Observational Mining and Managing Moving Pit Walls

Industry Guidance Note

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TABLE OF CONTENTS

1.0 INTRODUCTION

The initial design of open pit slopes is carried out by assessing if the selected slope geometry provides a factor of safety (FoS) between 1.1 and 1.3 for the shear strength of the likely failure surface(s). Experience has shown that within the accepted narrow range for the FoS, localized failure of the pit wall is to be expected.

With the monitoring technology currently available, experience has also shown that these instabilities and the associated movement can be managed such that operational safety is not compromised. Furthermore, analysis of observed slope performance provides detailed information and verification of actual geological and structural conditions, slope behaviour in response to mining, and understanding of the failure mechanism(s). Such information cannot be expected to be available with 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'.

This implies that the factor of safety is only a guidance for the selection of the slope geometry and that safely controlling the movements associated with expected instabilities is the primary mining focus. This notion that the prescriptive factor of safety approach is not adequate for the construction of large projects in many geological conditions is not new. An alternative approach was first introduced by Peck (1969) as the Observational Method and was described as a design solution which "*permits maximum economy and assurance of safety, provided the design can be modified as construction progresses"* In the Observational Method described by Peck the design focus was applied soil mechanics, as it pertained to the loading of foundations and the construction of earth dams. The method fundamentally required the measurement of pore pressures and the impact of those pore pressures changes on the measured displacements. By linking field measurements of pore pressures, measured laboratory shear strength and displacements the impact of the construction loading could be quantified and adjusted to achieve acceptable displacements.

Despite the factor of safety not being formally required to implement the Observational Method it was sometimes used to empirically establish a relationship between changes in the FoS and the associated displacements. It must be remembered that any empirical relationship between FoS and displacement is site specific and cannot be generalized.

Since 1969 the Observational Method has evolved and today is part of the formal design process referred to as Performance-based design (PbD). An essential element of PbD is the measurement of an observable behaviour. In the mining of a pit wall the observable behaviour is the measured pit wall displacements compared to the expected displacements. Numerical analyses can be used to predict expected pit wall displacements. The reliability of that prediction is significantly improved if, when developing a push-back, the experience and displacement measurements associated with the mining of the first pushback were used to calibrate the numerical model.

The purpose of this note is to provide industry guidance when mining marginally stable pit walls. The term Observational Mining is introduced that incorporates the necessary elements of Performance-based Design and the Observational Method as applied to open pit slopes.

An important distinction of the observational method in surface mining compared to it's use in civil engineering context is that an instability (or instabilities) may be tolerated throughout the life of a mine or cut; and it may be economically beneficial to progress mining below this instability if safety is managed.

The Observational Mining approach can be used to:

1. Identify a ***potential instability*** with sufficient time to implement a management strategy.
2. Evaluate the options for how to deal with the potential instability through mitigative design changes or operational controls.
3. Progress mining below an instability while minimising risk to personnel, if that is the desired option for the Business.

The ***potential instability*** may be:

a) A slope designed (and accepted by the Business) with a marginal safety factor (lower than industry standard design acceptance criteria) which may or may not be showing signs of movement, or

b) An area of movement detected through slope monitoring techniques, where such movement was not expected at the design stage.

1.1 When would an Observational Mining Approach be applied?

Examples of when the observational method would be applied to surface mining include:

- **Significant Change in Geotechnical Understanding**. When new geological, geotechnical, or hydrogeological information invalidates the baseline design safety margin, for example, when the factor of safety (FoS) is likely below the Design Acceptance Criteria (DAC) but remains uncertain.
- **Early Detection of Slope Movement**. When monitoring data and field observations reveal signs of slope stress such as dilation, cracking, or movement, indicating that the FoS may be marginal.
- **Known and accepted level of uncertainty in design**. When there is a recognized deficiency in geotechnical and ore body knowledge that introduces high uncertainty into the design assumptions and/or mining is progressed without meeting industry standard study definitions.

- **Goodbye Cuts**. When final pit stages or "goodbye cuts" require adaptive strategies to manage increased geotechnical risk due to reduced design flexibility and opportunity for maximising ore gain.

Important: Observational Mining is not an alternative to thorough geotechnical investigation and design. It cannot be used as a design approach by itself to negate geotechnical investigation and sound pit wall design.

Observational mining carries elevated safety and economic risks which must be managed by the Business.

1.2 An outline of slope behaviour

All slope failures are proceeded by precursory deformations. Following from the "Initial Deformation" stage a slope can follow one of several common trends, as shown in Figure 1-1.

