faults, including the Oliver Fault and Rainbow Fault in the MBX Pit and the SS Cross Faults in the SS Pit.

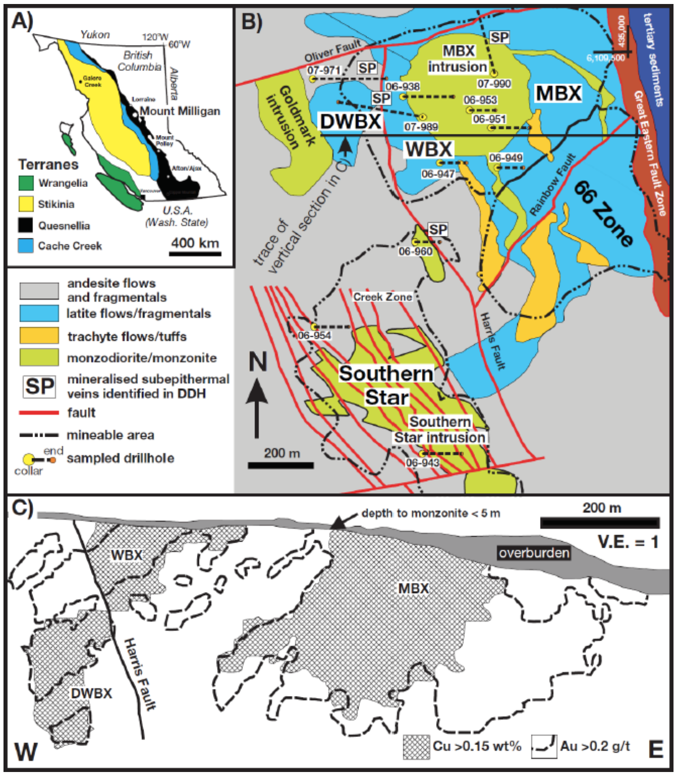

Figure 2. Geological setting of Mount Milligan deposit.

The simplified lithological and structural setting indicates that potential adverse structural features will likely be exposed along the easterly to southerly facing, West to North Walls of the proposed open pits.

2.3 Feasibility Pit Slope Design

KP completed an open pit geomechanical site investigation program in 2007 as part of the feasibility study. This program included only seven site-specific oriented core holes as shown in Figure 3 (KP 2008). A simplified geotechnical model comprised of Overburden, Intrusives (Monzonite), Volcanics (Andesite and Latite) was developed.

The intact rock strengths were generally found to be strong; with a typical Unconfined Compressive Strength (UCS) of approximately 90 to 110 MPa in the Andesite and Monzonite units. The rock masses exhibit significant jointing, and there is substantial variability in the orientation of discontinuities within the rock mass. The rock mass quality was characterized as FAIR to GOOD, while POOR quality rock was typically encountered at lithology contacts and fault zones. The MBX Pit was divided into seven design sectors correlating to the nominal pit wall orientations (North, East, Southeast, South 1 through 3, and West). Table 1 summarizes the recommended slope geometry, anticipated wall geology, and potential kinematic failure modes for the proposed MBX Pit.

