Managing Excessive Pit Wall Deformation of Weak Rock Mass

Salina Yong *Knight Piésold Ltd., Vancouver, Canada*

Daniel Yang *Knight Piésold Ltd., Vancouver, Canada*

Justine Ealy, Christina Foster *KGHM, Ruth, USA*

Abstract

Rapid acceleration of a large-scale creeping instability occurred in an open pit operation in 2016. A 150-foot-tall back scarp formed, tension cracks appeared near the pit rim, bulging formed in the lower slope, and debris reached the pit bottom. The instability displaced material over a hundred feet and buried the main access road. Monitoring of the initially slow-moving mass had commenced in 2013 with terrestrial radar, which was integral to managing the risk along with strategic mine planning. As a result, the instability was successfully managed and did not lead to safety incidents or equipment losses. Re-establishing access necessitated routing through the slide debris, which posed a risk to the road development due to the potential of heightening the back scarp. Dewatering and removal of the slide toe also posed risks to the road development and mine economics.

Analyses were completed to evaluate the stability of the back scarp and the proposed mining sequence of the slide toe with UDEC, RocFall, and Slide3. The analyses assisted rehabilitation by identifying influential factors, estimating the rockfall impact, and identifying areas of concern. The pit was successfully rehabilitated, not only with the insights provided by the analyses but also the vigilant guidance provided by the mine geotechnical team through real-time slope monitoring and inspections, continuous maintenance, and a flexible mindset for impromptu adjustments when needed. Mining of the pit was completed in 2020 and backfilling is ongoing. Recent monitoring data indicates the instability has stabilized at a displacement rate of nearly zero. This paper summarizes a case history where excessive deformation of a pit wall exposed in weak rock mass was successfully managed.

1 Introduction

The mine is located in the southwest US and has been operated intermittently by different companies since the late 1800's when gold and silver were first extracted. Significant deposits of copper ore were discovered shortly after, and mining of copper porphyry has been ongoing since. The property comprises several open pits, at various stages of operation and closure, that are mined by the conventional method of blasting and truck haulage to a processing plant.

The north wall of one of the open pits experienced a pit-scale instability in 2016 (Figure 1). Dewatering and removal of the slide debris were required but the main haul road was displaced hundreds of feet. Stability analyses were completed to assist the mine with planning for rehabilitation of the road and for the end-of-mine. The pit was successfully completed by way of the observational method, with the integral involvement of deformation monitoring and responsive strategic mine planning. This paper summarizes a case study of managing the excessive deformations of the pit wall that exposed weak rock mass.

2 Pit Instabilities

Mining of the pit commenced in 2012 and after some months, tension cracks appeared near the crest and the slope began to move. The mine geological model indicated the instability was bound by a fault along its southwestern flank and a second intersecting fault near its scarp. Mining of the fault-bounded rock mass was exposing progressively weaker units with depth. A network of prisms was installed to monitor the deformation and indicated heavy rainfall also accelerated movement. In the first three months of monitoring, the north wall had displaced 15 inches with velocities up to five inches per day when the pit was deepened a further 100 feet.

Over the next year, a third intersecting fault was exposed to bound the bottom of the displacing wedge of rock mass in the north wall. Mining at the toe of the north wall and elevated pore pressures from heavy rainfall and snowmelt again accelerated slope movement and the development of tension cracks (Figure 2). A terrestrial radar unit and the survey prisms indicated the north wall displaced two to six feet over a period of nine months. With rates greater than one inch per day at times, the mine plan was adjusted to incorporate a 200-foot-wide step-out and a Trigger Action Response Plan (TARP) based on velocity thresholds was developed. However, deformations became excessive (five feet over 30 days) a few months later and mining at the toe of the north wall ceased for two years.

Figure 1. Failure of the north wall (picture taken in early 2017).

Figure 2. Tension cracks above the north wall.

Mining resumed in late 2015 with a planned layback of the north wall, development of a lower haul road, and deepening of the pit. Tension cracks and slope deformation of the upper wall were observed in the following months. A year later, excessive slope deformation accelerated as the pit deepened and led to a cessation of mining. Radar data indicated that the wall displaced approximately 50 feet over the last month with rates up to 30 inches per day. Seepage along lower benches and ponding at the pit bottom were observed during a later inspection, indicating elevated pore pressures could have also been a contributing factor. At this point, the north wall was approximately 950 feet high and had exposed weak units. Slope deformation slowed and stabilized once mining stopped: a return to its characteristic creep behaviour.

In addition to the north wall, the east and south walls also experienced instabilities in the early phase of mining. Artesian conditions were encountered when a fault was exposed early (2013) in the development of the east wall. Slope movement and tension cracks developed as a result. A later (2015) failure involved two episodes that measured approximately 350 feet high and 400 feet wide (Figure 3). This instability was attributed to the exposure of a localized weak zone near the base of the pit wall and coincided with the observations of seepage and surface ponding. The nearby fault (first exposed in 2013) was likely providing the source of water as it is a known hydraulic conduit in the area. The instabilities were mitigated by incorporating step-outs, dewatering, and installing horizontal drains.

Figure 3. Failure of the east wall.

The south wall instability was minor and localized to the top two benches. It was also bound on its northwestern flank by one of the same bounding faults of the north wall instability. The rock mass involved was heavily altered, fragmented, and loose. Preceding heavy rainfall likely elevated pore pressures and triggered the failure.