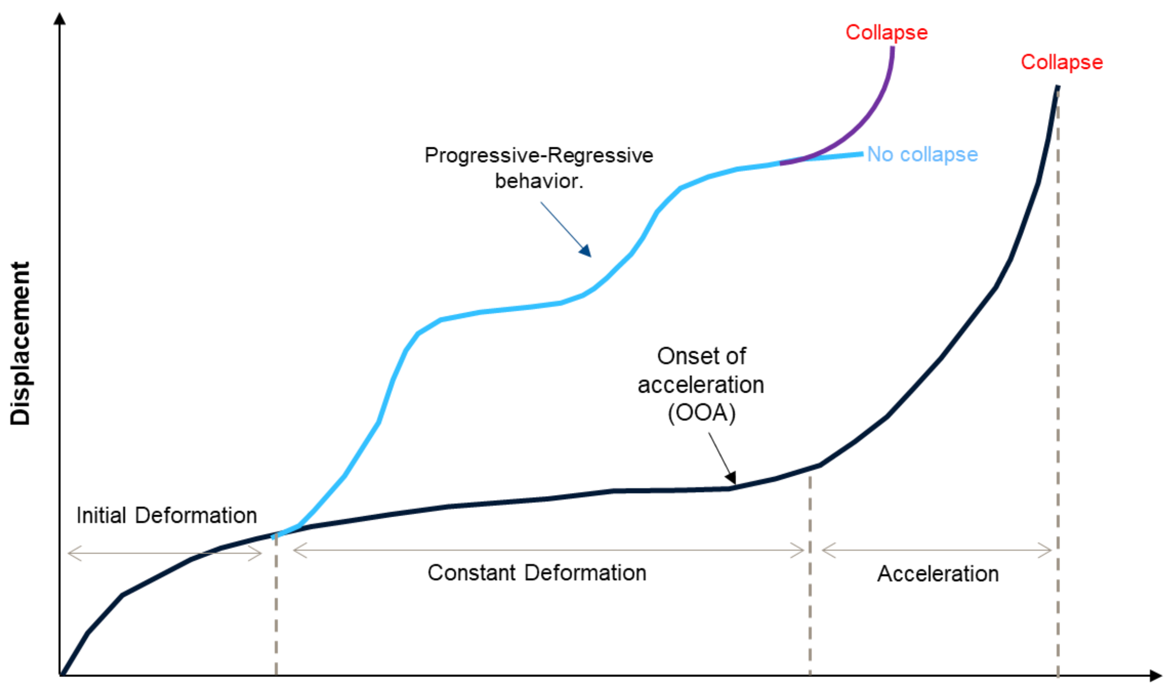

Figure 1-1 Slope deformation trends with time. (Adapted from Broadbent and Zavodni,1982).

Movement trends may be:

- Progressive (accelerating) to collapse
- Progressive-Regressive behaviour eventually resulting in a collapse
- Progressive-Regressive behaviour eventually stabilising
- Constant; but deformation rate increases in between progressive-regressive cycles

In reality, these general failure trends can look very different and are directly related to the instability mechanism. Examples of three different instability trends are shown in Figure 1-2.

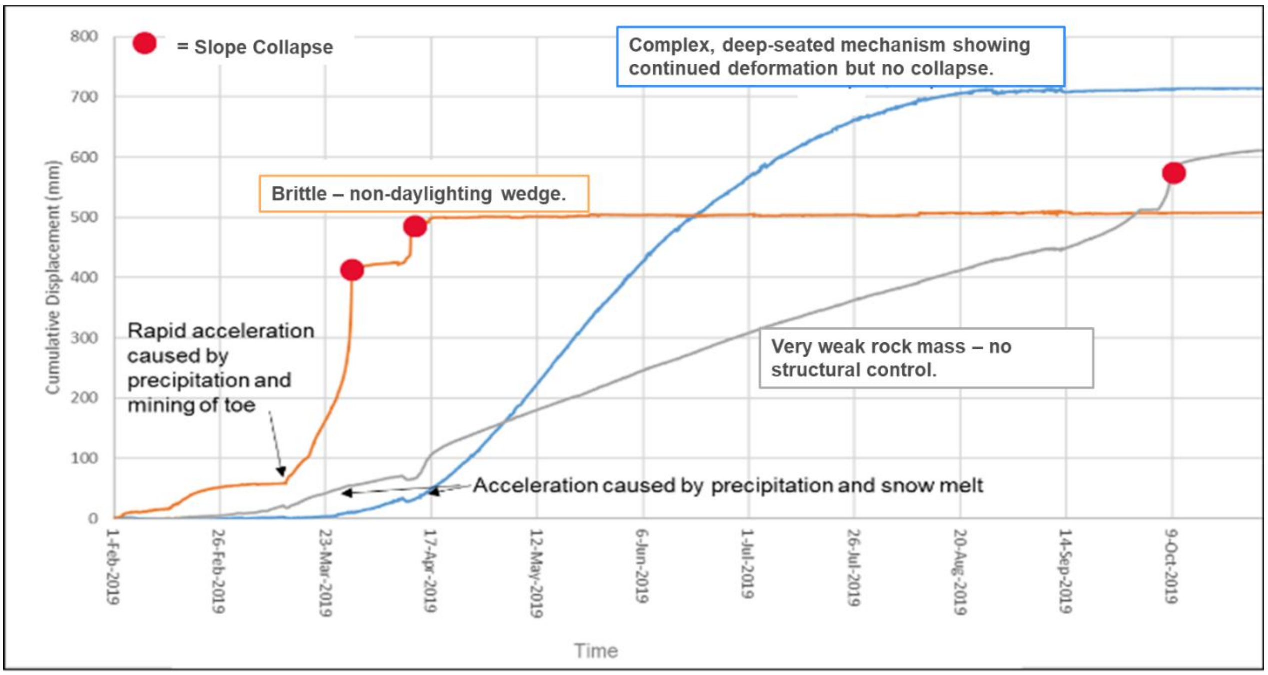

Figure 1-2 Examples of different instability trends as a function of mechanism (ref Bakken et al).

It is very challenging to predict how many progressive-regressive cycles a slope can tolerate before a collapse.