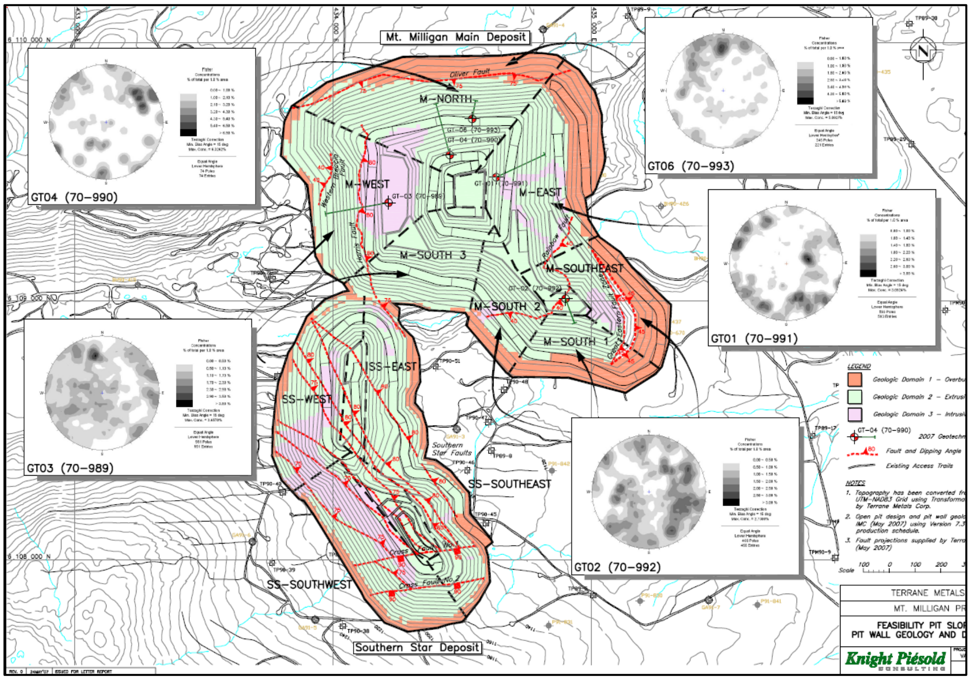

Figure 3. Feasibility study pit with design sectors and stereographs from 2007 oriented core holes

Table 1. Feasibility study MBX Pit slope recommendations.

Design Sector	Nominal Pit Wall Direction (°)	Pit Wall Geology	Bench Height (m)	Bench Width (m)	Bench Face Angle (°)	Inter-Ramp Slope Angle (°)	Kinematic Failure Mode
All	-	Overburden	15	8	40	30	
North	170	Andesite	30	14	65	47	Planar & Toppling
East	265	Andesite, Monzonite	30	14	60	42	Planar & Wedge
Southeast	225	Andesite, Monzonite, Great Eastern Fault	30	14	60	42	Planar & Wedge
South 1	005	Andesite, Monzonite	30	14	65	47	
South 2	045	Andesite, Monzonite	30	14	65	47	Toppling
South 3	010	Andesite, Monzonite	30	14	65	47	Toppling
West	080	Andesite, Monzonite	30	14	65	47	Wedge & Toppling

Kinematic stability analyses were conducted using the 2007 oriented core structural data to determine appropriate bench and inter-ramp geometries in hard rock. It is acknowledged that the large-scale structural features and rock mass structural sets defined from the 2007 oriented core hole data were inconclusive. Potential adverse structural features, expected based on the conceptual lithology and structural model, were not clearly identified in the feasibility study. Ongoing collection of structural data and refinement of the structural model were recommended throughout open pit operations.

The implementation of pit slope design also necessitates low-damage, well-controlled blasting and excavation practices, effective pit dewatering and slope depressurization, and systematic slope monitoring throughout pit operations.

3 Ongoing Data Collection and Geotechnical Model Refinement

3.1 Visual Inspection

Excavation of the MBX Pit commenced in 2013, utilizing the feasibility design pit slope geometry. Visual inspections were performed along each newly developed bench during the early phases of pit operations.

The uppermost 15 to 30 m of the pit walls consist of dense glacial till mixed with some interstitial alluvial deposits. The overburden bench faces were nearly vertical after the initial cut, but surface erosion and material degradation gradually broke the bench face angles to approximately 60 degrees over time.

Oxidized zones of volcanic andesite/latite rock were observed below the overburden throughout the entire pit. The oxidized rock is medium strong and relatively competent despite weathering/oxidization, but highly fractured with closely spaced (<1 m) jointing.

Unweathered Andesite Volcanics and Monzonite Intrusives underly the oxidized zone. Trachyte flows and tuffs form part of an extrusive package that is interbedded between the andesite volcanics and latite volcanics, making up portions of the West Wall. The trachyte unit is typically fractured and of lower strength compared to the surrounding andesite/latite volcanics.

As pit development extended below the overburden and oxidized rock zones and into the andesite and monzonite rock units, it was observed that bench-scale wedge failures within the West and North pit sectors were the most common forms of pit instability. The probability of wedge failures was underestimated in the 2007 oriented core data due to directional bias in drillhole creation and a significant distribution of randomly oriented joint measurements, which decreased the fidelity of the stereographic data. Structural data acquisition was deemed necessary during operations to refine the structural model.

3.2 3D Laser Scanning

In 2015, the mine implemented a rock mass structural data collection program for the MBX Pit, using the Maptek I-Site 8810 3D laser scanner. The scanning system integrates a digital camera, a simultaneous 3D laser point capture system, and photogrammetric structural data interpretation software. The scanner and interpretation software allows each discontinuity data point to contain the following information: coordinates and elevation, strike/dip and dip/dip direction, length of structural plane, area of structural plane, lithology, and discontinuity set.

Mine geologists conducted the laser scanning with a truck-mounted laser scanner along newly developed benches once scaling and cleaning activities were completed in 2015. The rock mass structural orientation data were collected based on bench elevations and pit wall sectors, as illustrated in Figure 4 (KP 2016).