3 Site Characterization

The west-trending ore body at the mine is about eight miles long and up to 1,500 feet wide. The rock mass is weak and fragmented due to hydrothermal alteration and faulting (extensional and normal) that dissected and rotated the deposit to its current configuration. The alteration and mineralisation are centered on a monzonite porphyry intrusion and associated skarns that cuts through the sedimentary host rocks.

3.1 Rock Mass Domains

The rock mass of the pit is comprised of six main lithologies and two alteration grades. The six units include porphyry (intrusive), limestone, sandstone, shale, rhyolite (volcanic), and fault zones. Significant degradation of the rock mass quality and strength are attributed to phyllic, argillic, potassic, propylitic, and gossan alteration or Grade (i), with examples shown on Figure 4. The second alteration Grade (ii) has little adverse impact on the rock mass quality or strength and includes silicification, silica-pyrite, decalcification alteration, and unaltered rock.

Site investigation data indicated that domaining by alteration grades provided a more meaningful understanding of the expected geomechanical response relevant to slope stability, as shown in Tables 1 and 2. Figure 5 shows that the areas of instability in the pit walls coincided with areas where the alteration was the weaker Grade (i) and indicated the rock mass was weak to medium strong (Table 1) and poor in quality (Table 2). The tabulated summary of strengths also suggests that intact rock fragments are stronger than the rock mass, which is an important consideration for developing analysis models.

Faulting is significant at the mine and generally delineates the geological and geomechanical domains of the pit. The fault zones are characterized by extremely fractured and/or altered rock that is often clay-rich with RQD values near zero. Three main joint sets can be identified from investigations and generally include a sub-horizontal set and two dipping (25-degree and 55-degree) towards the east.

Figure 4. Comparison of rock mass quality between the alteration grades.

Table 1. Rock mass strength by lithology and alteration grades.

Uniaxial Compressive Strength (ksf)		**Lithology**						**Alteration Grade**	
		Porphyry	**Limestone**	**Sandstone**	**Shale**	**Rhyolite**	**Faults**	**(i)**	**(ii)**
Field Estimate	Number of Runs	>400	>700	>200	>100	>1,000	>300	>1,400	>1,400
	Average	200	1,100	500	200	300	100	200	800
Field Point-Load Tests	Number of Samples	>100	>500	>100	>40	>300	>50	>400	>800
	Average	300	1,200	1,000	400	700	500	400	1,100
Strength Class		Weak to Medium Strong	Medium Strong to Strong	Medium Strong to Strong	Weak	Weak to Medium Strong	Weak	Weak to Medium Strong	Medium Strong to Strong

Table 2. Rock mass classification by lithology and alteration grades.

RMR_{89}	**Lithology**						**Alteration Grade**	
	Porphyry	**Limestone**	**Sandstone**	**Shale**	**Rhyolite**	**Faults**	**(i)**	**(ii)**
Number of Runs	>400	>700	>200	>100	>1,000	>300	>1,400	>1,400
Weighted Average	30-40	50-60	40-50	30-40	30-40	30-40	30-40	40-50
Quality Class	Poor	Fair	Fair	Poor	Poor	Poor	Poor	Fair

