SSIM 2023 – PM Dight (ed.)

doi:10.36487/ACG_repo/2335_0.01

Safe management and optimisation of deforming pit walls

G Abrahams *Rio Tinto, USA*

Abstract

Deforming pit walls are not uncommon in surface mining, primarily due to the complexity and unpredictability of ground conditions. Indeed, slope deformation beyond original design expectations should not always be considered unacceptable because, if managed safely and proactively, the mining operation can continue to optimise its planned ore recovery.

Due to the significant advances in slope monitoring technologies over the last 15 years, safe management of slope deformation is now very achievable with a high degree of confidence provided that monitoring and reconciliation approaches are best practice. Furthermore, the author argues that early detection of slope deformation should also be industry standard since this allows the economic risk of any slope instability or complete failure to be assessed and then managed more optimally.

Analysis of observed slope performance provides detailed information and verification on actual geological and structural conditions, slope behaviour in response to mining, and identification of the actual failure mechanism/s. Such information cannot be expected to be available at such a high level of confidence during the initial design stage.

A detailed back-analysis of an area of deformation, obtained by both sub-surface and surface monitoring, will enable the different remediation options to be assessed. This may include continuing to mine the existing designed slope, but with Factor of Safety (FoS) below the original design acceptance criteria (DAC) and, in some cases with an FoS ≈ 1, if slope behaviour is considered to deform gradually rather than collapse catastrophically and all safety aspects are fully managed.

Review of high precision slope performance data for a historic slope should be a critical part of future slope designs to enable fully optimised slope designs. This may even enable the option to consider relaxing the DAC when the potential failure mechanism is much better understood.

This paper reviews case studies of slope deformations with very different behaviours and economic risks, and shares learnings to provide guidance on managing both the safety and economic aspects of pit wall instabilities. A proposed process flow is provided for how slope deformations should be assessed, risks identified, managed and incorporated into future slope designs and mine plans.

Keywords: *slope stability; deformation; collapse; observational mining*

1 Introduction

Deforming pit walls may be unexpected to a mine operation as it moves from design to execution, but they are not uncommon in the industry. Indeed it could be argued that slope deformations, if managed safely, are part of an optimised design.

Due to the significant advances in slope monitoring technologies over the last 15 years, safe management of slope movement is now industry standard. A thorough slope monitoring process should be part of any surface mining operation; where the rigour of the monitoring program is commensurate with the risk.

In addition to managing the safety aspects, analysis of observed slope performance provides detailed information and verification on actual geological and structural conditions, slope behaviour in response to mining, and identification of the actual failure mechanism/s. Such information cannot be expected to be available at such a high level of confidence during the initial design stage. The concept of obtaining additional geotechnical information from slope monitoring data is not new. Wyllie & Mah (2004) stated 'because of the unpredictability of slope behaviour, slope monitoring programs can be of value in managing slope hazards, and they provide information that is useful for the design of remedial work'. Furthermore, this idea of gaining knowledge from slope behaviour to modify designs as mining continues is essentially part of the observational mining approach first documented by Peck (1969).

In this paper, we review case studies to show how slope monitoring technologies can be used to manage slope failures safely and also provide critical geological and geotechnical information which can be used to optimise slope angles potentially below typical design acceptance criteria (DAC) for maximum ore recovery. For such an approach to be possible, flexibility must exist within the mine plan. A mine plan that simply cannot change with time will require slope designs to meet a higher DAC. Most importantly, throughout the optimisation process the safety risks must always be fully managed.

2 Case study 1: the O-Slide remnant

2.1 Geotechnical summary

The O-Slide remnant (OSR) is a complex instability along the south wall of the pit that sits within sercitically altered monzonite. The monzonite is highly fractured with rock quality designation values of 20–30%. It is bounded to the east by a large known fault system, and movements occur along multiple shear surfaces between 30–100 ft below the surface. Two significant faults persist through the OSR block. Rock fabric within the monzonite consists of north–south intermediate dipping sets and northwest–southeast intermediate dipping sets which result in wedge failures on a bench scale. The overall movement extends from the haul road, six benches down to the operating level (Figure 1). Design inter-ramp angle (IRA) is 38°.

2.2 Historical performance and design

In previous mining cuts, the historical O-Slide has always existed in some form and deformation has been significant. Surface water infiltration and toe mining of key blocks would accelerate slope movement. Historically, deformation of the O-Slide has been substantial (50+ cm per year) but it had never collapsed catastrophically. In 2019, a step-in at the toe and large buttress was constructed to prevent slope acceleration. This historical knowledge was critical for allowing a future design to proceed despite having a Factor of Safety (FoS) ≈ 1 (discussed later in the paper).

Historical data was used in the current design factoring in sub-surface shear locations into stability models. FLAC3D models did identify the broad OSR instability area, however, the strength reduction factor (SRF) was approximately 1.2 and the design was considered stable.

2.3 Early detection

Two to three small bench failures did occur within the OSR as mining progressed. These were remediated with 'dozer trims' which is essentially mining out most of the failed material and trying to get behind, or close to, the failure surface. Low-level movement rates, around 0.2–0.3 in/day (5–7.6 mm/day), were detected in live radar, GPS and prism data.

Dissection of the radar monitoring data showed several moving areas within the OSR block. These areas would move with different orders of magnitude but responded and moved together. Separate radar shapes and names (Tuchel, Organa and Gunhorn) were given to each area (Figure 1). Analysis of each individual area and the response spatially to blasting and mining was important for identifying new structures and determining the failure mechanism (discussed in Section 2.5).

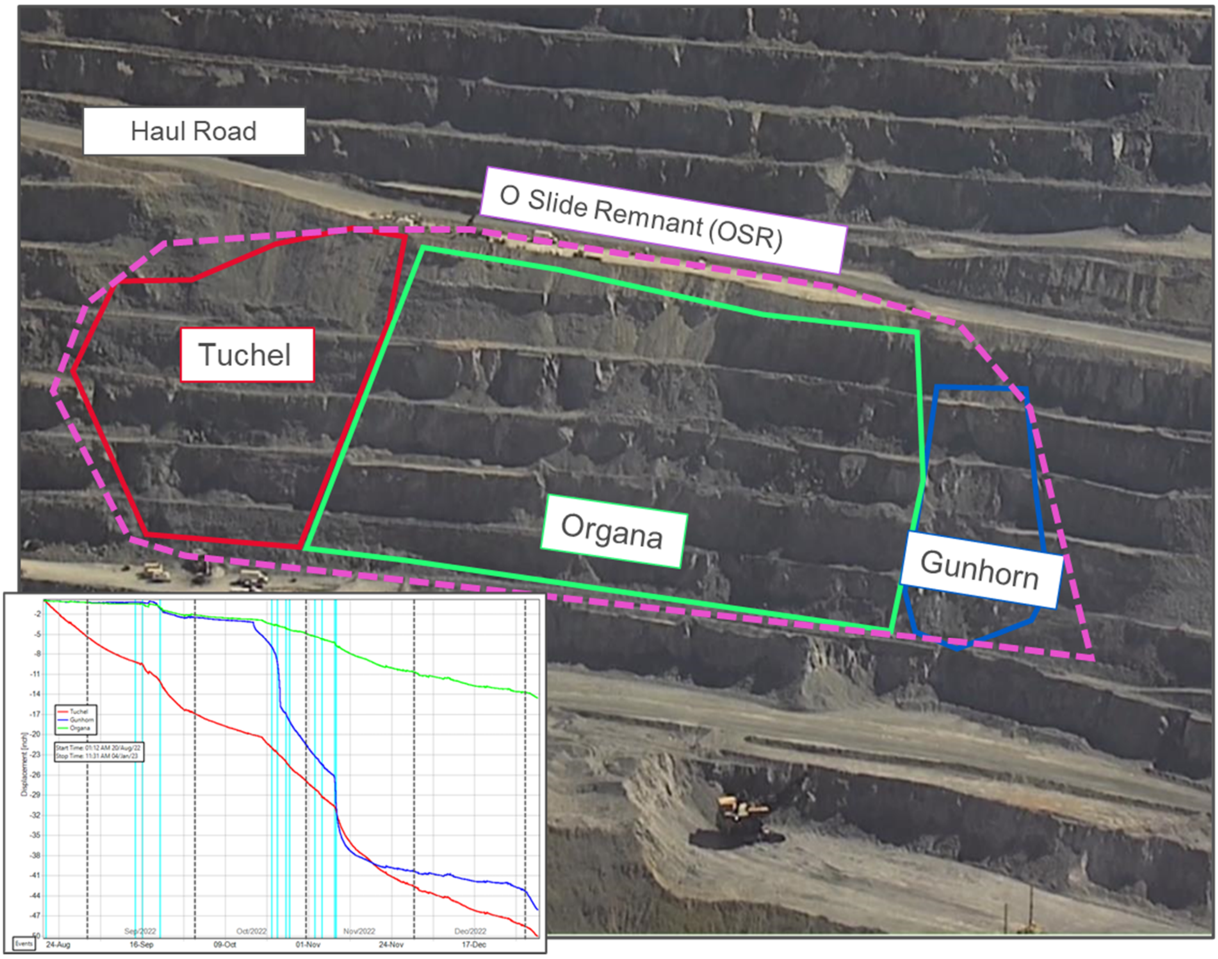


Figure 1 Radar data showing different movement zones within the O-Slide remnant block. Time series data for each zone is shown on the bottom left. Vertical blue lines are rainfall events which were a clear cause for slope acceleration, in addition to blasting and toe mining

2.4 Safe management

In January 2023, increased movement rates were observed following heavy precipitation events and a trim blast at the toe. The area remained isolated for two days until rates became regressive; then mining of the blasted muck was allowed to resume. During mining, slope acceleration occurred again and a larger movement area was detected. This movement extended further south and up to the main haul road. A runout analysis was conducted using DAN3D to guide isolation extents.