The rock mass structural orientations data collected from laser scanner was exported to a stereographic interpretation program for joint set delineation and further kinematic stability analysis. Select stereographic bench-scale wedge analyses for the 2015 MBX Pit Upper West and Lower North sectors are illustrated in Figure 5 (KP 2015).

The stereographic plots reveal that each pit sector has one or two predominant structural sets. The dip directions of the major structural sets appear to follow the wall orientations and dip toward the center of the MBX deposit. Bench-scale wedge and planar failures seem to be the likely kinematic failure modes for the West and North Walls of the MBX Pit. This structural feature was not clearly identified in the oriented core holes conducted during the 2007 feasibility study but was observed during visual inspections and confirmed by laser scanning.

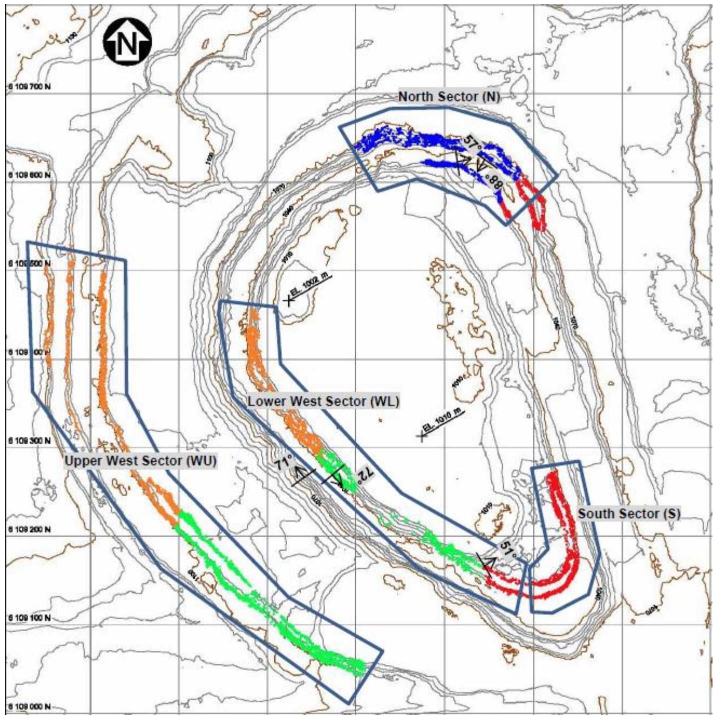

Figure 4. 2015 MBX Pit laser scanning sectors and data point locations.

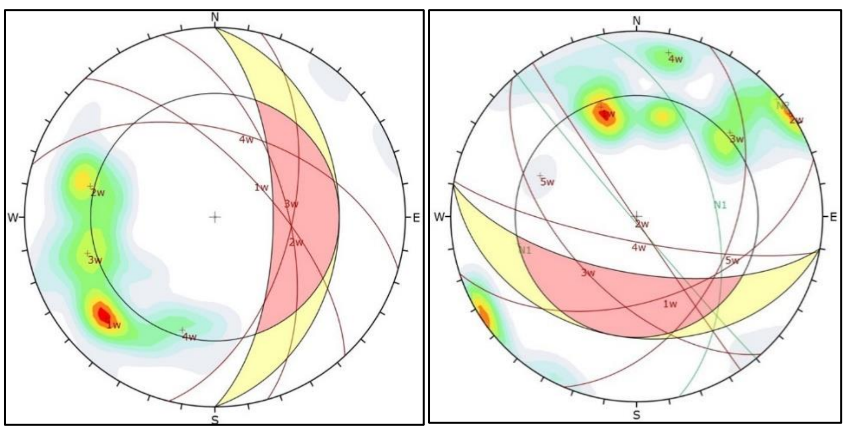

Figure 5. Bench-scale stereographic wedge failure analysis plots for upper West sector (left) and lower North sector (right) of 2015 MBX Pit.

It is acknowledged that the rock mass structural data collected by laser scanners may be affected by trace exposure and line-of-sight biases. Terzaghi weighting was applied in the stereographic plots to correct the bias by increasing the weight of under-represented discontinuity surfaces; however, the identified structural sets still strongly correlate with the wall orientations of the MBX Pit. The I-Site laser scanner, mounted on a pickup truck, collected data from multiple locations for a certain bench, not just from a single shooting point. Therefore, the line-of-sight biases may be offset given sufficient overlaps between each shooting point.

3.3 Geological Mapping

In 2018, the mine enlisted an independent engineering geologist to conduct physical geological rock bench mapping and provide field data collection training at the MBX Pit. The geological mapping aimed to assess discontinuity characteristics alongside structural orientations. Additional information, including discontinuity type, aperture, persistence, infill materials, and weathering, was gathered through physical mapping. The mapped structural data were integrated into 3D structural geology wireframes to support the development and refinement of the geotechnical model.