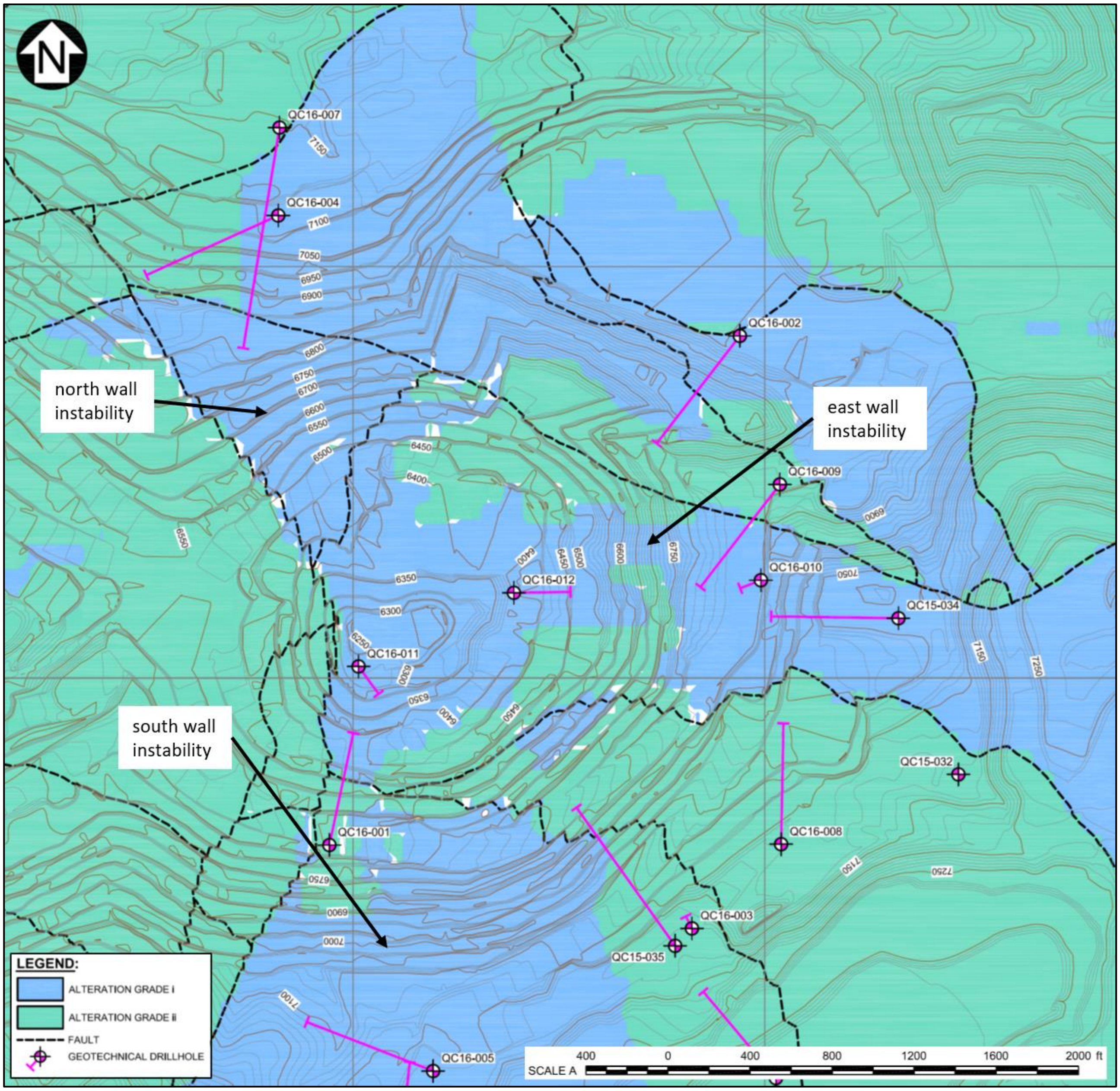

Figure 5. Alteration grade map (2016 topography).

3.2 Groundwater Conditions

A conceptual groundwater model was developed by a hydrogeological consultant based on monitoring data from piezometers installed throughout the life of the mine. The model was used to assist with the development of dewatering plans and targets as mining progressed, which in turn required updates to the model as new information was made available.

In the north wall, high downward gradients were observed, even across a fault and suggested the presence of low permeability materials such as faults, anisotropy in shale beds, and mineralized bedding planes. The data also suggested pore pressure reduction lagged significantly behind advancement of the pit bottom. In addition, it was suggested that long-term pumping stresses in the deeper groundwater system could be influencing the vertical gradients locally and along significant geological structure. The installation of horizontal drains was recommended for reducing pore pressures to assist with slope stabilization.

Data from piezometers installed in the east wall indicated little to no vertical gradients, which suggested the rock mass was less faulted and potentially more isotropic than the north wall. However, anecdotal experience from mine staff indicated some degree of low permeability structural or bedding features. Water levels in one location supported the possibility of a structurally-controlled boundary. Dewatering was strongly recommended with a combination of horizontal drains, in-pit borehole sumps, sumps, and inclined wells to reduce the pressure in the east wall.

Diversion of surface run-off from upland areas was also recommended to minimize water from flowing onto active pit slopes in the north and east walls.

4 Displacement Monitoring

The observational method was an important element of the approach used by the mine to manage the large deformations of the pit walls, not only to achieve the end-of-mine design but also for supporting the ongoing backfilling operations of the pit. Initially, the TARP thresholds were developed from prism monitoring (Figure 6) and entailed five levels of actions. When deformation monitoring transitioned to terrestrial radar units (Figure 6), the TARP was simplified to three levels of actions. Mining was to stop at the highest threshold level of 3.6 inches per day for prism monitoring and later, three inches per day for radar monitoring. The threshold levels were developed specifically based on the deformations of the north wall instability and the learnings of the mine in managing the instability. Hence, the TARP is specific for a creeping mode of deformation and is not suitable for a brittle mechanism.