Slope deformation may be due to:

- Blast vibrations
- Removal of toe support
- Crest loading
- Daylighting, or close to daylighting, key structures

- Pore pressure increases
- General creep due to gravity

When advancing a mining cut below an instability the goal is to keep the slope deforming at “manageable” rates or decreased rates trending towards stable. However, this can never be guaranteed, and the operation must be capable of safely managing a potential collapse and accepting of the economic consequences of a collapse. These economic consequences must be evaluated against the economic costs to mitigate slope movements (i.e., step-ins, unloading of the crest, depressurization, etc.).

Mitigative design changes would ideally result in regressive behaviour with the slope becoming stable. However, design changes are typically costly, or can be extremely costly, to a mining operation and the benefits of achieving a stable slope have to be carefully evaluated (i.e. costs of mitigation, impacts on the mine plan, etc.).

1.2.1 Slope Movement and Factor of Safety

The relationship between slope movements and factor of safety is complex, however, in simple terms the following descriptions are provided:

- When a slope is accelerating (progressive behaviour) the Factor of Safety (FoS) or the SRF (Strength Reduction Factor) is less than 1. But we don’t know how much below 1.
- When a slope is moving at a constant rate the FoS is at or close to 1.
- When a slope is decelerating (regressive) the FoS is at or slightly above 1.
- When a slope shows no signs of movement it is greater than 1 but it is difficult to know by how much.

2.0 OBSERVATIONAL MINING AND MANAGING A PIT SLOPE INSTABILITY

2.1 Process Flow

The framework, or process flow, for Observational Mining and Managing Instabilities is shown in Figure 2-1. This guidance note discusses all the factors which should be considered at each stage.

These steps are not necessarily sequential. Some may occur simultaneously once an instability is detected.

Observational mining is a continuous, iterative process with commitment to constant re-evaluation and change.

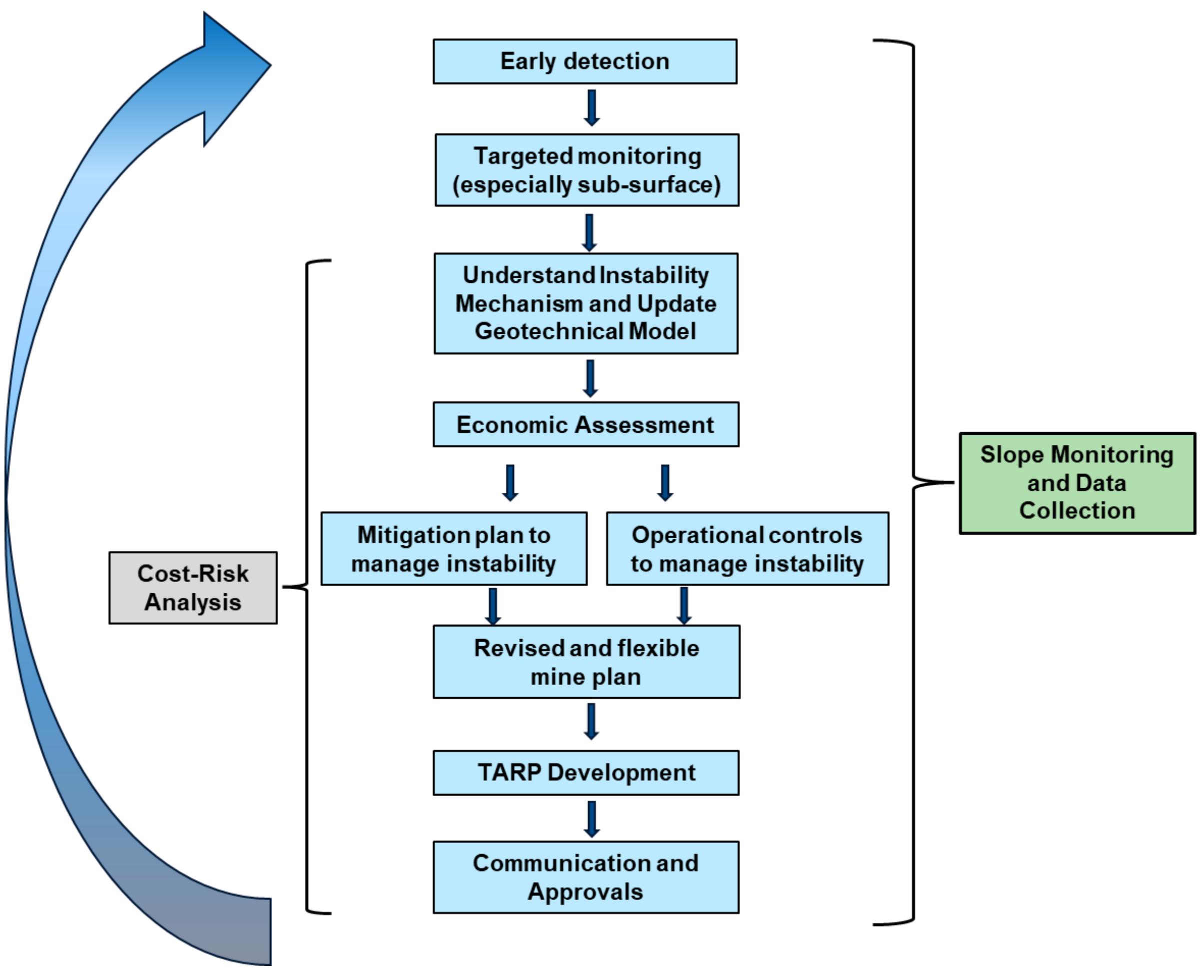

Figure 2-1 Process flow for Observational Mining.