The areas covered by the 2018 surface geological mapping at the MBX Pit are illustrated in Figure 6 (SRK 2019). This mapping work reaffirmed the presence of NW to northerly trending, moderately to steeply dipping strike-slip faults and NE trending extensional dip-slip faults, aligning with the conceptual structural model.

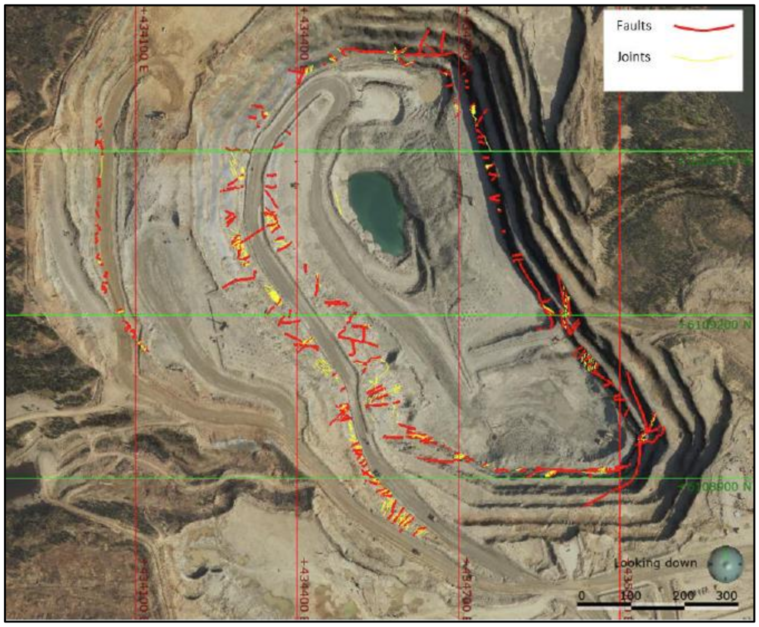

Figure 6. 2018 MBX Pit geological mapping areas.

All mapped joint orientation data for the MBX Pit and SS Pit are plotted in stereography, as shown in Figure 7 (SRK 2021). The predominant joint sets in both pits are very similar, with a dominance of NW to WNW striking, moderately to steeply dipping rock mass structures. This closely aligns with the strike-slip fault trends within the Mount Milligan property.

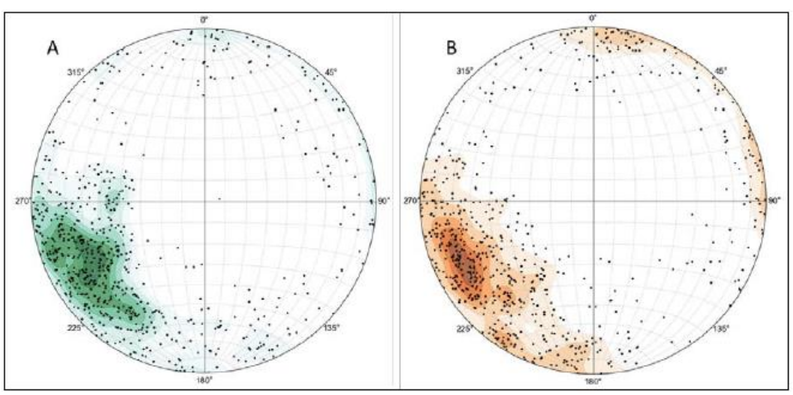

Figure 7. Stereographic plots of 2018 mapped discontinuity data for MBX Pit (A) and SS Pit (B).

3.4 Geotechnical Model Refinement

Mine geologists have consistently updated and refined the lithology and structural models through various ongoing data collection programs throughout the operations. The updated geotechnical domains encompass the Overburden, Oxide, Monzonite Stock (Intrusives unit), Volcanics (Andesite and Latite), Trachyte Volcanics, and

Post Mineralization Dykes. Figure 8 displays an updated pit geotechnical model, featuring geotechnical units and major faults, projected to the 2023 MBX Pit surface.