The velocity ratio (current velocity/previous velocity) was calculated at 1.3 over six hours. Inverse velocity plots averaged over three hours were noisy, but indicated a possible failure within two days. Time series radar data of the movement is shown in Figure 2. The area at the toe and the haul road above were isolated which meant no ore delivery during this time.

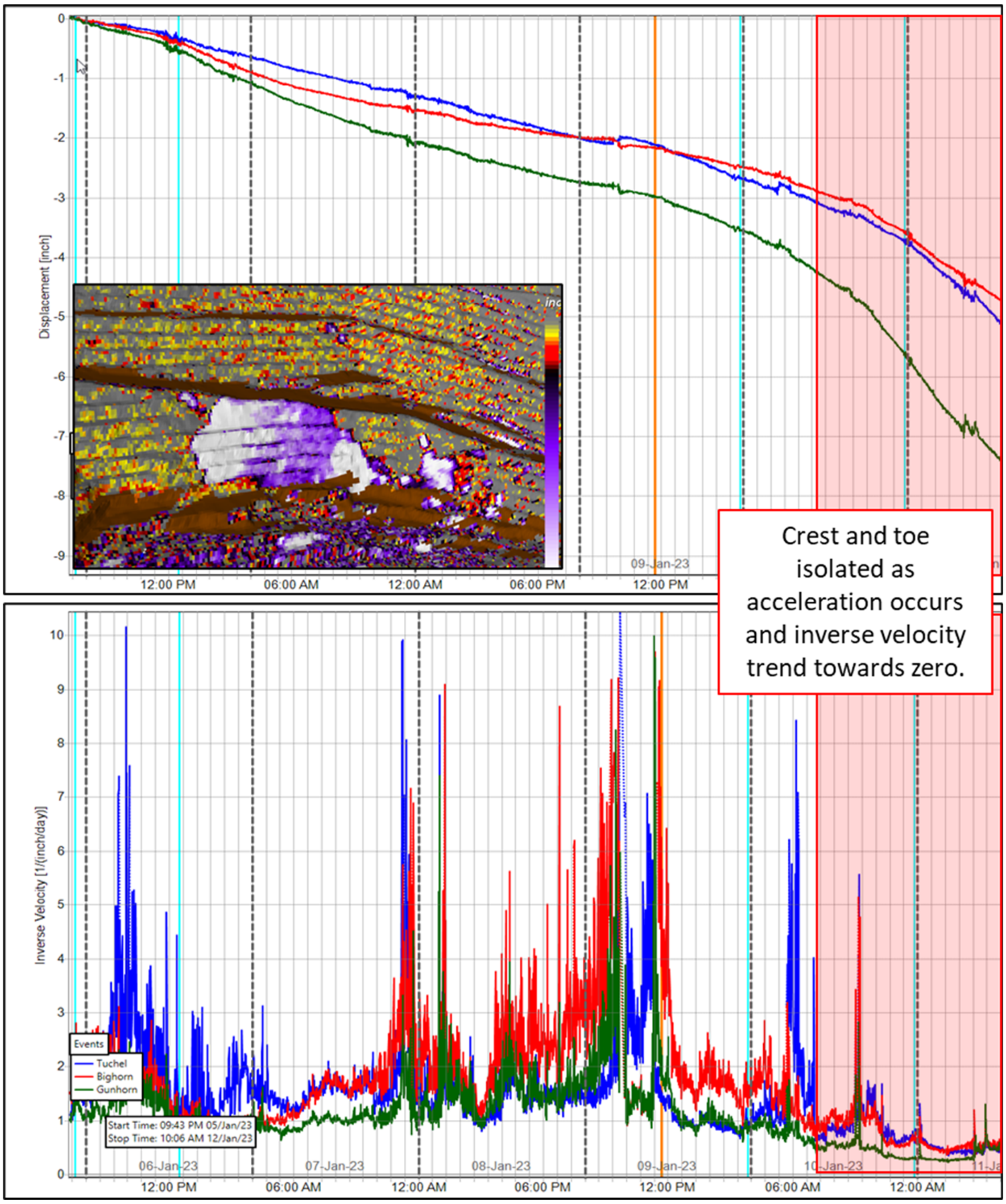


Figure 2 Deformation and inverse velocity plots for O-Slide remnant five days prior to isolation

The slope never did collapse, nor did it reach phase ambiguity (phase ambiguity is discussed in Section 5.1.4). Regressive trends were observed two days later (inverse velocity plot also flattens off) and access to the cut was re-opened. Significant deformation did occur within the rock mass itself and was observed as vertical cracking in the bench faces and as cracking in the outside of the haul road.

2.4.1 Notes on making the isolation decision

There was a strong view within the geotechnical team that the OSR would not collapse in a catastrophic way; more that it would continue to deform and then exhibit regressive behaviour. This view was based on:

- Inverse velocity plots having a shallow gradient.

- Historically, the O-Slide has never collapsed catastrophically. Instead, deformation has been significant, thus reducing potential kinetic energy build-up which could release giving rise to a more catastrophic event.

However, in such situations where there is always a significant degree of uncertainty, and safety must not be compromised, the decision was made to respect the observed acceleration and inverse velocity trends and still isolate the area. The decision carried a lot of weight due to the production impacts associated with it. All underground mining had to stop and personnel evacuated, in addition to all surface mining personnel below the haul road. Knowing that a collapse was unlikely but still evacuating the pit is not an easy position to be in. When communicating this action to the mine general manager and managing director, open transparency behind why and how the decision was made provided clarity. Expressing the degree of uncertainty but stating the 'what-if' case and safety implications helped gain support.

2.5 Slope optimisation and re-design

This section discusses how monitoring data was used to determine the engineering geological mechanism and the optimised design for managing the slope movement.

2.5.1 Observations and analysis from monitoring data

Radar data was draped over a 3D photogrammetry drone flight and geological and structural data was added. Sharp contacts of the radar data showed that additional structural controls existed which had not initially been identified at the design stage (Figure 3). Some of these controls were planar faults within the intrusive unit; others were faulted lithological contacts between intrusives and limestones. These structures could then be added to the structural model and characterised in the field.

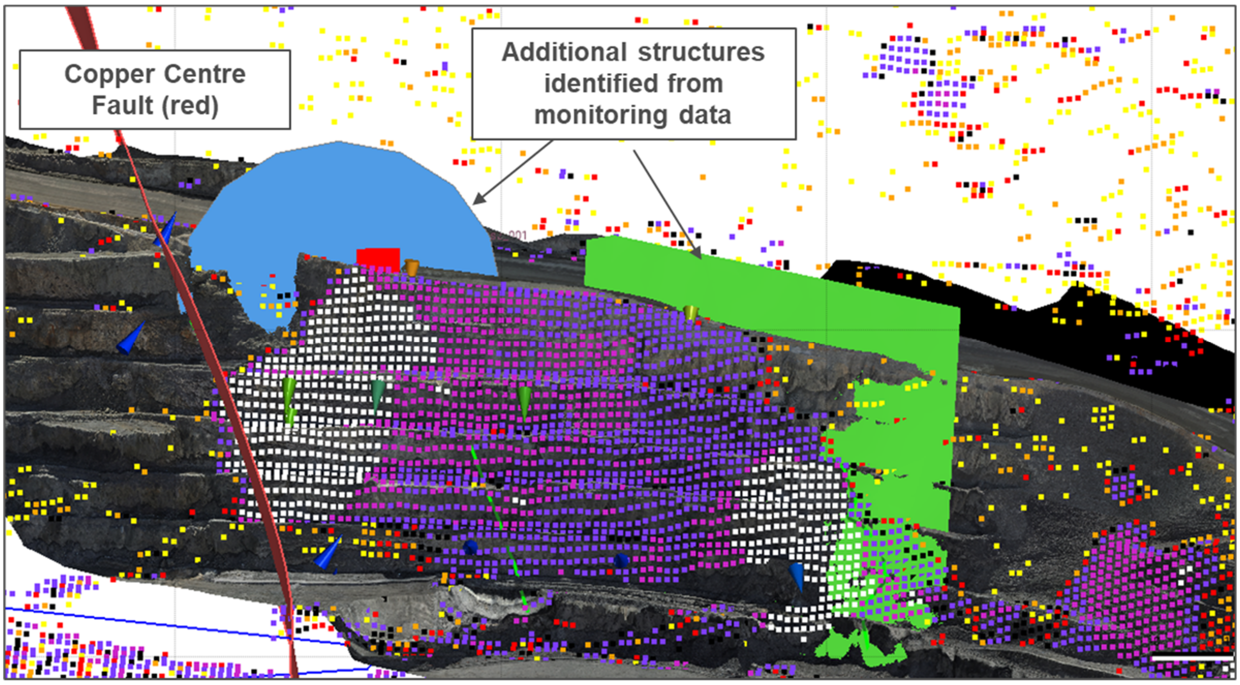


Figure 3 Draping georeferenced radar data of 3D drone flight allowed identification of additional controlling structures that were built into updated structural model

Review of mining sequence and shovel position with radar data also showed how sensitive the OSR was to mining in specific locations, and these locations coincided with the newly identified structure (Figure 4). Field characterisation of the structure was undertaken and it was then added to the structural model.