2.2 Early Detection

Early detection can be defined as "***sufficient time between detection of a potentially moving area and the ability of the operation to develop, and act on, a remediation plan before an unrecoverable progressive trend develops"***. This initial movement is the background displacement associated with "pseudo-elastic" slope dilation.

Early detection of a potential instability is the first step to identifying and then managing a deforming pit wall.

Slope instabilities are mostly detected through a comprehensive monitoring network. Although the slope is typically designed to a sufficiently high FoS, model uncertainties can lead to unexpected ground conditions, and an instability can develop.

In some cases, detection of potentially unstable areas may be done at the design stage. i.e. the slope is purposefully designed at a low safety factor and a potential instability is identified. This can be achieved through detailed interpretation of the engineering geological model and/or review of slope performance in previous cuts. Sensitivity runs should be conducted at the design stage to test for potential adverse scenarios.

For a slope to be designed and mined at a low safety factor (i.e., below the Design Acceptance Criteria) the economic drivers must be such that a shallower slope angle is not financially viable.

Prior to proceeding with such a design, the risks associated with deformation and potential collapse must be acknowledged and accepted by the Business. The area is identified as a potential hazard to be confirmed when the slope is exposed and managed according to a pre-arranged mitigation strategy. A comprehensive slope monitoring network capable of detecting small movement is critical in this case.

How early a movement area can be detected will depend on the monitoring capability, the size of the moving area and the failure mechanism itself. A larger, more ductile moving mass will have a greater chance of early detection. Early detection can occur months or years prior to a collapse.

2.2.1 Detecting Small-Scale Movements

Early detection is about identifying very small-scale slope movements i.e. just above detectable limits or "background noise". We want to see the Initial Stage of deformation (Figure 2-2).

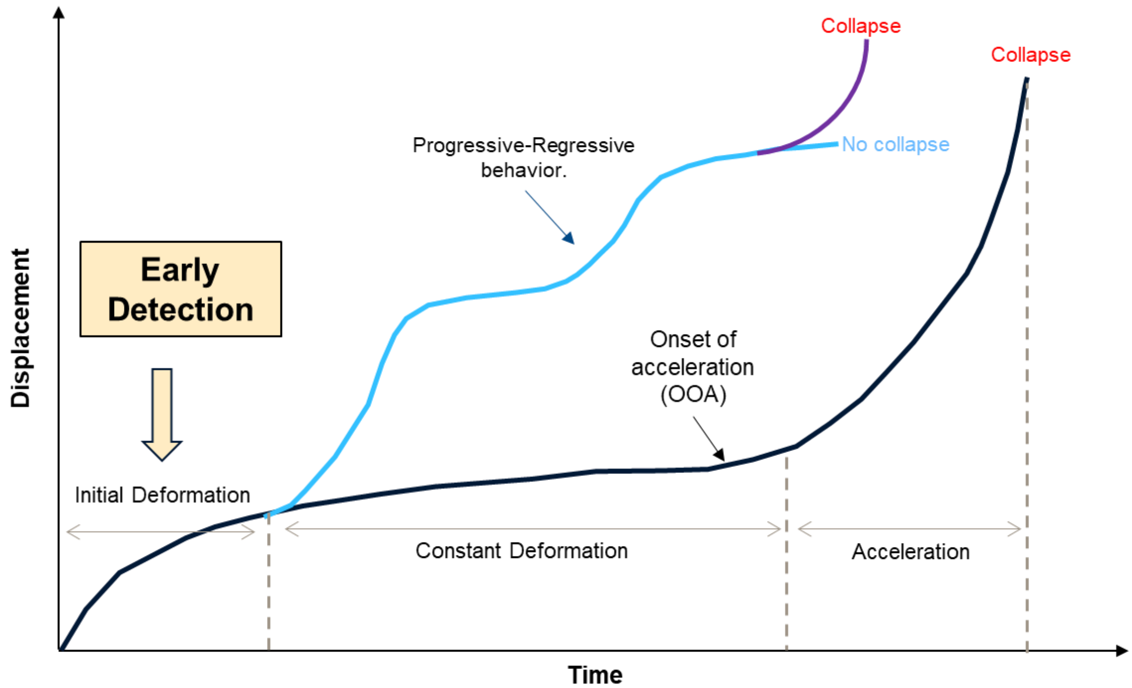

Figure 2-2 Sketch of where Early Detection fits along a typical deformation plot.

Early Detection is accomplished through a combination of:

- **InSAR data**. Higher resolution data can detect smaller risks. The industry standard is to use 3 m X or C-band data, acquired from two different perspectives to maximise coverage. Images are commonly acquired every 11 days for each perspective, but more frequent data is often available, if needed. The update frequency is a site decision; some InSAR providers offer flexibility, providing more updates in times of need. Ensure persistent, non-persistent and distributed scatterers are being monitored.
- **Sub-sampled ground-based radar data**. Sub-sampling data is about extracting slower movement rates from the daily noise. It is important to utilize long term data sets (several months) which have a baseline such that slow movement rates can be detected. Good practice can detect <10mm/month of change. Ground Based-SAR data sets that span 6+ months are generally needed. Remember to sub-sample over different time periods to evaluate the data. Options may include 12hrs, 24hrs, and 7 day periods, however, it depends on baseline movement rates and/or radar detection limits.
- **Dense and accurate prism layout**. Readings should be taken automatically every 1-3 hours. Plots of deformation or velocity with time must be looked at over several weeks to observe possible increases in movement. Binning of data can help identify movement trends.