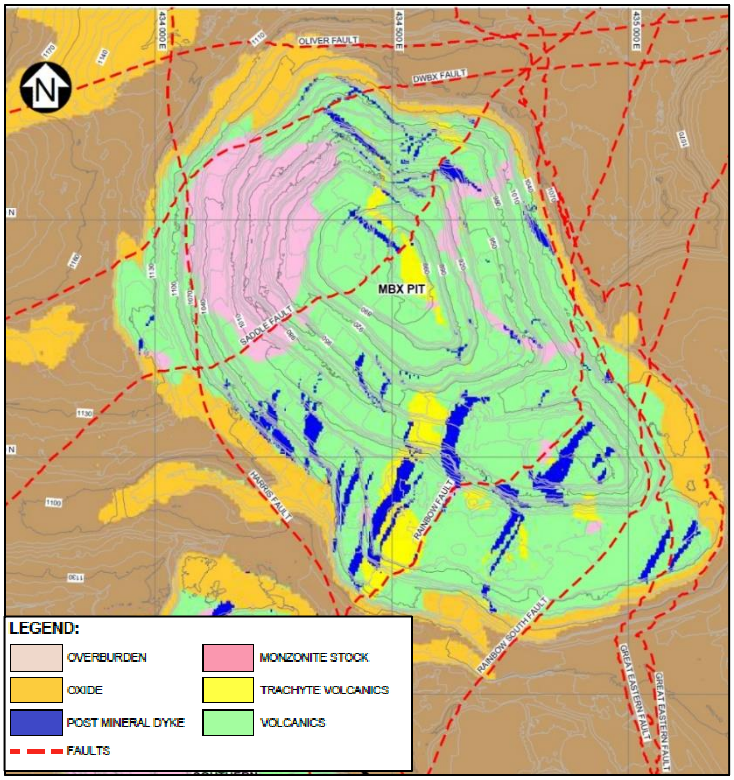

Figure 8 2023 MBX Pit projected wall geology map.

Refinements to the geotechnical model have been ongoing as pit development progresses. Pit wall mapping and resource drilling by the mine contribute to updates in the geological model and fault zone structural model. The most notable changes to the geological model since the development of the feasibility design are the delineation of post-mineralization dykes (PMD) within the MBX Pit. The delineation of major faults within the MBX Pit has also been refined since the feasibility study, particularly regarding the extents and orientation of the Great Eastern Fault, Rainbow Faults, and Saddle Fault.

Laser scanning of newly exposed pit walls has been the primary source of rock mass structural data updates. The structural data is used as part of ongoing pit wall stability assessments that target newly developed pit walls and determine if wedge, planar, or toppling failures are kinematically possible and require mitigation measures. Multiple sources of rock mass structural data collection have confirmed the existence of multiple random joint sets within the volcanics and intrusives package. Bench-scale and/or multiple-bench-scale wedge instabilities are expected to be the primary concern for pit operations.

4 Operational Monitoring

4.1 Ground Control Monitoring Plan

In addition to regular visual inspection and ongoing geotechnical data collection, the mine implemented a progressive pit monitoring program after the initial development of the MBX Pit while the overall pit wall exceeded a height of 100 m. A Ground Control Monitoring Plan (GCMP) was subsequently prepared to provide information utilized in planning, designing, and managing all aspects of the open pit ground control during mining operations. The GCMP is a living document that had undergone several revisions as additional geotechnical information and/or site-specific pit operating experience was gained. The GCMP serves as an effective all-in-one document that presents all aspects of the project background, design criteria, hazard management and risk reduction, and documentation and verification requirements (KP 2022). Key information presented in the GCMP include:

- Typical geotechnical hazards that may occur, along with guidelines for hazard classification, assessment, and prevention.
- Risk reduction guidelines for mine planning, blasting, rockfall control, water management.
- Critical controls, monitoring guidelines, Trigger Action Response Plans and Emergency Response Plans for effective hazard response.

4.2 Surface Prism Monitoring

The mine initially employed a total station and prism array to monitor Phase 3 MBX Pit operations in the early years. These prisms were strategically installed along critical West Wall benches and the haul road at regular intervals to enable continuous displacement monitoring.

Regular prism surveys and reviews were conducted to generate alarms in case movement thresholds were reached. However, the prisms proved ineffective in an environment with random adverse rock mass structural features. The prism monitoring system failed to detect a 60 m high multiple bench rapid slide that occurred within the Phase 3 West Wall of the MBX Pit (KP 2018). Subsequently, the prisms were abandoned and replaced with more advanced slope monitoring measures.

4.3 Automated Slope Monitoring with Laser Scanner

The preponderance of pitward-dipping structures, blast-induced wall damage, surface water inflow, and groundwater pressure has led to bench and multi-bench scale failures occurring throughout mining operations. Automated monitoring for early detection of slope instabilities was deemed necessary for ongoing risk management as pit depth increased.

In 2018, a stationary laser scanner system was acquired for automated slope monitoring. However, automated monitoring using the laser scanner posed challenges as the high level of detail capture resulted in an excess of false alerts triggered by small-scale movements, such as rock raveling or snow settlement. Consequently, the automated system was found to be unsuitable for monitoring in 2020. Nevertheless, the mine continues to utilize a portable laser scanner for manual scans of the pit.