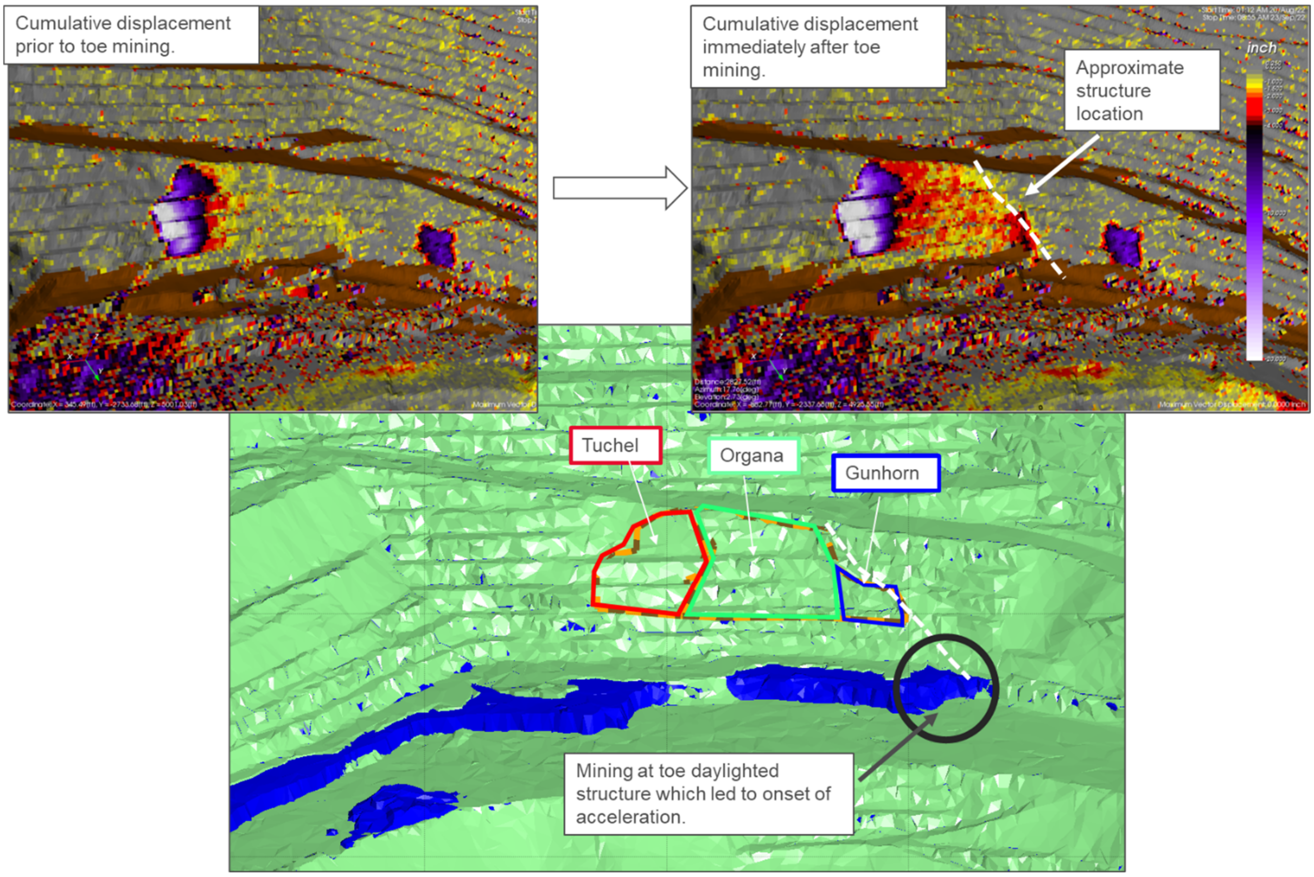


Figure 4 Comparing radar data with mining locations to show acceleration following removal of material which then daylighted a key structure

Sub-surface instrumentation consisting of shape axial arrays (SAAs) and time domain reflectometer (TDR) cables was added at crest and toe of area once movement was identified. Shear locations were reviewed to further identify and confirm locations of structures and shear surfaces at depth. Displacement data from SAAs was plotted against surface displacement data to assess movement throughout the block.

Visually, the rock mass could be seen breaking apart over time with vertical cracking appearing in the bench faces. This was a result of extensional movement along the northwest–southeast striking joints as the slope dilated.

2.5.2 Economic risk assessment of future instability

An economic risk assessment involved reviewing production impacts caused by continued slope movements and by potential collapse. These are summarised in Table 1.

Table 1 Summary of production impacts as a function of continued deformation compared to slope collapse

Type of movement	Production impact
Continued deformation with localised periods of acceleration	Periodic isolation required of entire lower pit and underground during acceleration periods Pausing for several days after blasting at toe
Collapse	Loss of all or part of haul road Dilution and sterilisation of ore

Evaluation of the production impacts and the risk to the haul road above, led to the decision that a slope re-design was required.

2.5.3 Remediation and re-design: mining a slope with Factor of Safety ≈ 1.0

The proposed re-design consisted of a step-out at the current elevation with a buttress built to provide toe support. Below the step-out, the IRA would be reduced from 38° to 34° and stack height limited to five benches. The re-design would defer ore to the next cut; however, the difference in net present value (NPV) was within the 'noise' of economic and scheduling model predictions and therefore not considered significant in comparison to the risks identified with mining the current design.

Despite the shallowing of the IRA, deformation of the slope was still expected per the following comments:

- A back-analysis of the failure mechanism was undertaken in Slide 3 and RS3 using the revised structural and geological inputs from the monitoring data. The model was well calibrated with current movements and then used for input into forward analysis.
- Results of the models showed FoS/SRF <1.0 and that deformation would occur. This agrees with what has been observed in the current and previous cuts. Strain of approximately 0.4% was observed in 2019 and up to 6% was observed in this cut without any collapse; which provided further confidence the slope would deform but not fail catastrophically.

Catastrophic collapse of the slope is not expected to occur based on historical performance of continued deformation and dilation of the rock mass. That is not to say it would definitely not happen. Controls put in place to manage this deformation during mining included:

- Safety aspects of a potential collapse would be managed through rigorous slope monitoring program, with redundancy built in, and a trigger action response plan (TARP).
- Production delays were built into the mine plan for when acceleration may occur requiring isolation; pauses after blasting to evaluate slope response; and to grade and potentially fill the haul road above as a result of movement below.
- Blasting controls to reduce slope response: vibration control timings to keep frequencies above 20 Hz and peak particle velocities below 3 inches per second, light charge weights, increased stand-off distances between buffer row and design toe.
- Horizontal drilling to continue depressurisation.
- Continued monitoring coverage and addition of sub-surface instrumentation on the extra-wide benches.

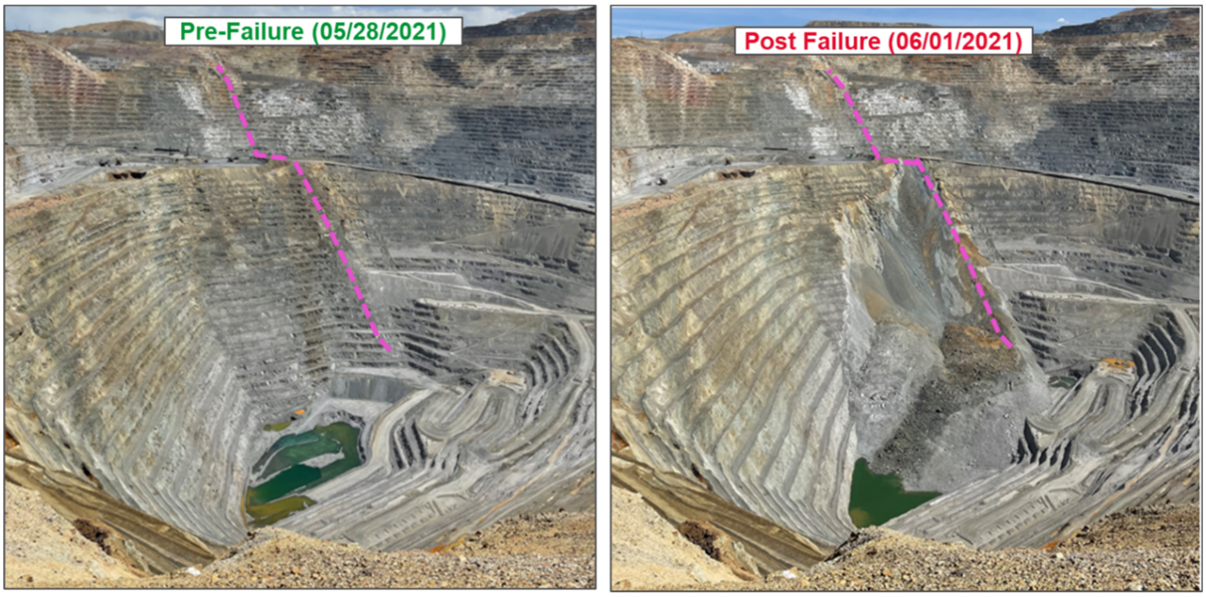
3 Case study 2: southeast wall of the Leo slide and Revere unload

This case study provides an example of:

1. Safe management of a large, more brittle slope collapse.
2. How analysis of deformation behaviour from the slope collapse was then applied to design and manage the economic risks of a large moving area (the Revere) in the subsequent pushback.