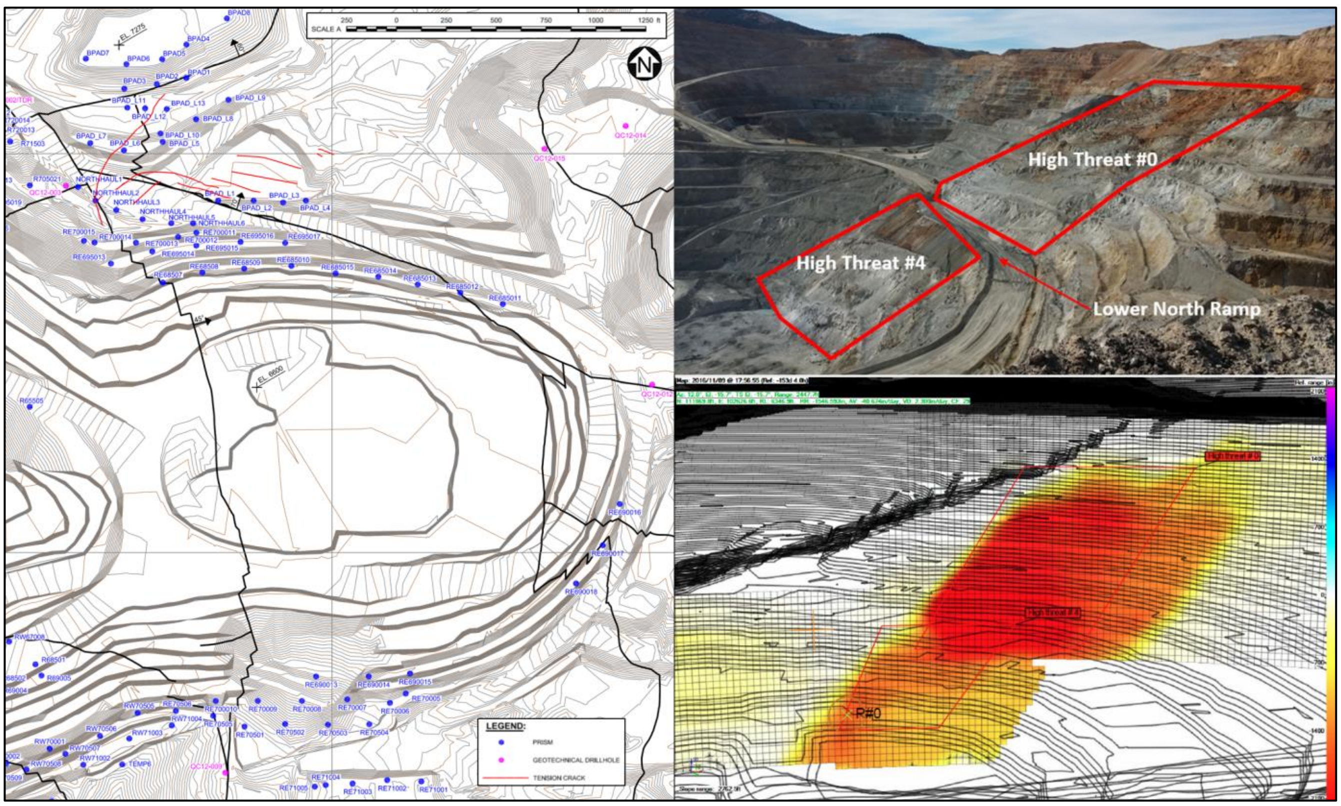

Figure 6. Displacement monitoring by survey prisms (left) and terrestrial radar (right).

The TARPs were applied to time series plots of the monitoring data. Recommendations based on data trends were relayed to the mine geotechnical group to assist with operational decisions and mine design planning. The inverse velocity method, a plot inverted velocities over time, was also utilized for the north wall failure in 2016 (Figure 7). This approach was used to successfully predict three large-scale slope failures in poor and fair quality rock mass in other open pit mines by Rose and Hungr (2007). A runout failure is expected when the instability is projected to have an inverse velocity of zero. As shown in Figure 7, the inverse-velocity trends of the north wall suggested a runout danger in the beginning October 2016. However, mining was paused to repair the haul road and the inverse velocity trends flattened out then decreased incrementally when mining resumed. At the beginning of November 2016, the mine was advised to pause mining for a period until the deformation rate decelerated. Over this period, the north wall displaced approximately 30 inches per day.

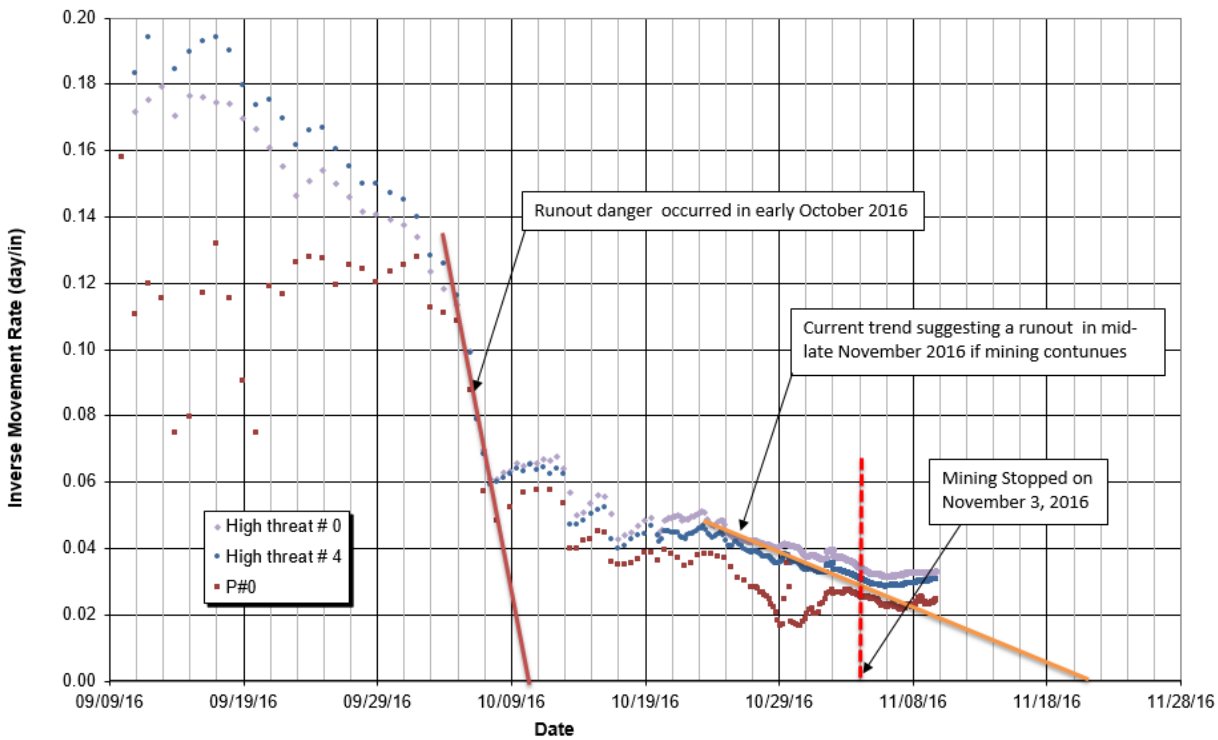

Figure 7. Inverse velocity trends of the north wall 2016 instability.

Following the stoppage of mining, the slide debris of the north wall instability continued to creep towards the bottom of the pit (Figure 1). This movement displaced the haul road approximately 300 feet towards the pit bottom and locally increased the height of the back scarp to approximately 150 feet. Radar monitoring indicated the creep was stabilizing at a rate of four to five inches per day. The mine requested assistance with the design and planning of the rehabilitation to dewater the pit and to resume mining in 2018.