4.4 Automated Slope Monitoring with Slope Radar

The mine purchased an automated slope radar scanning system in 2021 after on-site trial runs of the system and data management software were conducted by the vendor to demonstrate coverage areas and motion sensitivity.

The slope radar scans the entire coverage zone every two minutes and utilizes a Digital Terrain Model (DTM) of the scanned surface. Scanning areas are manually delineated by creating polygons on the pit wall surface and directing the processing software to only monitor the selected areas for movement. The mine excludes the tops of benches or haul roads when delineating the polygons, limiting movement alerts triggered by mine personnel or equipment. Scanning areas are typically limited to two to three benches and are added or edited as new walls are exposed or altered. The DTM is subdivided into “pixels”, which have a surface area of 1 to 2 m^2 depending on the total surface area of the DTM. Pixel displacement between scan intervals is used to calculate movement velocities per pixel, which are averaged over a three-hour period to reduce false alarms caused by individual data spikes.

Alerts levels based on velocity thresholds will be triggered if enough contiguously connected pixels exceed specified velocity thresholds. Table 2 summarizes the average velocity thresholds and response plans for each alert level used for the Mount Milligan open pit operations, targeting structurally controlled rapid slides of hard rock mass. Recommended warnings and alerts are sent directly to mine personnel if trigger levels are reached.

Table 2. Slope radar monitoring velocity thresholds and action plan.

Level	Velocity Threshold (mm/hour)	Velocity Threshold (mm/day)	Mining Action
4	>3	>72	Stop mining and withdraw equipment from the area of influence of the instability
3	1 – 3	24 – 72	Daily visual inspection
2	0.3 – 1	6 – 24	Bi-weekly visual inspection
1	<0.3	<6	Weekly visual inspection

Figure 9 presents an example of the scanning areas selected for the West and North Walls of the MBX Pit. Pixel velocity is represented by a heat map showing the corresponding alert level per threshold. The radar is repositioned as needed to maximize coverage of actively mined areas, as walls that are obliquely angled to the radar unit have poor to no coverage.

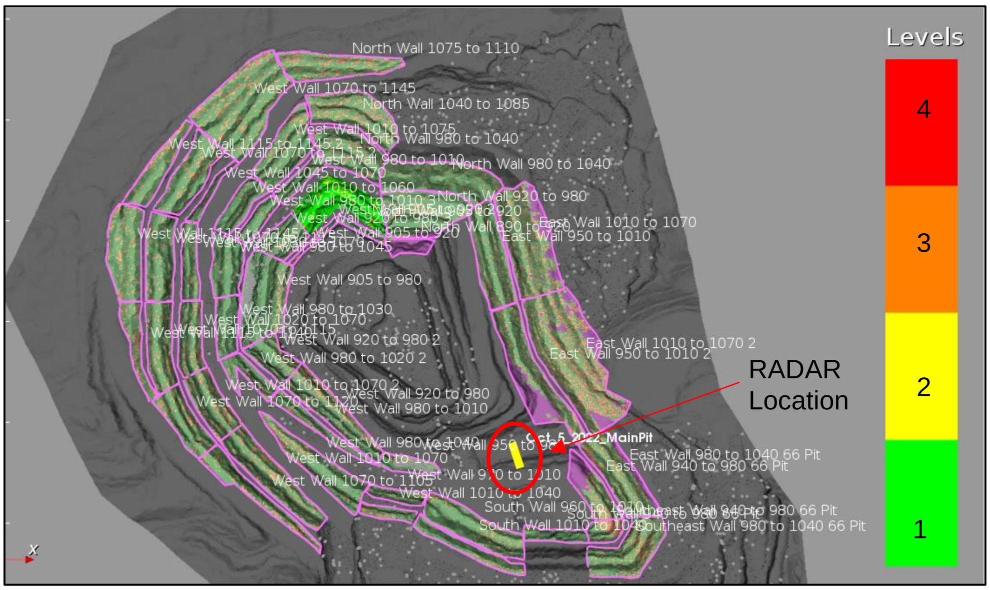

Figure 9. 2023 MBX Pit slope radar scanning areas with alert level heat map.

The radar system has proven effective in tracking slope movements, allowing for early detection of progressive slope failures. Figure 10 shows an example of a wedge failure development that was detected in October 2022 after an alert was triggered approximately 24 hours prior to the failure occurring. The movement was detected above an active work area and early detection allowed for removal of personnel and equipment well in advance of the failure occurring.