3.1 Summary of the Leo failure

On 31 May 2021, the Leo slope sector (southeast wall) of the Bingham Canyon Mine collapsed. The failure was 1,500 ft high and 1,500 ft wide and involved around 21 Mt of rock (Figure 5). The IRA was approximately 36°. The Leo failure was controlled on the western side by the Lark Fault. This is an extensional bedding fault that persists over 2,000 ft up the south wall. The fault contains low plasticity clay and varies from around 3 ft to 4 in in thickness. The eastern release of the failure consisted of a step-path propagation along smooth orthogonal joint sets within the (PQM) unit. At the toe, the failure propagated through monzonite rock mass.



(a) (b)

Figure 5 The southeast wall (a) before and (b) after the Leo collapse. The Lark Fault is shown in pink

3.2 Early detection

Movement within the Leo sector had been identified one year prior to collapse. During this time, monitoring data was continually reviewed and geological, structural and rock mass models updated following similar approaches as those presented in OSR case study previously. Failure mechanism were interpreted and back-analysis models attempted and continually refined.

Monitoring coverage consisted of:

- Reasonable prism coverage with limited numbers in the Leo centre and top sectors. The robotic total station was positioned at pit bottom with good line of sight.
- Five radar units to provide coverage of the whole slope area and redundancy as needed.
- Sub-surface instrumentation was not available with one TDR installed on 10 February 2021 at the southwest toe area of the slope (this subsequently sheared).

Early identification of deformation led to development and implementation of an area-specific TARP five months before failure. Key parameters used were velocity, velocity ratio and inverse velocity. TARP triggers and responses are summarised in Table 2. Removal of critical infrastructure and re-alignment of the haul road away from the crest area was done three months prior to collapse.

Table 2 Summary of trigger action response plan (TARP) triggers and responses for Leo movement zone

TARP level	Trigger	Response
1	Velocity <0.07 in/day	Mining with monitoring review after each bench
2	Velocity >0.07 in/day	Mining pause to allow slope to relax
3	Velocity > 0.5 in/day Velocity ratio >1.5	Isolation of toe
4	Inverse velocity shows failure within 3 days	Extended isolation of toe and crest far beyond worst case modelled runout analysis predictions

36 Mt of ore were mined from the Leo sector since detection of initial deformation and prior to slope collapse through rigorous slope monitoring and mining pauses as required (which were part of the TARP). The failed mass consisted of predominantly high grade ore and as such the economic impact of the failure was positive in terms of free cash flow over the next five years.

3.3 Safe management of the collapse

Figure 6 shows radar data seven days prior to collapse, along with when each TARP level was actually triggered. The TARP 4 isolation trigger was initiated slightly earlier than dictated by the TARP (around 3.5 days to predicted time of failure) to coincide with evening shift change, i.e. no night shift work would be undertaken in isolation areas. The accelerating trends looked very convincing, and it was considered easier to evacuate in daylight than coordinate an evacuation six hours later during night shift. The isolation extents were increased to include the entire of the lower pit and the underground operations. It took three hours to fully evacuate equipment and personnel. There were no fatalities, injuries or mobile equipment damage from the collapse.

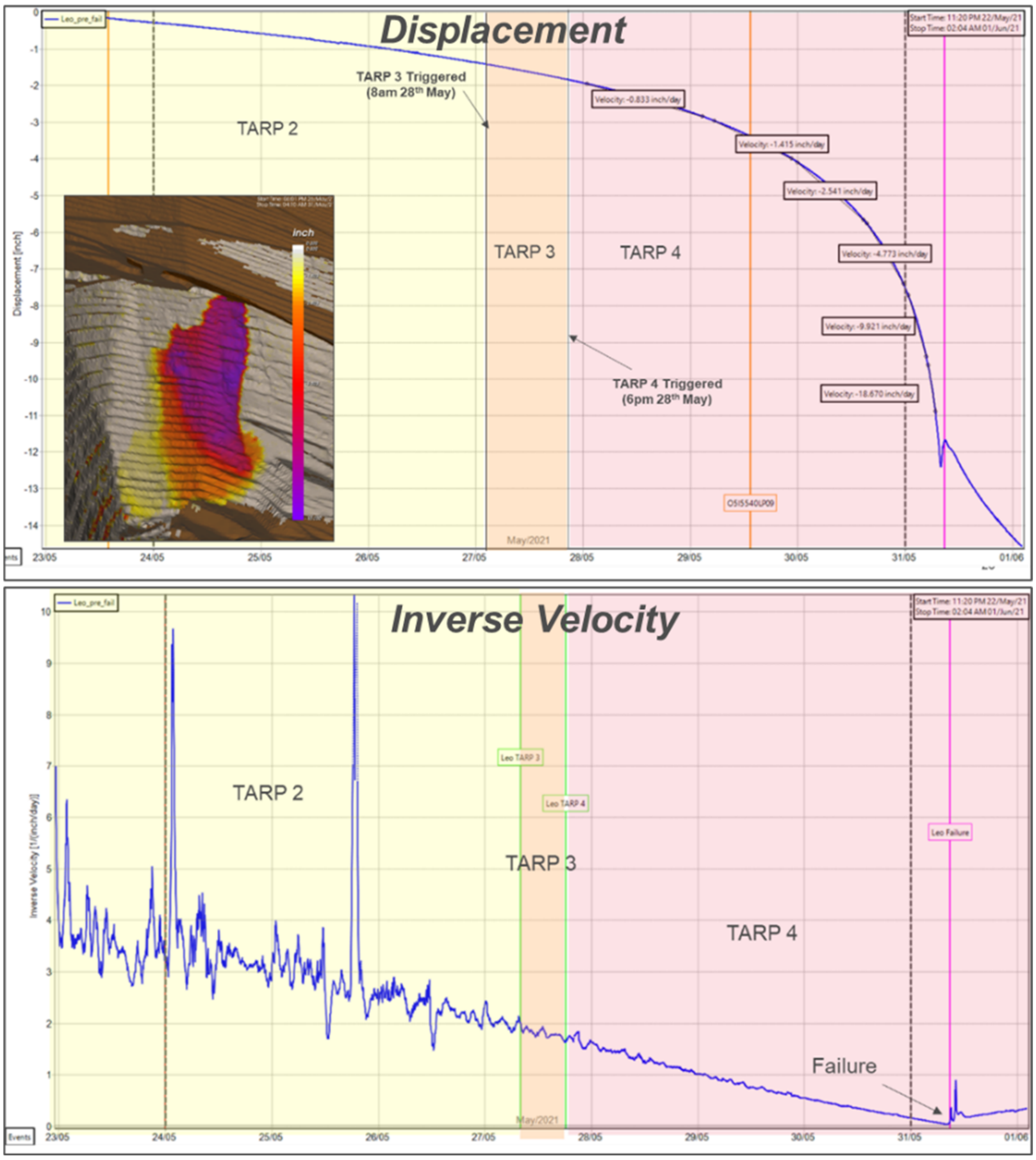


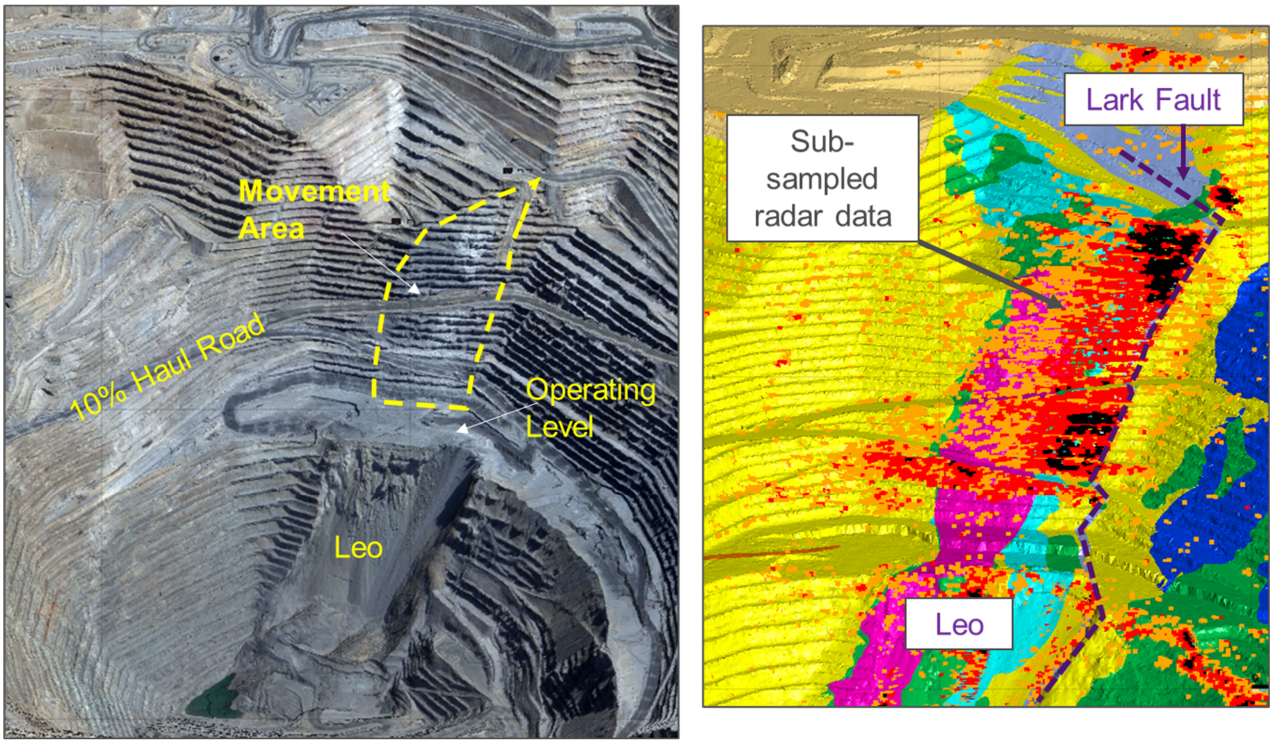
Figure 6 Deformation and inverse velocity plots for Leo, seven days prior to collapse. The time each trigger action response plan (TARP) level was triggered is shown in the background. Note that TARP 3 lasted less than one day before TARP 4 was triggered. Note the steep inverse velocity gradient compared to that of the OSR in previous case study

3.3.1 Looking back on managing the collapse: author's comments

Isolating a large operation can be an intimidating decision to make. At the time of isolation, there was uncertainty regarding what a failure would actually look like, i.e. would it collapse or would it just slump slightly? If the latter, would all this isolation effort and production loss be considered an overreaction? In retrospect, the dramatic collapse of the Leo justified the early isolation and extended isolation boundaries, but what a collapse will actually look like is rarely known ahead of time.