- **High precision GNSS units**. High precision, automated Global Navigation Satellite Systems (GNSS) units can be a tool for early detection and have the benefit of producing 3D vectors. GNSS units are typically easy to install and maintain and, unlike prisms, do not require line of sight to a monitoring station.

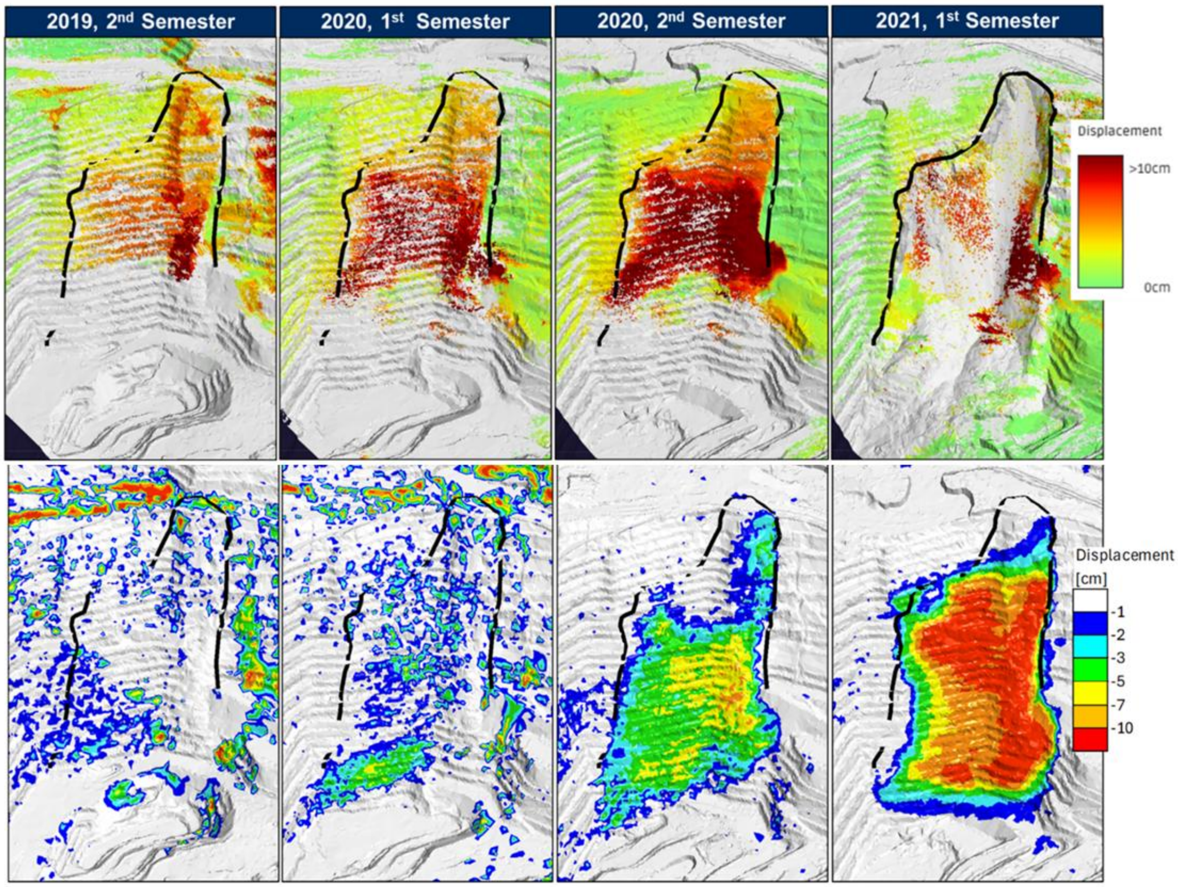

Figure 2-3 Example of slope instability detected by InSAR (upper series) in 2019 and then by ground based radar (lower series) one year later in 2020 (*Mellea et al 2025*). The slope collapsed in 2021.

Prisms and Global Navigation Satellite System units provide 3D displacements which are valuable for interpreting the slope mechanism.

With radar technology constantly improving, early detection is increasingly possible with live radar too, which may work as an alternative or compliment sub-sampling.

Remember, if total stations and radar units get moved around (due to mine planning requirements) then the only consistent data set available to review long term trends will likely be InSAR and potentially GNSS stations.