5 Stability Assessments

The mine proposed to re-establish access along the original haul road alignment, which required crossing the slide debris and managing a potential rockfall hazard due to the increased height of the upslope scarp. Following completion of the stability assessment to evaluate the hazards of the proposed road access, the mine was able to dewater the pit and mine a significant volume of the slide debris. Stability assessments were then completed to assist the mine with planning for the end-of-mine that required consideration of both the instabilities in the north and east walls.

5.1 Pit Rehabilitation

An assessment was completed to evaluate the stability of the back scarp and the rockfall hazard. The stability of the back scarp was evaluated with the discontinuum code, UDEC (Universal Distinct Element Code, Itasca 2014), while the rockfall hazard was evaluated using RocFall (Rocscience 2004).

The stability assessment of the scarp involved two scarp heights and three scenarios for considering rock mass structure. The height of the scarp was increased from its existing dimension to 200 ft to evaluate the response to removing the slide debris at its base. The influence of the rock mass structure was evaluated with increasing complexity from only considering the faults to including a series of tension cracks with the faults and finally, the addition of relaxation joints to the model with the faults and tension cracks. The results of the first two scenarios that evaluated the influence of the rock mass structure suggested similar failure mechanisms, as shown on Figure 8. For the existing scarp height, the predicted failure is localized and could occur as slabs or blocks toppling onto the slide debris. Increasing the height of the scarp suggested the failure would also be localized but suggested a change of the failure mechanism to one of rotation at the base of the unsupported scarp. The third scenario, which included the addition of a shallower-dipping relaxation joint at the base of the scarp, represented an extremely adverse combination of structural features and would critically require a highly unlikely persistent joint to daylight at the base of the scarp. The predictions of the third scenario were not considered as a result.

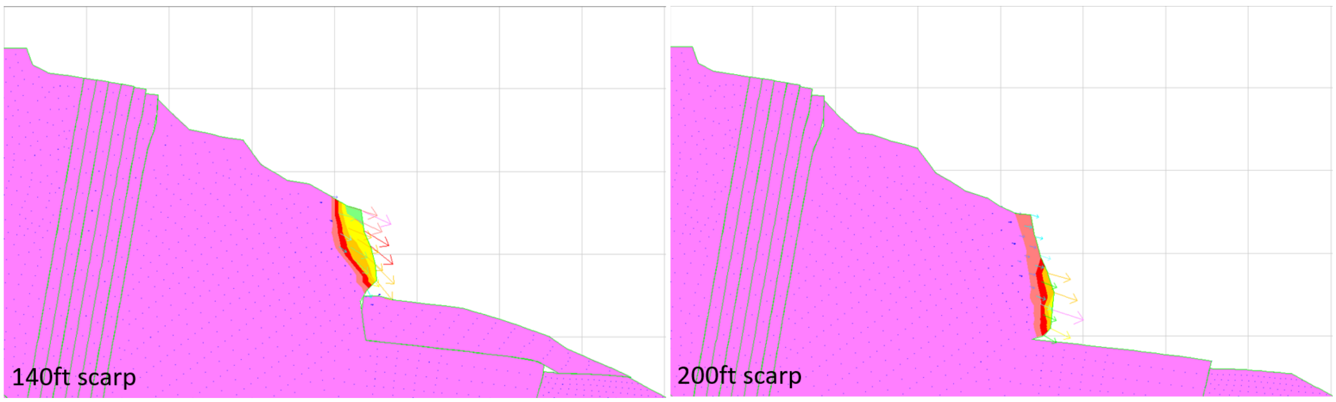

Figure 8. Predicted displacement magnitudes and velocity vectors of the back scarp.

The rockfall hazard was also evaluated by considering two heights for the scarp. The model assumed falling rocks would initiate immediately above the back scarp and involve rock dimensions of 0.1 to 10 square feet (13 to 1,300 pounds). The results for 200 rockfalls are shown on Figure 9 for the existing scarp height, which predicted a longer runout distance. The rockfall runout was estimated to end near the proposed road alignment and a six-foot-tall rockfall barrier was recommended as a result. Increasing the scarp height was not predicted to generate higher energy rock fall due to a flatter talus slope that was assumed to form because of the creep.