3.4 Key learnings and application to the next pushback

The subsequent pushback above the Leo failure was being mined concurrently. The same structural controls existed in this cut back potentially creating a very similar failure mechanism with movement being controlled by the persistent clay-rich Lark Fault. Early detection from sub-sampled radar, InSAR, prisms and GPS identified a large, very slow-moving mass in the next cut that appeared to replicate the Leo mechanism (Figure 7).



(a) (b)

Figure 7 (a) Location of moving area in the next cut above the Leo failure; (b) Sub-sampled radar data draped over geology model shows movement controlled by Lark Fault

Economic impacts of such an area collapsing were potentially extremely impactful on the operation. A collapse would take out two haul roads and bury significant amounts of ore. Following this economic assessment, it was considered that this area could not be allowed to progress to failure.

Careful assessment of the Leo deformation trends one year prior to failure were examined (Figure 8). The following observations were noted:

- Several cycles of progressive–regressive behaviour with small amounts of deformation occurred prior to onset of acceleration that led to collapse.
- A small trim block was blasted and mined in March 2021 which caused a very slight acceleration (to rates of only 0.08 in/day), but this likely triggered irrecoverable acceleration to failure.
- The Leo collapsed at a relatively low strain of approximately 0.6%.

- At a slope height of 1,500 ft and slope angle of 37°, the slope was clearly unstable. Keeping the next pushback below that slope height–angle relationship would be required.

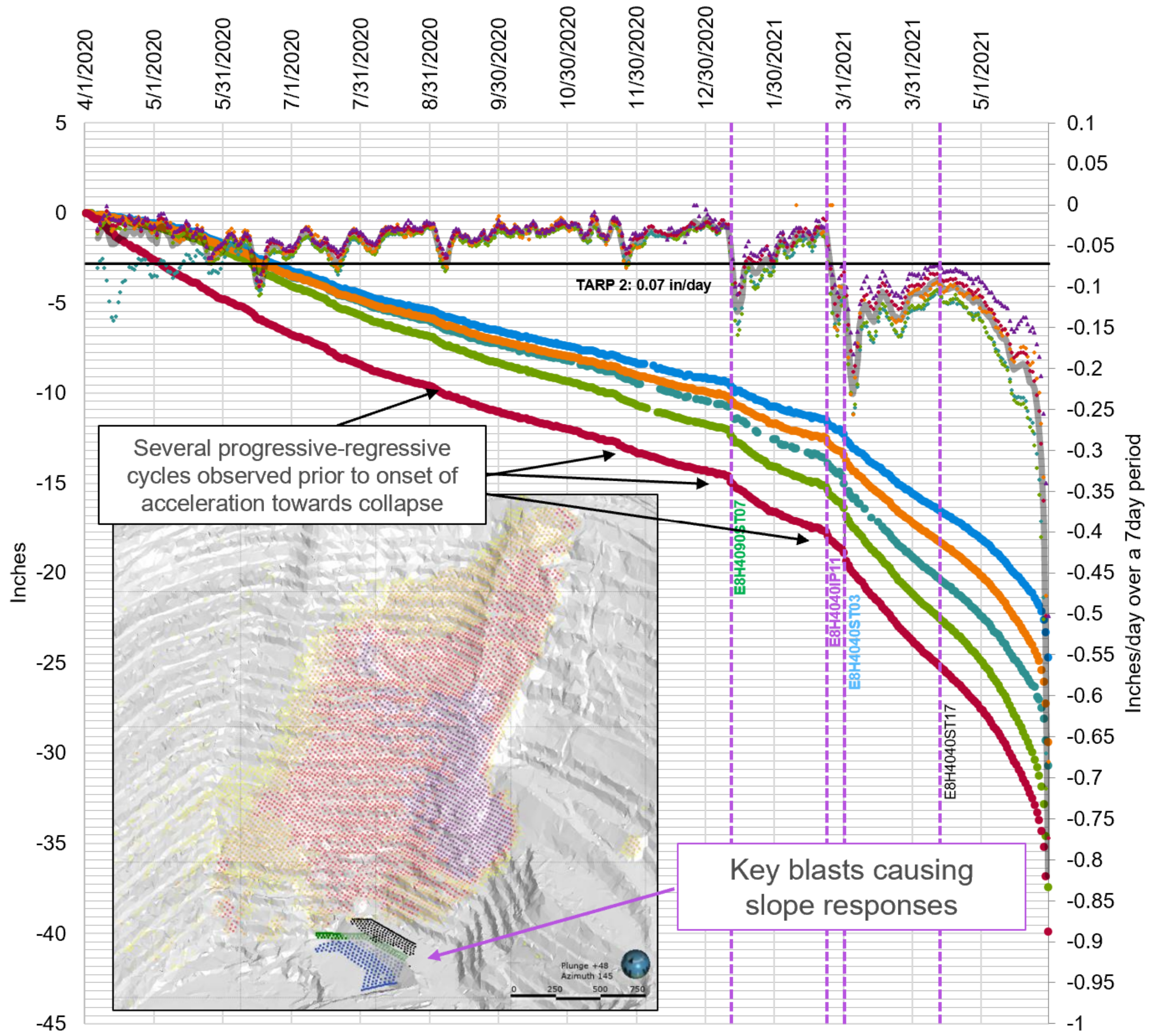


Figure 8 Prism data showing deformation on left axis and seven day velocity on right axis. Clear progressive–regressive cycles of deformation were observed during blasting and mining of the Leo prior to collapse. However, the actual velocities during these progressive cycles were relatively low prior to the onset of failure

These learnings were applied as a proxy to the new moving mass above which led to the following actions:

- Very tight TARP trigger levels had to be applied so as not to mine a 'key block' which then resulted in slope failure several months later.
- A 250 ft step-in was taken following acceleration in slope deformation and movement rates reaching approximately 0.1 in/day. While this is still a relatively low deformation rates, given the brittle behaviour of the Leo, this was considered the most appropriate response to manage the economic risks. A buttress was then constructed on the step-in to further reduce slope deformation.
- Unloading of the crest as mining at toe progresses to ensure slope height does not get to critical level.
- Shallowing the IRA from 36 to 34° in the current wall.

The actions above allowed the south wall deformation area to decelerate and show regressive trends in all instrumentation. Mining is able to continue below and continuous ore feed can be provided from the cut.

4 Case study 3: upper slice 2 wall, 5 bench instability

This case study is used as an example of a moderate-sized instability which progressed to failure relatively quickly and then was remediated as part of contingency planning built into the annual mine plan.

The instability referred to as the 'Chiefling' failed on 24 January 2022 at approximately 1:50 pm. The failure was predicted using live radar monitoring and the area below fully isolated prior to collapse. The failure was approximately 300,000–400,000 tonnes (Figure 9). This specific failure was not anticipated at the design stage primarily because the right release structure and lithological variability were not identified in the structural and geological models. However, the possibility of inter-ramp scale failures of a similar size were highlighted in the design work. This led to development of an 'optimised' and 'base case' slope design (discussed in Section 4.4).