InSAR – A few things to remember

1. **Sensitivity & underestimation**. InSAR provides 1D line measurements along a specific line of sight. The direction of ground displacement will rarely coincide with this line of sight and InSAR will therefore commonly underestimate the total displacement magnitude.
   Solution: Monitor from two perspectives which increases coverage, provides displacement direction and reduces underestimation.
2. **Phase ambiguity**. Ground based radars suffer from this speed limit issue; they 'run out of room' in their wavelength, analogous to a clock reaching midnight and going back to zero. This issue does not exist for satellite InSAR because data is analysed spatially during post processing; a luxury not available to a real-time ground based radar. Assuming modern processing techniques (see also **8**), the wavelength can be far exceeded, by counting the phase cycles as the displacement intensifies across an area.
3. **Phase aliasing**. This is the real speed limit for satellite InSAR. When the phase cycles mentioned above are too close together, they can no longer be counted. This is analogous to contour lines on a map getting too close together once the ground is sufficiently steep.
   Solution: More frequent data or a longer wavelength.
4. **InSAR doesn't measure height well**. Unlike LiDAR, InSAR measurements only work when the ground is undisturbed. Excavation, dumping and blasting all ruin this consistency and InSAR is blind to these events.
   Solution: Use LiDAR to monitor height change, but don't expect InSAR level precision.
5. **InSAR in Mining**. In addition to 4, mining activity is not the friend of InSAR. However, when the ground surface is disturbed, some InSAR approaches can recover as soon as the activity moves on.
   Solution: Use a provider that supports 'Non-Persistent Scatterers'.
6. **Precision, not accuracy**. InSAR can offer mm precision (a measure of repeatability), but because of issues caused by 1, 3 and 4, InSAR may often not be accurate (a measure of truth). Luckily, geotechs mostly use InSAR to track trends, which precise measurements excel at.
7. **Uncertainty**. There is no agreed method for estimating InSAR uncertainty and approaches vary from ignoring the issue completely, to sophisticated modelling of the signal to noise. Be sure to challenge providers about their method for approaching uncertainty.
   Solution: Use well established InSAR providers.
8. **Not all InSAR is the same**. The InSAR industry is unregulated and prone to wild claims from enthusiastic beginners. Pay attention to:

   a. Processing techniques and which scatterer types are supported.
   b. How quickly results are delivered after an image.
   c. How consistent the service is.
   d. How responsive the service is.

Solution: Use well established InSAR providers.

9. **Data Quantity**. InSAR processing involves complex modelling in order to remove unwanted effects and isolate displacement. 15 images is typically the minimum number of images needed to estimate full time series based InSAR results.
   Solution: Budget for more data than you think you need.

10. **Early Detection, not Critical Monitoring**. InSAR images are acquired every few days and results have a delivery lag of hours to days, depending on the provider. Safety-critical alerting makes little sense for this kind of data.
    Solution: Consider InSAR a strategic tool that informs decisions about how best to utilise more tactical, critical monitoring tools.

11. **InSAR Displacement Direction**. Given either ascending (flying north, looking east) or descending (flying south, looking west) data, a single line of sight displacement map can be produced. Given BOTH, in addition to the two line of sight maps, an up-down and an east-west map can also be produced. Some vendors may also go further and produce a total magnitude map and a direction layer which maps the solved direction for each pixel. Because most SAR satellites fly almost exclusively pole to pole; this makes them insensitive to horizontal north-south displacement.
    Solution: A new generation of recently launched inclined orbit satellites makes possible full 3D InSAR.

12. **Vegetation**. This creates extra uncertainty at best and complete noise at worst for standard SAR data in the X and C radar bands.
    Key factors: The lushness, size and density of the vegetation.
    Solution: Longer wavelength data in the L-band gets around this issue, at the expense of some measurement precision (L-band can achieve cm precision, X and C can achieve mm precision). NISAR, launched in October 2025, will provide free, global coverage, L-band data.
    Use cases for L-band: closed vegetated sites, forested geohazards that could threaten site access, very fast displacement (longer wavelength data has a higher speed limit).

13. **Looking back**. Historic SAR data exists for every site back to 2015 or 2016. Data is patchier prior to that, but still often available. Use cases: historic baseline assessments, past incident investigations, long-term dewatering displacement analyses, InSAR baseline data for beginning monitoring immediately (see also **9**).

14. **Snow**. Sites that have a reliable and persistent snow season are often not monitorable during these periods and users may choose to pause InSAR each winter.

Key factors: temperature, available sunlight, slope aspect, latitude, altitude and snow depth. These factors affect how the snowpack changes between images; InSAR can therefore still be effective when the snowpack is not changing. Low precipitation Arctic sites and/or high altitude sites may be monitorable year-round.
Solution: for intermittent snow: Sites that receive occasional snow will retain much more coverage if Non-Persistent Scatterers are supported by the vendor (see also **5**).

Prism and GNSS Monitoring – The do's and don'ts for successful early detection

Prism Monitoring:

- Care should be taken to ensure a robust and stable total station installation. Movement of the total station will show up as (false) movement on the prisms, so it's crucial to either have a stable mount, or where that isn't possible, to account for the movement in the prism data processing.
- Ensure that a proper coordinate system is established for the prism monitoring setup including control points. It's common to need to move the total station in mining operations, and without sufficient control points it's difficult to establish continuity of the long-term data without jumps in the data.
- The prism monitoring data is completely dependent on the operation of the associated total station, so ensuring adequate redundancy with communications and power systems is important to avoid a single point of failure that would cause data gaps for many prisms.
- Total stations measure both slope distance displacements and full 3D displacements. While the slope distance displacements can be measured directly, 3D displacements require Control Points (aka Backsights) to determine the location of the total station. Care establishing these points will improve the ultimate success of the prism monitoring system.
- Atmospheric conditions affect the distances measured by total stations so measuring the atmospheric conditions (i.e., temperature, pressure, humidity) is important to obtain accurate measurements.