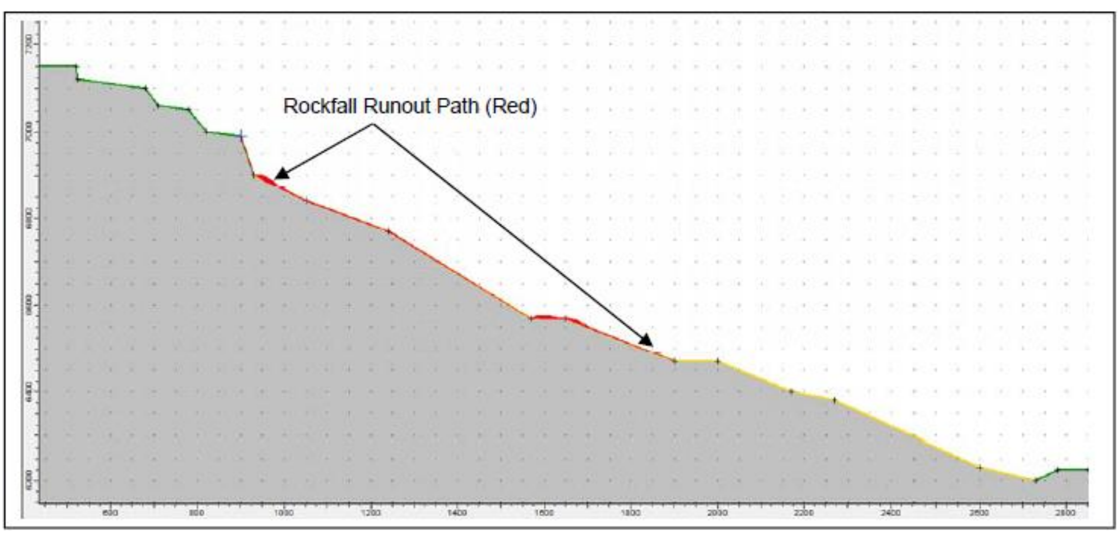

Figure 9. Predicted displacement magnitudes and velocity vectors of the back scarp.

The stability assessment indicated the proposed road access could be re-established with a minor potential for rockfall that could be easily mitigated. Close slope monitoring was also recommended during construction, along with maintenance as needed.

5.2 End-of-Mine Planning

The potential risk of the proposed mine plan (Figure 10) for removing the toe of the slide debris of the north wall instability was evaluated by completing a three-dimensional limit equilibrium stability analysis using Slide3 (Rocscience 2018). The stability assessment considered four scenarios to evaluate the sensitivity of both the 2018 pit geometry and proposed mine plan to piezometric conditions.

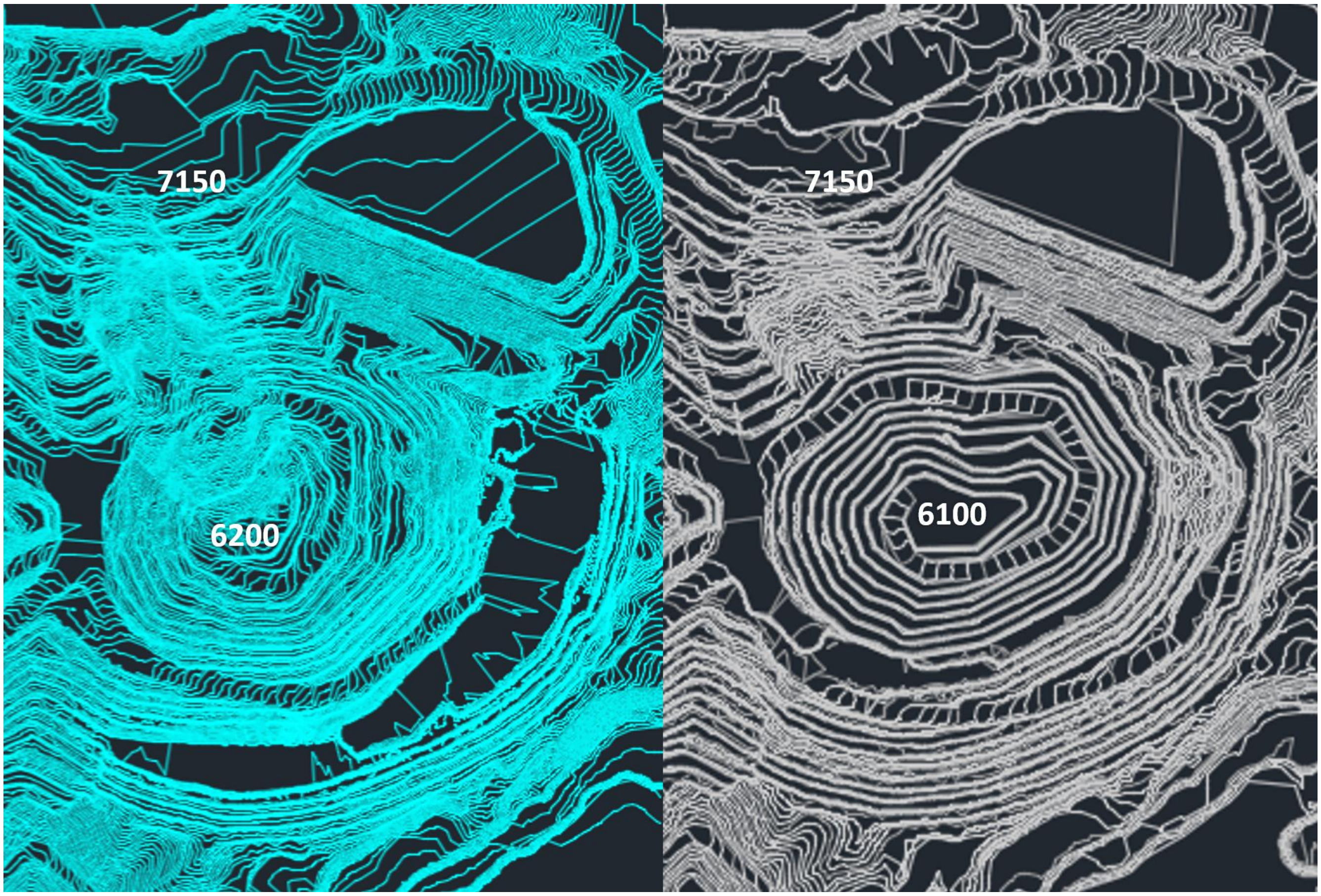

Figure 10. 2018 geometry of the pit (left) and the proposed mine plan (right).