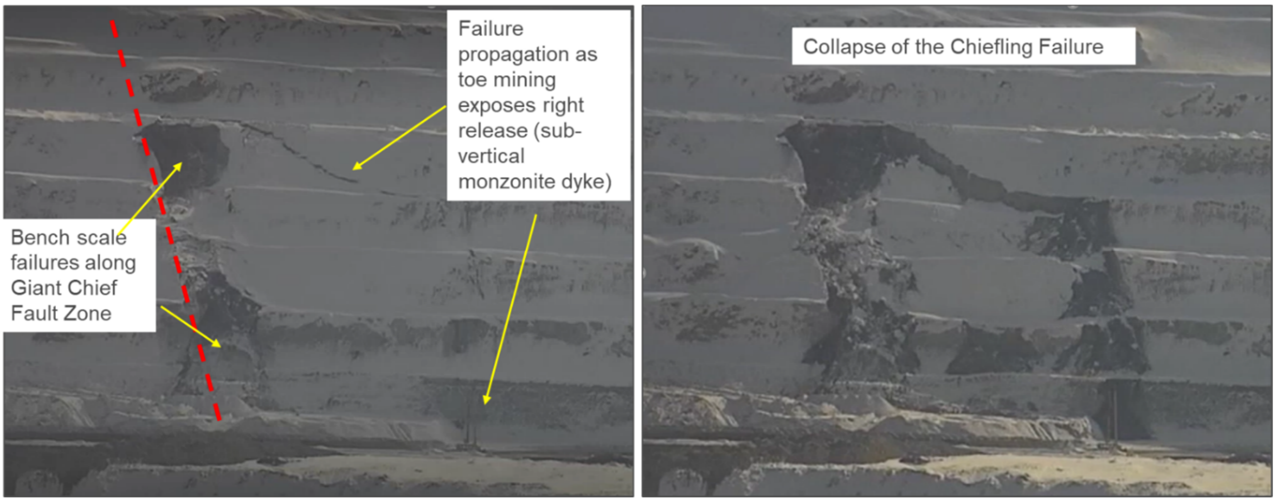


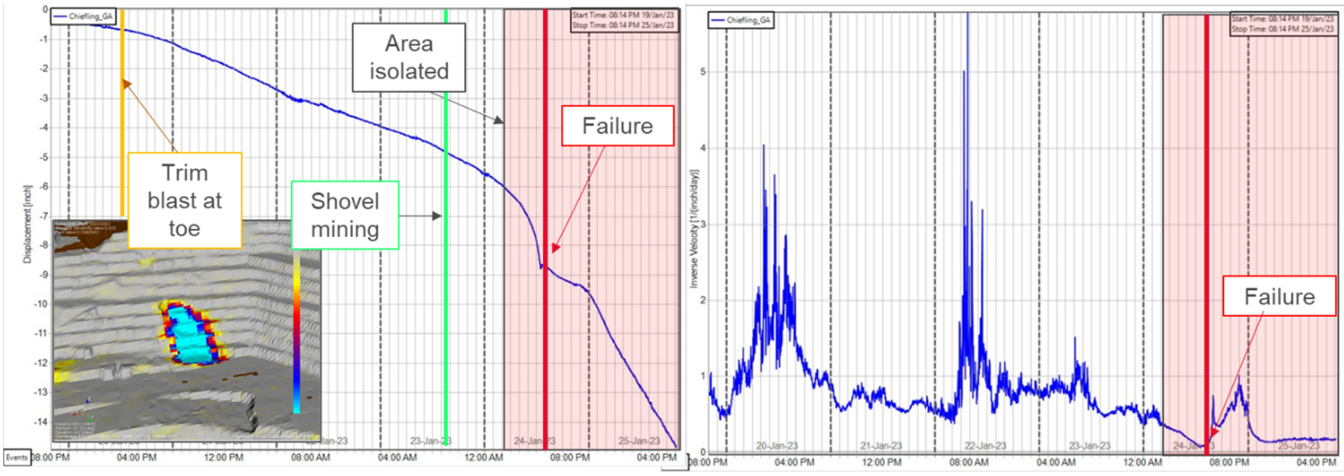
Figure 9 The Chiefling failure was structurally controlled on both sides with weak rock mass failure through the toe

The slope was five benches, 250 ft tall, 300 ft wide and failure surface approximately 50 ft depth behind slope based on measured back scarp height. Movement was controlled by a large, previously known lateral fault system to the east (Giant Chief Fault), together with intermediate bedding dipping slightly steeper than the IRA and then a faulted intrusive dyke on the western side which also provided lateral release. The dyke was not known about prior to movement. The rock mass comprised weak altered breccia and weak sedimentary units.

4.1 Safe management

Bench scale instabilities had been observed along the Giant Chief Fault as mining progressed. When the slope was five benches high, trim blasting at the toe caused slight acceleration. Toe mining right to left of the trim shot then exposed the monzonite dyke which was the right lateral release. This caused further acceleration observed in radar data. The area was rapidly isolated and failure occurred approximately 24 hours later. Deformation and inverse velocity plots from radar data seven days prior to failure are shown Figure 10. In this case, an area-specific TARP had not been developed due to relatively rapid onset of acceleration. Instead the previously developed pit-wide TARP was followed in combination with site experience for identifying and predicting slope movements and collapses.

After collapse, the slope continued to deform and the rock mass disintegrate. Over seven feet of deformation occurred in six days after initial failure. In order to keep mining below, a slope re-design was required.



(a) (b)

Figure 10 (a) Deformation and (b) inverse velocity plot five days prior to failure. The initial onset of acceleration can be seen after blasting. Shovel mining caused the rapid acceleration which led to collapse approximately 24 hours later

4.2 Geological and structural model update

Slope monitoring data was draped over a 3D photogrammetry drone flight model of the failure. Existing geology and structural models were incorporated and verified against field and monitoring observations. Mapping of newly identified structures was then possible and built into the 3D model. This work identified the previously unknown right release to be a 50–100 ft thick sub-vertical monzonite dyke with a faulted contact of low friction material. The back release was a series of steep to intermediate dipping joint sets that were able to connect between the Giant Chief Fault (left release) and the monzonite dyke. Within the failure, a previously unknown, very weak, altered breccia pipe allowed the failure to collapse through the toe.

4.3 Remediation and slope re-design

The remediation design was to cut out as much of the failed material as possible and leave a shallower slope in place. The design consisted of 55° bench face angle at the top, then a 32–34° face in the centre and leaving a 37° (approximate angle of repose) buttress at the toe (Figure 11). This was made possible by the extra-wide geotechnical bench that existed as part of initial slope design at the failure crest. This remediation work is done by dumping in material from the crest to build-up a working platform for dozer and hydraulic.

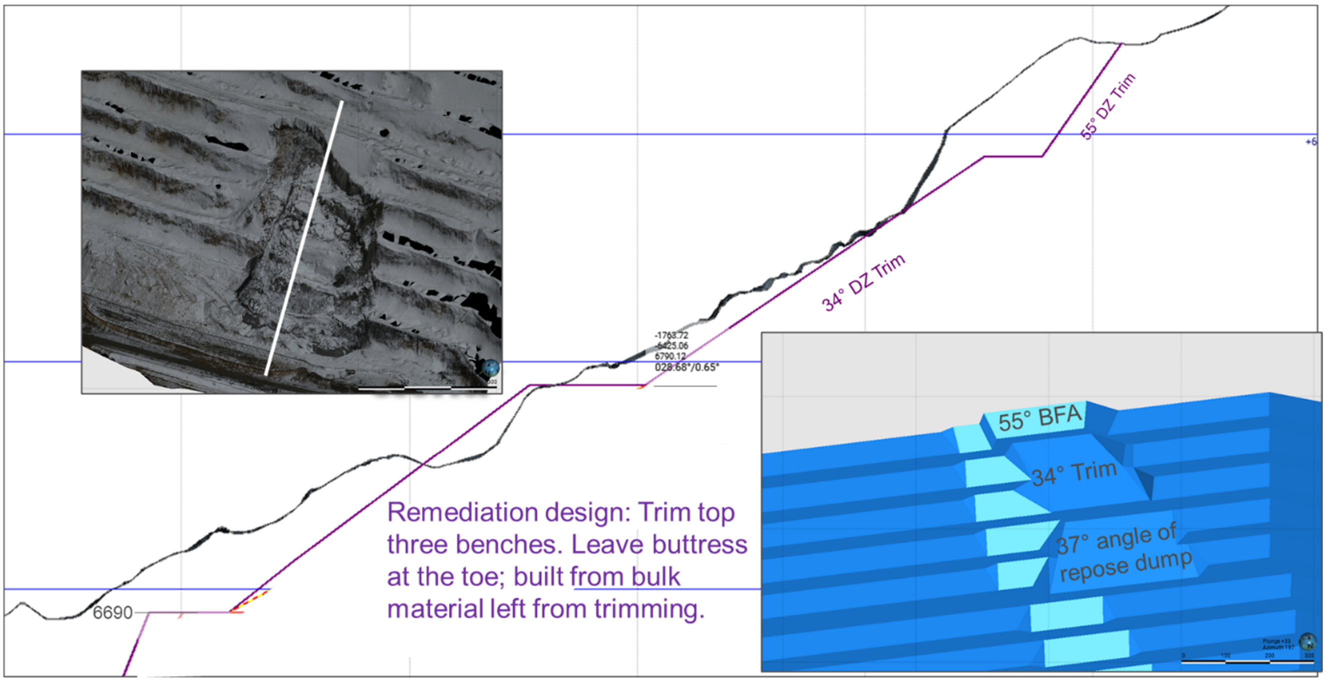


Figure 11 Remediation design of the Chiefling failure. Shallowing the slope using dozer and excavator (DZ Trim) reduces the chance of future instability by getting behind or close to existing failure surface

4.4 Mine planning and geotechnical contingency

Contingency for this mining cut was built into the mine plan in two ways:

1. The design slope IRA of 36° was considered as an optimised case; that is, the NPV value was built on a base case of shallower IRAs, but the optimised case would be mined initially such that any additional ore recovered was considered as an upside. The slope could be reduced to the base case, if wall performance was not considered suitable.
2. Allocation of 'geotechnical tonnes' into the annual plan. These tons are spread out evenly month-by-month to allow for remediation work of minor to moderate-sized failures. Note that this approach would not work for a large slope collapse.

5 Learnings and key points

5.1 Safe management

With the advancements in technology over the last 15+ years, it is an industry expectation that all slope failures should be managed safely. Regarding defining a procedure as such, it is considered dangerous to recommend a process flow or 'procedure' for safe management for the following reasons:

1. The geological and rock mass conditions are typically different and thus the failure mechanisms and slope behaviours are different at each site and within different domains.
2. The ability of each mining operation to respond to a slope movement will vary; as will the location of personnel and equipment on the ground at a given time.
3. The experience of the geotechnical engineer/s will vary at each operation.

However, based on the author's experience of managing slope instabilities and the case studies in this paper, the following comments and guidelines can be made.