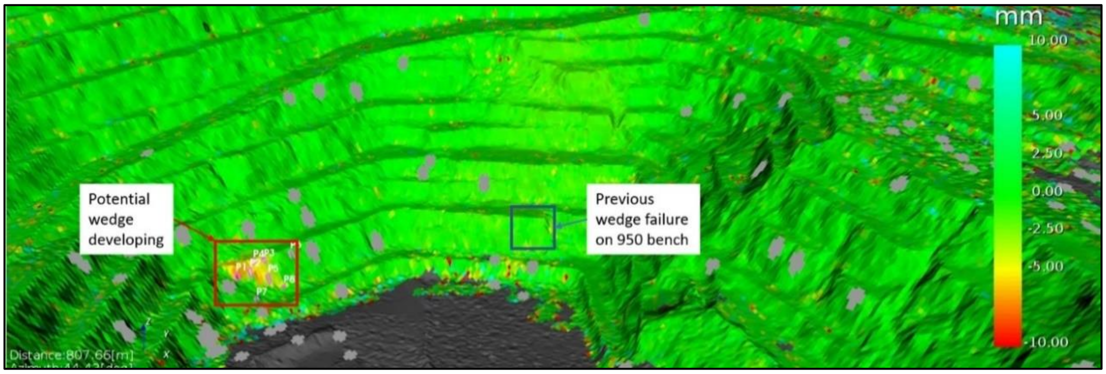

Figure 10. MBX Pit slope radar early detection of wedge formation in West Wall.

Displacement and velocity readings of the failure presented in Figure 11. The radar system was effective in detecting the initial movements and velocity changes in the failure zone several hours before rapid slope movement occurred.

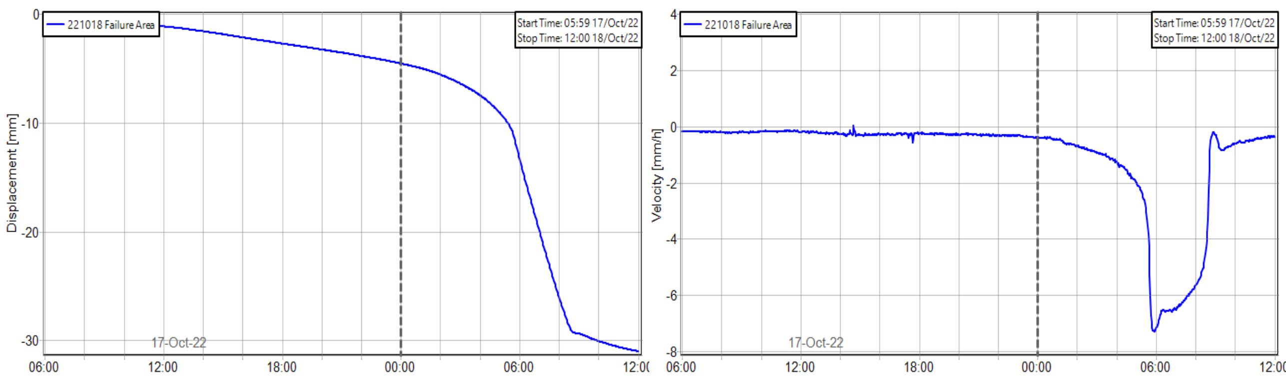

Figure 11. Displacement and velocity vs. time for detected wedge failure.

Despite the effectiveness of the system, optimization of scanning areas and motion detection parameters was necessary. The initial settings of the radar system triggered false alerts due to small-scale movements, such as loose rockfall and minor raveling of the pit walls. The primary focus of optimizing the monitoring system was on adjusting the scanning area size to strike a balance between movement sensitivity and reducing false triggers.

The software used the size of the scanning area to determine the number of contiguous pixels required to trigger an alert level. Initially, a small scanning area of 12 m² was used, triggering alerts if three contiguous pixels exceeded a velocity threshold, resulting in an unacceptable number of false alerts. Throughout 2022, the mine gradually increased the scanning area size from 25 m² to 45 m², decreasing the number of false alerts but not achieving the desired frequency reduction.

In June 2023, a missed alert resulted in a rockfall, prompting a back analysis of the monitoring data to minimize false alerts without compromising the detection of actual slope movements. The analyses involved adjustments to the scanning areas and time windows over which the data were averaged. The scanning area was modified between 45 m², 90 m², and 135 m², and time comparison windows were reviewed at 1, 3, and 6 hours for each area. It was determined that the optimal scanning area is 90 m² (sufficient to cover a 30 m wide by 30 m tall double bench) with velocities averaged over a three-hour window. These settings utilize a pixel size of approximately 1.2 m and trigger an alert if 62 contiguous pixels are in motion, effectively mitigating false alerts caused by small-scale rockfalls or raveling. The mine plans to maintain these settings until another slope movement occurs, providing an opportunity for further back analyses and calibration.