The modeling results are shown on Figure 11 and identified areas of concern for the 2018 geometry and the proposed mine plan for mining out the toe of the slide debris. The areas of concern for the 2018 pit were the upper and middle north wall, which coincided with zones of highest displacements captured by the radar unit. The lowest factors of safety were predicted near the nose with the adjacent pit (immediately above the original haul road) and the localized back scarp (evaluated previously) for both geometries. An additional area of concern for the proposed mine plan was identified near and below the north wall nose with the adjacent pit. Figure 11 also shows sensitivity checks completed for variable groundwater conditions and rock mass strength. In addition, a simplified stability evaluation of the toe of the slide debris was also completed (not shown) and indicated that stability was marginal.

The mine re-established the haul road in late 2018 after the stability analysis and successfully completed the proposed mine plan in mid 2020. The road was well-maintained despite the continual creep deformation and the back scarp increased in height without the occurrence of significant rockfalls. A depression above the haul road formed naturally, likely due to continued downward creep of the slide debris, and became an ad hoc catch basin for the random rockfall. Implementing of a real-time slope radar monitoring system was proven to be the key to success. During mining of the north toe, monitored displacement rates reached near 30 inches per day several times and monitoring the trends provided timely guidance for pausing mining activities to prevent uncontrolled runouts.

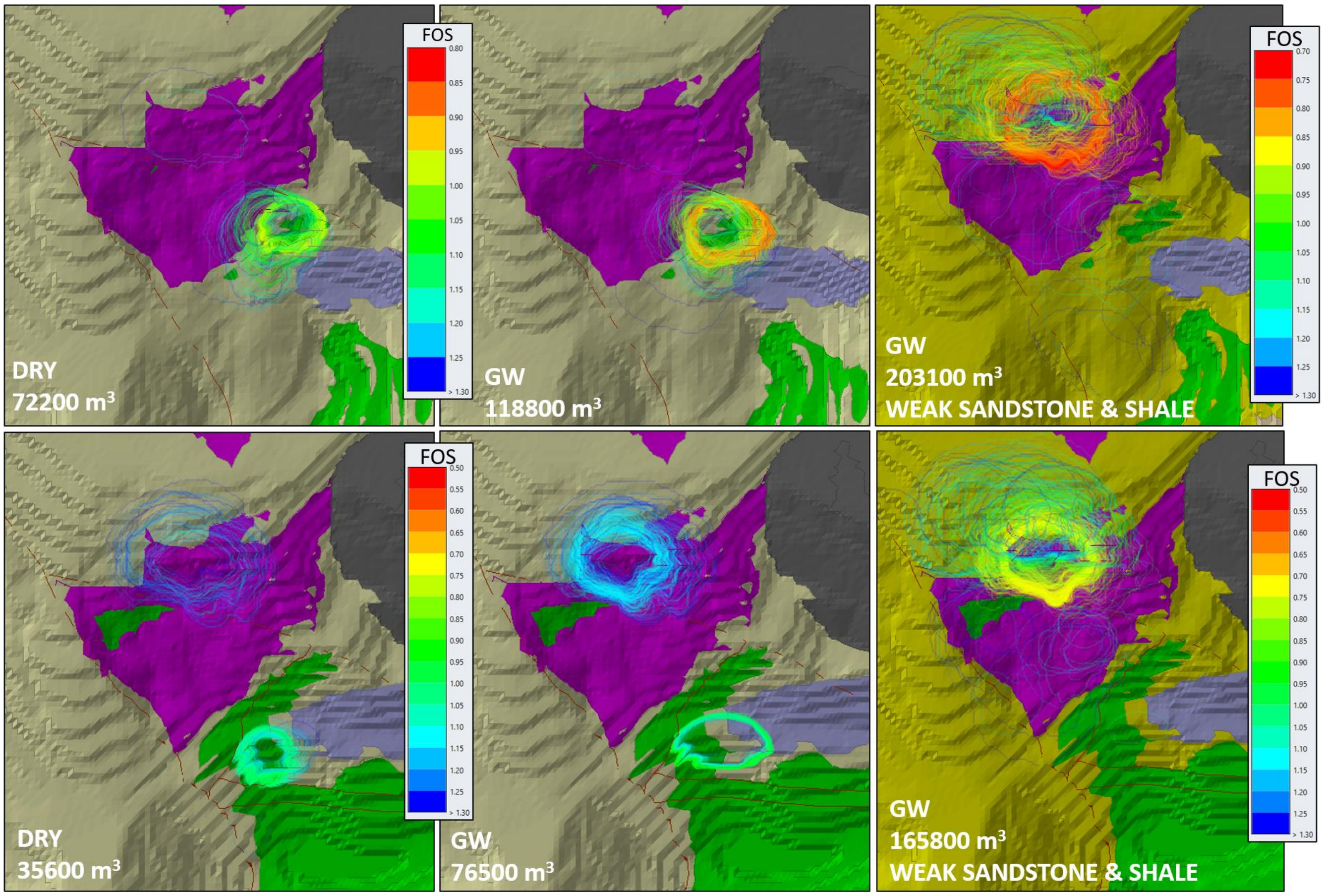

Figure 11. Areas of concern identified by limit equilibrium analysis, 2018 pit (top) and toe removal (bottom).