5.1.1 *Development of area-specific TARP*

The TARP should be the over-arching document that prescribes all the aspects of both safety and economic management of a deforming slope. The TARP is not a generic one, but specific to the instability failure mechanism and geological controls. Broadly speaking, TARP levels 1 and 2 will be economically focused; that is the triggers are tight and relate to early detection. The responses involve understanding the failure mechanism and then implementing controls and design changes to prevent a collapse. TARP levels 3 and 4 will relate to safe management of a slope deformation that is trending to collapse.

It may be that early detection is not possible for all failures. Some may develop with little warning and progress to failure within days. In this case, it is necessary to always have a site-wide TARP with guidelines on isolation triggers (typically TARP levels 3 and 4). Several papers and publications exist with good information on TARPs and TARP development, including *Guidelines for Slope Performance Monitoring* (Sharon & Eberhardt 2020) and work by Bakken et al. (2020).

5.1.2 *Runout analysis and isolation extents*

Once a moving area is detected, a runout analysis should be conducted to guide isolation extents. Failure depth from sub-surface instrumentation is useful in defining estimated failure volumes. A Fahrboschung approach and a 3D analysis provide good estimates. A large amount of contingency must be applied when defining actual isolation extents to be used in the TARP. There will always be varying amounts of unease within an operational workforce and this further amplifies the importance of extending isolation boundaries far beyond any worst case runout prediction.

5.1.3 *Isolation triggers and operational responses*

Triggers used for safe management are typically velocity, velocity ratio and inverse velocity. The applications of these are discussed in the following sub-sections:

5.1.3.1 ***Velocity***

Specifying a velocity as a trigger is extremely arbitrary and should not be used by itself for safe management even if the geotechnical engineer has a thorough understanding and monitored history of the failure. Furthermore, the value used will depend on the instrumentation and line of sight. However, with experience, suitable values can be obtained which may relate to acceleration towards failure.

5.1.3.2 ***Velocity ratio***

Velocity ratio is an extremely powerful trigger as it can be effective regardless of the failure mechanism or historical knowledge of the slope behaviour. Velocity ratio essentially defines the onset of acceleration and then how that acceleration continues with time. As general reference, velocity ratios of 1.3–1.5 provide good triggers for isolating areas.

5.1.3.3 ***Inverse velocity***

Inverse velocity is a widely recognised approach for prediction. On this subject, Dick et al. (2014) suggested that the linear-fitting procedure should only include data following the identification of onset of acceleration (OOA) points. They also advised that additional fitting should be performed if a trend update point, i.e. significant change in the acceleration trend, is detected. The author, broadly speaking, agrees with these suggestions and makes the following additional comments:

- A steeper gradient and smoother inverse velocity line may indicate a more brittle collapse.
- Conversely, a shallower gradient and 'noisier' inverse velocity line indicates perhaps more ductile deformation is likely and the slope may not collapse (Figure 12). These situations can be difficult to manage since the engineer should always 'obey' the inverse velocity predictions and may be forced to isolate an area but may lose credibility if a visual collapse does not occur. In reality, the slope

may have 'failed' over a period of 1–2 days (sometimes weeks) or so; it's just not seen visually by the mining operation.

- The user must not rely too precisely on the time to failure prediction when deciding on when to move equipment and personnel from the impacted area. Inverse velocity predictions are not always linear and actual time of failure may often be sooner than predicted time to failure. A significant buffer must exist between predicted time to failure and the time required to evacuate people and equipment. Using three days to failure as a trigger for evacuating personnel and mobile equipment proved successful for managing large failures such as the Bingham Canyon Leo Failure. However, some instabilities may not allow for such warning, typically these are smaller failures (two to five benches) where a key structure is rapidly daylighted as a result of toe mining.
- While the pressure may be such that the mining operation wishes to continue mining for as long as possible prior to a collapse, this is never the reaction after a collapse. The common response once a slope has failed is 'we're glad evacuation occurred with plenty of time to spare'.

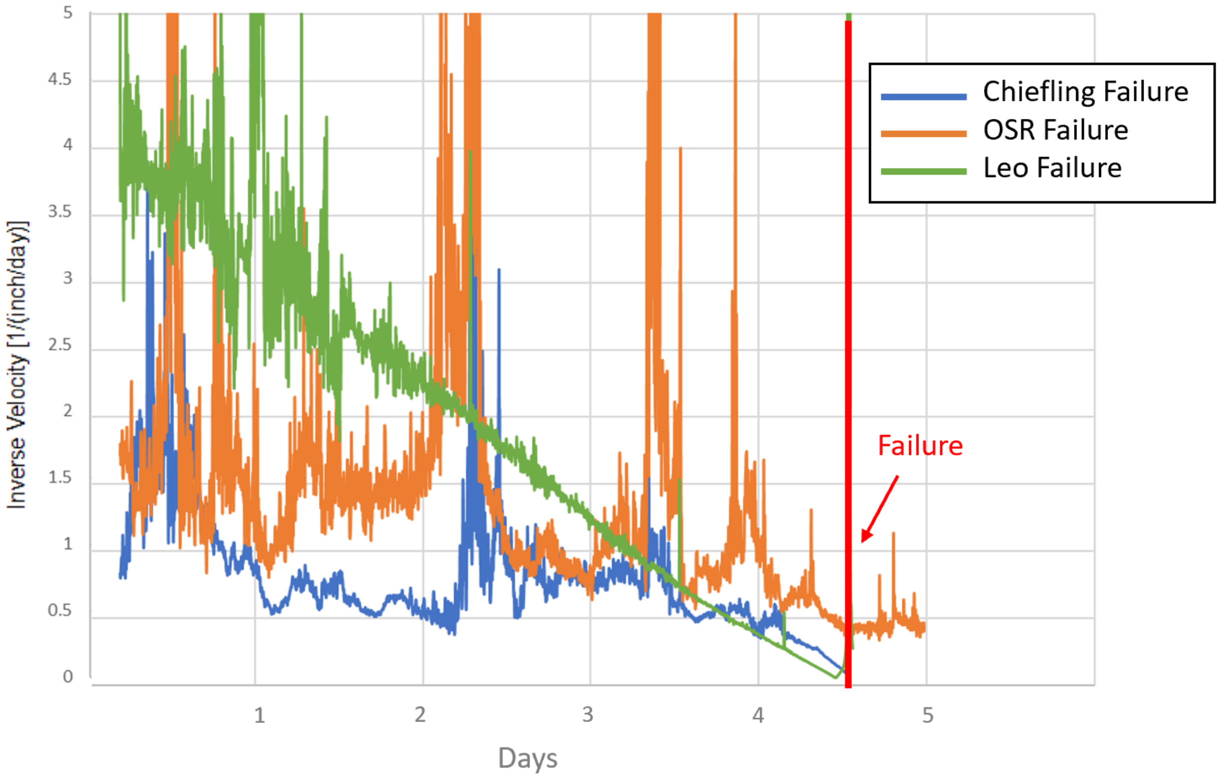


Figure 12 Three inverse velocity lines for the three case studies are plotted on the same graph five days prior to failure. The Leo failure (catastrophic collapse) has a steep gradient and very clean trend; the Chiefling failure shows a steepening cleaning trend approximately 10 hours before failure. The OSR is noisy and trend is shallower. This slope did not go into phase ambiguity, instead it just deformed then showed regressive behaviour (hence the flattening of the line)

5.1.4 A note on phase ambiguity

Phase ambiguity occurs when the slope is moving too fast for the radar to detect. At this point the operation is essentially blind with regard to real-time monitoring. Typically, a collapse of some form will occur within minutes to tens of minutes after phase ambiguity occurs. Isolation of all personnel and equipment must have taken place a significant time before this occurs. Radar signatures showing phase ambiguity are generally clear but can also appear to show abrupt slowing down which must not be mistaken for actual deceleration.

6 Economic management

In addition to safety management, a huge amount of data and understanding can be obtained from monitoring data to allow economic management of deforming pit walls to maximise ore gain given the geotechnical challenge that may exist. This process of updating designs based on observed slope performance and updated geotechnical conditions is essentially the observational mining method that is becoming increasingly discussed in surface mining literature. Several key aspects are critical in being able to economically manage and optimise deforming pit walls as shown in the process flow in Figure 13. These steps are not necessarily sequential; some may occur simultaneously once a moving area has been detected. Aspects of each step are discussed in the following sub-sections.