GNSS

- Ensure that the GNSS base station is established on a stable point with a clear view of the sky. Movement of the GNSS base station will show up as movement on the GNSS monitoring points so a stable base is important.
- Ensure GNSS monitoring points are installed with as clear a view of the sky as possible. Reflections of the satellite signals (multipath) off of nearby structures, pit walls, etc., can cause spikes in the data which makes early detection of trends more difficult. It doesn't

matter if the reflection happens at the base station or monitoring point antennas, so a clear view of the sky is important for both.

- Most automated GNSS applications for monitoring require a data link from the monitoring points to a network / server for processing. Ensuring sufficient radio coverage is critical to ensure that all raw GNSS data is received for the best possible processing result.
- GNSS units with an external power source (e.g. a solar panel) that can keep the unit running continuously produce dense data sets that can then be filtered to provide a rolling average over, for example, 3 hours.
- GNSS units that collect data periodically should be configured to produce a measurement every 1-3 hours. These data sets typically contain more 'noise' and the plots of deformation or velocity time-series must be evaluated over longer time periods (e.g., days or weeks) to minimize the effects of noise and detect possible increases in movement. Binning of data can help identify trends.

Geological and geotechnical mapping is also part of Early Detection. The Geotechnical and Geology Teams should determine if critical structures are being observed as the slope is excavated which may cause a potential instability. The structural model should be updated accordingly as new structures are identified.

2.3 Targeted monitoring with emphasis on sub-surface instrumentation

Immediately following early detection, additional monitoring equipment should be placed and read with increased frequency. The operation should consider:

- Additional ground-based radar coverage with improved line of sight, and to provide redundancy in event of an outage.
    - Recommend placing radar system in the known failure direction to achieve most accurate measurements of deformation.
    - If radar unit can be placed adjacent to total station this makes it easier to interpret data since slope distance values between the total station and prisms should be similar to those from radar.
- Increased prism and GNSS network
- High focus on sub-surface instrumentation. Time Domain Reflectometers (TDR's), inclinometers and shape accel arrays (SAAs) help identify shear surface(s) and define the failure depth. This is critical to understand the failure mechanism and carry out runout assessments. SAAs and inclinometers can plot displacement with time for specific areas of interest, as well as giving a displacement vector.

  - Note: the greatest magnitude of displacement observed will likely be through sub-surface instrumentation rather than surface instrumentation (Figure 2-5).
- Sub-surface instrumentation should include nested vibrating wire piezometers (VWPs). These can be installed in the same hole and are valuable for understanding hydrogeological impact on slope performance.
  - VWPs should be installed in the transient zone as well as at depth to monitor pit scale groundwater levels
  - In many cases slope movement increases when transient pore pressures increase.
  - Transient pore pressures should be plotted against slope movement and rainfall data to evaluate the impact on slope stability and the potential effectiveness of depressurisation for managing the instability.

Note: If diamond drilling is to be used to install sub-surface instruments across potential failure surfaces, care is required not to discharge significant amounts of water into/along the failure surface. A select amount of diamond drillholes is likely low risk; however there are examples where prolonged diamond drilling into an underground orebody from behind a pit crest that resulted in a progressive response in the slope measured by radar with pore pressure increases also measured by nearby VWPs.