Attention turned to the pit's east wall since the mining strategy of the north wall was well-established. During completion of the proposed mine plan, a wall-scale instability occurred as weaker rock was exposed and an extremely wet spring elevated pore pressure conditions in mid 2019. A back-analysis of the east wall failure was completed with Slide3, which provided calibration of material strengths and piezometric conditions for the predictive analysis of the proposed end-of-mine design and the initial stage of backfill. This mine plan involved mining beyond the debris toe of the north wall instability, including the original haul road. Backfilling was to occur from a newly-established haul road along the south wall. The results shown on Figure 12 indicate stability was expected to be marginal, which implied careful monitoring and strategic mining were required to complete the end-of-mine design. The results of the initial backfill, to establish the new haul road, showed the buttressing effect of the backfill but also indicated the road switchback should be extended towards the northeast to better buttress the existing toe of the east wall instability. Elevated piezometric conditions were also shown to reduce the factor safety and improved drainage of the rock mass was recommended as a result.

Mining of the pit concluded in 2020 with the mine extracting a significant quantity of additional ore from the pit despite the excessive deformations through its mine life. The newly established haul road along the south wall buttressed the east wall instability with an initial filling direction towards the west. Backfilling from the west also began and eventually buttressed what was left of the slide debris from the north wall instability. Currently, backfilling of the depleted pit is ongoing as shown on Figure 13. Recent monitoring data indicates the instabilities have stabilized with a velocity of nearly zero. The pit was successfully rehabilitated due to the vigilant guidance provided by the mine geotechnical team through real-time monitoring and inspections, continuous maintenance, and a flexible mindset for impromptu adjustments when needed.

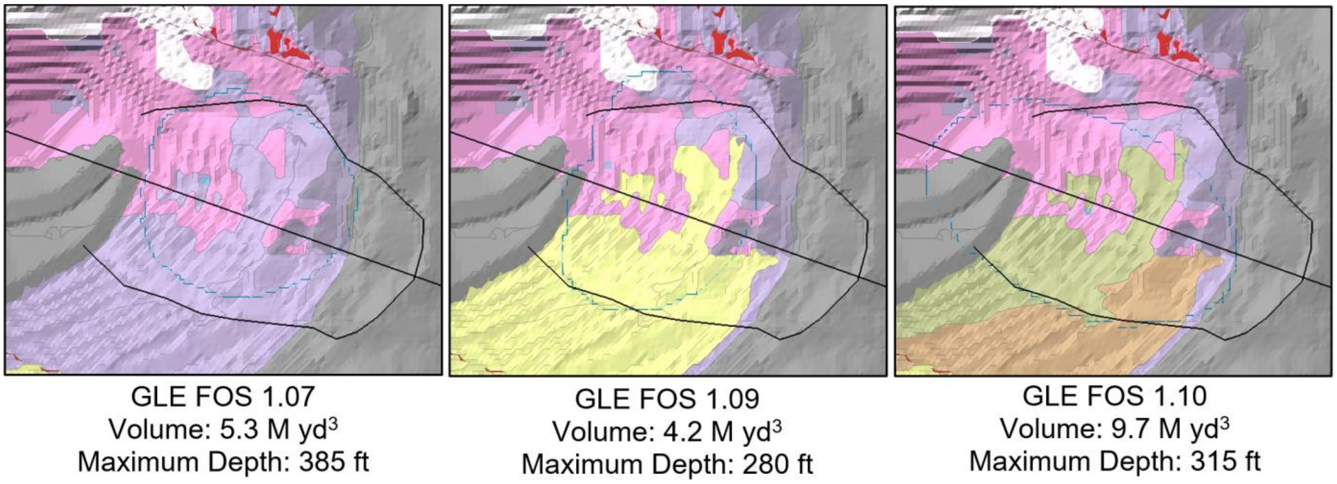

Figure 12. Factors of safety prediction for east wall failures for the end-of-mine plan with initial backfill.

Figure 13. Overview of the north wall after mine completion (late 2020).

6 Key Learnings

The key learnings from this case study revolve around the critical elements of the observational method. The mine understood the importance of managing deformations and established a monitoring system at the first sign of instability. Transition to state-of-the-art technology that provided flexibility and real-time monitoring was vital and implemented early. The site-specific data was used to develop response triggers and an associated action plan that evolved as new data became available and the understanding of the rock mass and site conditions improved. A conceptual groundwater model was developed with piezometric monitoring data that both provided insights for understanding the influence of rock mass characteristics on pore pressure build-up and dissipation, as well as providing a tool for developing dewatering targets that were refined as more information became available. The modelled pore pressure distributions were then used as inputs for slope stability assessments, which provided an important spatial distribution based on site-specific geometry and hydrogeological responses. The mine was able to adapt and pivot strategically, guided by tools like the inverse velocity method and stability assessments, to extract additional ore, all the while managing creeping wall-scale instabilities that required periodic pausing and active maintenance of key infrastructure.

The instabilities were complex due to the spatial variability of key geomechanical and hydrogeological domains but the triggers were consistent and mitigation was simple. The rock mass is weak and fragmented: alteration played a critical role, as did the faults. The faults were important boundary conditions, not only for delineating the rock mass into domains but also for controlling the kinematics of instabilities. The faults also acted both as groundwater flow conduits, including the development of artesian conditions, and barriers. Elevated pore pressures were managed through several methods and accommodated where mitigation was challenging. Step-outs were effective, as was pausing mining.

7 Acknowledgement

The permission of KGHM is gratefully acknowledged.

8 References

Itasca Consulting Group Inc. (2014). Universal Distinct Element Code (UDEC) Version 6.0 User's Guide.
RocScience Inc. (2002). RocFall Risk Analysis of Falling Rocks on Steep Slopes User's Guide.
Rocscience Inc. (2018). Slide3 2018.
Rose, N.D., Hungr, O. (2007). Forecasting potential rock slope failure in open pit mines using the inverse-velocity method. International Journal of Rock Mechanics & Mining Sciences 44: 308–20.