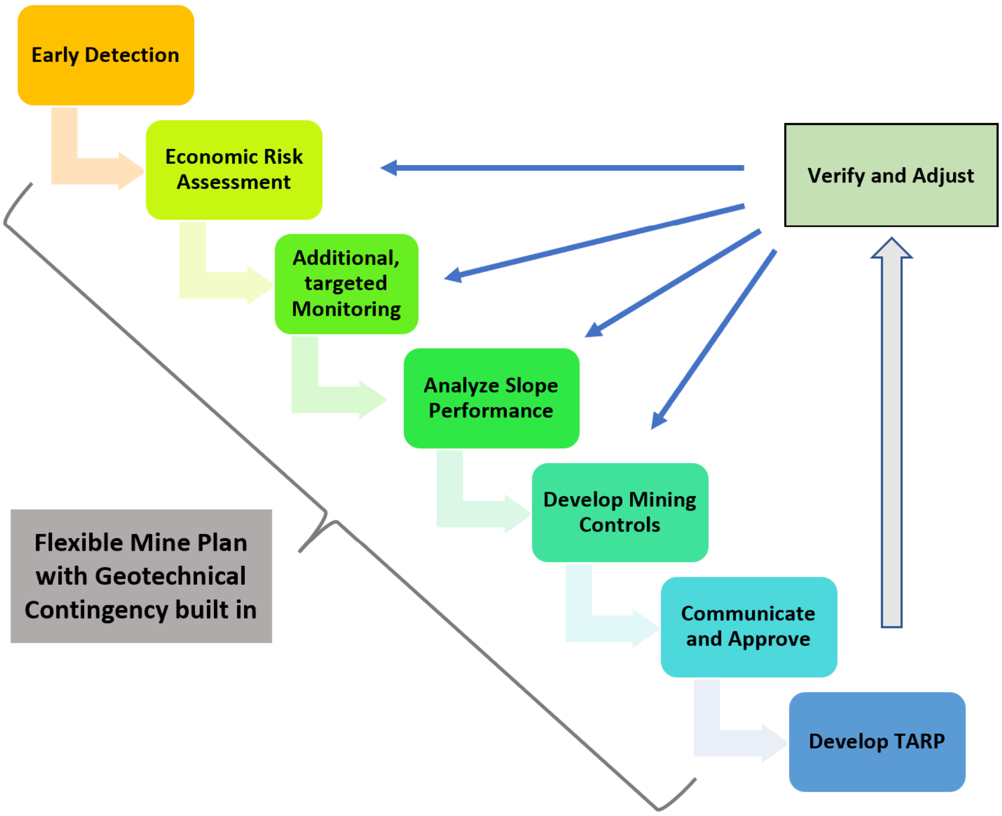


Figure 13 Process flow for economic management of deforming pit walls. A flexible mine design is critical for this process.

6.1 Early detection

Early detection can be defined as sufficient time between detection of a moving area and the ability of the operation to develop, and act on, a remediation plan before an unrecoverable progressive trend develops.

Early detection of any moving area is the first step to identifying and then managing deforming pit walls. With the suite of technologies available and the economic benefit that can be gained from early detection, one can argue that this too should be industry standard.

Early detection is done through a combination of InSAR data, sub-sampled radar data and a dense prism and GPS layout. With radar technology constantly improving, early detection is increasingly possible with live radar too. How early a movement area can be detected will depend on both the monitoring capability but also the size of the moving area and the failure mechanism itself. A larger moving mass will have a greater chance of early detection. In some cases, early detection could be months or years prior to a collapse. Also, the greater amount of displacement, the greater the chance of early detection. However, as demonstrated in this paper, many large failures may not deform significantly prior to collapse.

It should be noted that detection of potentially unstable areas may also eventuate from design work through detailed interpretation of the engineering geological model and/or review of slope performance in previous cuts. While these areas would typically be designed at an acceptable DAC, it may be that in some areas, DAC is not achievable and the risk of deformation is accepted. This acceptance would likely only be taken at a mature operation with strong historical knowledge and significant experience managing deformation.

6.2 Installation of additional, targeted monitoring equipment

Immediately following early detection, additional monitoring data will be necessary to give the required 2D and 3D data, and to provide redundant monitoring coverage. Sub-surface instrumentation may already exist if the design had anticipated potential movement but in most cases, additional sub-surface instrumentation will need to be installed to target shearing surfaces and help define the failure depth. Budgeting for this can be difficult as it may fall under capital rather than operating budgets. However, there is a sound safety and business case to be made that will grossly outweigh any unplanned spend.

6.3 Economic risk assessment

Assessing the economic risk of a collapse once a moving area is detected allows the business to assess the full suite of options of how to proceed. A risk assessment may look at semi-quantifying, in NPV or free cash flow, the impacts of a failure on factors such as ore dilution, impact to ore delivery, damage to infrastructure etc., then evaluating these against remediation costs, step-ins or the risk of continuing with the current mine design. The risk assessment should be updated as understanding of deformation mechanism changes and as pit layout changes.

6.4 Data review process

This step involves analysis and of monitoring data to gain a thorough understanding of the failure mechanism to then evaluate options for how to manage the situation.

The data review process involves the following:

- Merge monitoring data with 3D photogrammetry model.
- Update geological and structural model (locations and characteristics).
- Understanding of failure mechanism.
- Evaluating mining, blasting and rainfall responses.
- Review prism and GPS vector data. Look for changes in vector direction spatially.
- Review monitoring data to look at number of progressive–regressive cycles a slope has undergone.
- Estimate %strain applied to slope.

6.5 Develop mining controls

Once the data review and analysis work has been undertaken, controls will be needed to manage the moving mass. These may include:

- Controls required to continue mining current design (blasting controls, mining rates, depressurisation options; review slope performance after each bench).
- Unload designs.
- Step-ins.

- Buttressing.
- Re-designing the slope below, which may also require additional operational controls.
- Ground support may also be an option in some limited cases.

6.6 Geotechnical contingency and flexibility in the mine plan

Building geotechnical contingency and flexibility into the mine plan is required to allow for pauses in certain areas of the operation caused by deformation or a collapse. Such options may be in the form of:

- Allocated geotechnical tons throughout the year that allow for failure remediation or clean-up.
- Build-up of ore to stockpile to survive any ore dips as a result of instability.
- An optimised slope design and a base case slope design that can be used as a 'fall-back' option.
- Mine shallower 'working slopes' and learn from these, gradually pushing back to an optimised slope design.
- Alternatively, mine aggressive 'working slopes' to learn limits of stability and allow the operation to manage deforming walls; then finish with an optimised final wall.
- Develop a 'plan B' if a collapse were to occur.

7 Conclusions and considerations for the industry

From the work presented in this paper and the exposure to managing a number of slope deformations in a large, economically and geologically challenging surface mine, the following closing comments are made:

- Importance of the structural model
  - All slope deformations in rock masses with strengths greater than R0 have a significant amount of structural control. This may be a discrete fault or contact that was not identified at the design stage. It may be strength characteristics that were over-estimated due to averaging of laboratory data or it may be localised, unfavourable variations in structure orientation such as bedding or foliation variations across a pit wall. The latter is often a result of measuring a large amount of joints, bedding etc., and then taking the average for that set, rather than looking at the variations spatially across the pit or geotechnical domain. In short, obtaining, and continuing to obtain, sound structural and geological data is challenging at the design stage and instead, priority is given to complex modelling and stability analysis. Though all stages of the mining cut, these models and their inputs need to be rigorously reconciled to the data from mapping newly exposed bench faces and additional drilling.
- Importance of the engineering geological model
  - The majority of failures are not identified at the design stage. From review of design work flows, we see all too often that a large amount of geotechnical data is input into very complex and sophisticated numerical models where we then await the predicted failure surface or mechanism. A more reasonable approach would be to review all the geological, structural and rock mass data to develop a 3D engineering geological model. From this, use sound engineering judgement and historical wall performance data (if available) to predict what possible failure mechanism/s could occur. Then, if appropriate, numerically model those specific mechanisms in an attempt to quantify the FoS. This idea is not new per se; Carter (2015) and Carter & Barnett (2021) have produced several papers stressing this point. By no means would this approach ensure all potential instabilities are identified at the design stage, but it would make designs more defensible. Furthermore, identifying potentially unstable areas at the design stage; such potential movements can then be economically assessed and the business can decide if such risks are acceptable.

- How can we incorporate slope movement into the design approach?
  - With monitoring technology being as advanced as it is, our ability of early detection is ever increasing, which in turn allows us to evaluate potential economic impacts of an early detected collapse and adjust mine plans accordingly. Therefore, do we need to update the industry standard DAC to factor in an operations capability and economic risk acceptance to manage a moving pit wall? Such an approach may look at ore delivery year on year, flexibility within the mine plan, and economic sensitivity of pit wall angle to an operation, in addition to the expected FoS. This could translate simply as asking what failures can we 'deal with' at the operational stage without the project becoming uneconomic?

Already, several papers have been written on factoring uncertainty and risk into DAC (Steffen et al. 2008; Hawley & Cunning 2017). A revised industry standard could allow a more widely accepted and flexible approach for mining deeper and more aggressively as long as the safety risk is always managed.

References

Bakken, KM, Chapin, GK & Abrahams, MG 2020, 'Trigger action response plan development and optimisation at the Bingham Canyon Mine', in PM Dight (ed.), *Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 177–190, https://doi.org/10.36487/ACG_repo/2025_07

Carter, TG 2015, 'On increasing reliance on numerical modelling and synthetic data in rock engineering', paper presented at the 13th ISRM International Congress of Rock Mechanics, Montreal.

Carter, TG & Barnett, W 2021, 'Improving reliability of structural domaining for engineering projects', *Rock Mechanics and Rock Engineering*, vol. 55, no. 12.

Dick, GJ, Eberhardt, E, Cabrejo-Liévano, AG, Stead, D & Rose, ND 2014, 'Development of an early-warning time-of-failure analysis methodology for open-pit mine slopes utilizing ground-based slope stability radar monitoring data', *Canadian Geotechnical Journal*, vol. 52, pp. 515–529.

Hawley, PM & Cunning, J 2017, *Guidelines for Mine Waste Dump and Stockpile Design*, CSIRO, Carlton.

Peck, RB 1969, 'Advantages and limitations of the observational method in applied soil mechanics', *Geotechnique*, vol. 19, issue 2, pp. 171–187.

Sharon, R & Eberhardt, E 2020, *Guidelines for Slope Performance Monitoring*, CSIRO, Carlton.

Steffen, OKH, Contreras, LF, Terbrugge, PJ & Venter, J 2008, 'A risk evaluation approach for pit slope design', paper presented at the 42nd US Rock Mechanics Symposium, American Rock Mechanics Association, Alexandria.

Wylie, DC & Mah, CW 2004, *Rock Slope Engineering*, 4th edn, Spon Press, New York.