5 Ongoing Risk Management and Pit Development

The mine engaged qualified geotechnical engineers for semi-annual pit inspection and auditing services throughout pit operations. These inspections encompass a visual inspection of the pits, a review of performance data acquired by the mine operators, and an evaluation of the proposed pit plans for upcoming operations. The structural, geological, and hydrological data collected by the mine is utilized to evaluate the pit slope stability and develop recommendations for ongoing mine planning and risk mitigation.

Ongoing kinematic analyses of the laser scanning data have been the primary method for assessing the stability of the interim pit wall geometries and identifying the risks of instabilities forming. The risk of adverse structures developing in the pit are assessed by calculating the Probability of Failure (POF), which is the percentage of discrete structures within a selected joint set that meet the conditions for wedge, planar, or toppling failure. Predictions of bench and inter-ramp scale performance utilize a POF threshold of 30% and 15%, respectively. Annual kinematic analyses of the laser scanning data from interim pit walls have consistently indicated a high likelihood of bench scale wedge and planar failures, especially within the North and West wall areas of the pits. These failure modes were underrepresented in the 2007 data that formed the basis of the original geotechnical model. Analyses of the updated structural dataset predict failure probabilities in general accordance with bench scale pit wall performance, where bench scale wedge failures occur multiple times throughout the year, especially during freeze thaw cycles or the spring freshet season. These analyses results are utilized for identify critical pit wall areas where failures are kinematically possible, allowing the mine operators to focus slope monitoring and maintenance efforts in these locations.

Multiple-bench instabilities have been historically controlled by the interactions between the large-scale faults and PMDs and pit wall geometry. Continual refinements to the pit geological model and the delineation of major faults are completed as part of ongoing data collection. The pit excavation plan is reviewed and updated as new data is collected and interpreted. The risk of inter-ramp scale instabilities developing is mitigated by adjustments to the pit wall geometry and the overall pit mining plan.

Pore pressure management is achieved through installation of horizontal drains are installed in newly exposed pit walls. Drains locations are selected targeting observed seepage locations and monitored throughout the year to track flow rates and responses to seasonal changes. These drains have been effective in reducing the frequency and size of bench scale block failures within the pit wall.

The mine is currently proposing a revised Life of Mine (LOM) ultimate mining plan for the Mount Milligan open pits, incorporating a major pushback along the existing West Wall of the MBX Pit. In 2023, a supplementary geomechanical drilling program was implemented, consisting of oriented core drillholes located within the West Sector of the proposed ultimate pit boundary. The structural data from this program will be used in conjunction with monitoring and mapping data to refine the geotechnical model, update the LOM pit slope design, and develop risk mitigation strategies for pit operations. A vibrating wire piezometer installation program was also implemented to provide more detailed information on groundwater levels and pore pressure responses to seasonal weather conditions, pit development, and the implementation of dewatering measures.

Anticipated adjustments to the LOM ultimate pit design include avoiding adverse lithology contacts and faults in the long-standing interim pit walls and final walls, adopting single benching configurations for the oxidized zone in the SS Pit, as well as addressing the Great Eastern Fault and PMD exposure zones along the upper Southeast Wall of the MBX Pit.

6 Summary

The original design of the Mount Milligan open pits was based on limited geological and hydrogeological data. Ongoing data collection throughout pit development was critical in refining the pit geotechnical model. Ongoing geotechnical data collection and automated slope monitoring have also provided in-depth understanding of rock mass characteristics and wall performance and guided the optimization of the LOM ultimate pit design for the Mount Milligan Mine.

Risk mitigation within the MBX Pit has improved throughout the previous decade of pit development. On-site experience and knowledge of the pit wall structure and geology has allowed for development of an effective Ground Control Management Plan. Identification of higher risk wall areas is facilitated by reviewing the detailed structural data obtained by the laser scanner of pit walls combined with geological mapping and delineation of large-scale structures within the pit. Refinements to the pit wall geometry and implementation of horizontal depressurization drains haven proven successful in mitigating bench and inter-ramp scale failures.

The automated radar monitoring system is an effective tool for tracking slope movements and early detection of bench scale and multi-bench scale movements within the pit walls. When used in conjunction with regular inspections and monitoring plans as prescribed by the GCMP the mine operators have developed a comprehensive system for identifying hazardous pit wall conditions and quickly applying risk mitigation measures. Overall mine safety is enhanced by effective implementation of these real-time monitoring measures.

7 Acknowledgements

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