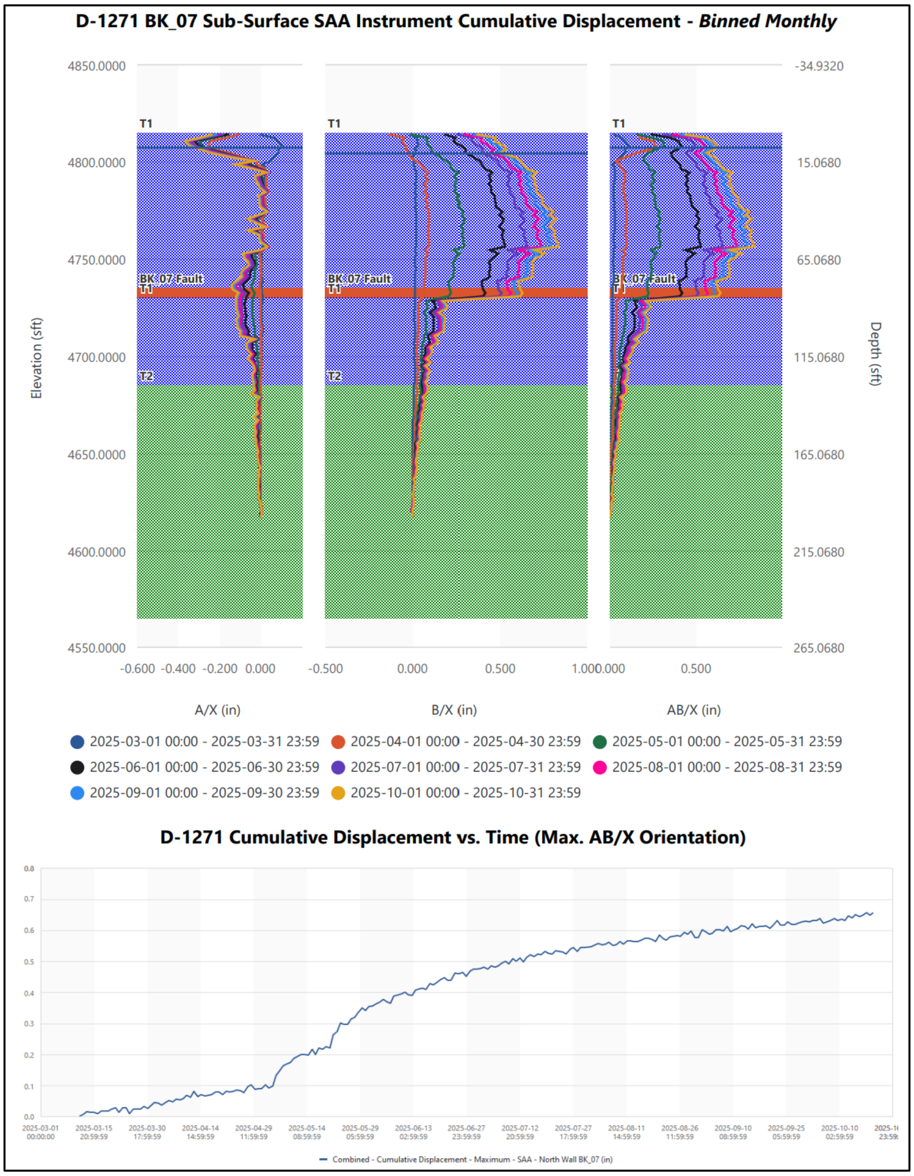

Figure 2-4 Shape axial array data showing shearing along a fault structure (top). Cumulative displacement is plotted along the fault structure (bottom).

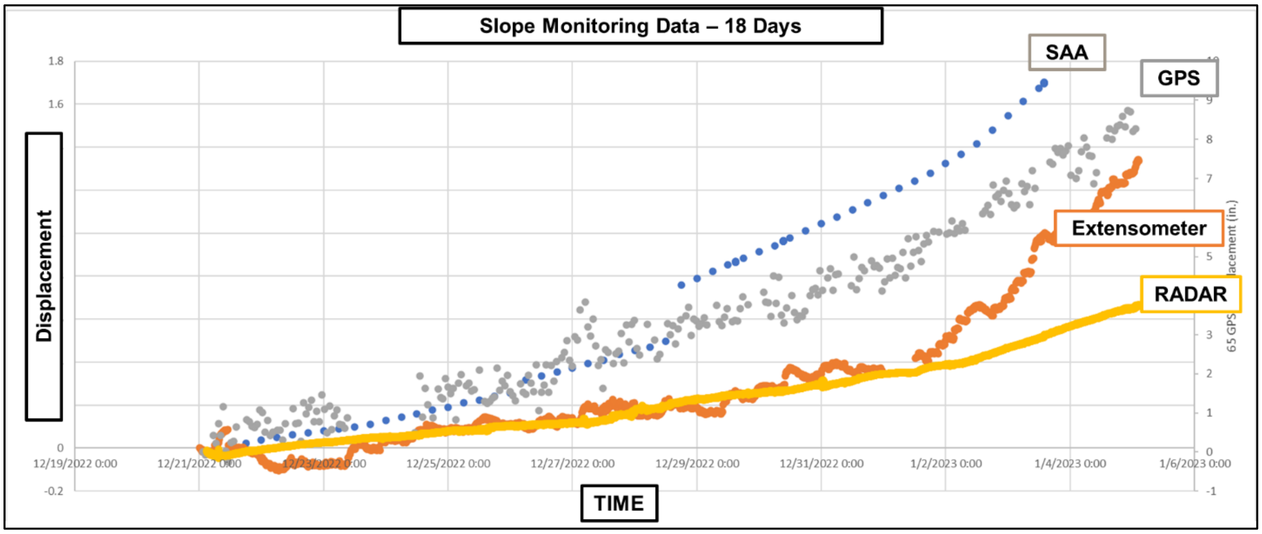

Figure 2-5 Different slope displacement magnitudes measured with different instruments for the same instability.

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 after Early Detection to target shearing surfaces and help define the failure depth.

Budgeting for sub-surface instrumentation can be difficult as it may fall under capital rather than operating budgets and the unanticipated movement will unlikely be in the capital plan. However, there is a sound safety and business case to be made that will grossly outweigh any unplanned spend. Combining sub-surface installations with planned geology drilling programs may be an option.

While more capitally intensive, consideration should be given to using sub-surface instrumentation that can withstand large strains e.g. Smart Markers.

2.3.1 Visual Inspections

Visual inspections are a critical part of a slope monitoring plan; and may form part of Early Detection.

The geotechnical team should walk, photograph and document the slope instability as much as safely possible.

Drone footage is a valuable addition to visual inspections where benches cannot be safely accessed.

The frequency of visual inspections should be increased as slope deformation develops.

- At a minimum, visually inspecting an instability two to three times a week is recommended. This should be increased to daily inspections as velocity increases.

- Tension cracks should be spray-painted and surveyed.
- Any rockfalls should be documented and surveyed.

2.4 Understanding the instability mechanism and updating the geotechnical model

Observed slope performance should be used to provide detailed information and verification on actual geological and structural conditions, slope behaviour in response to mining, and understanding 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.

2.4.1 Develop the Conceptual Model

A **sound conceptual failure model should be developed.** This is done through incorporating monitoring data and field observations (seeps, rock mass changes, tension crack locations, etc.) into the geotechnical model and updating the geotechnical model with new information. Steps may include:

- Draping terrestrial radar data over photogrammetry or lidar models and updating the geological or structural model where movement occurs along previously unidentified structures, rock fabric, or lithological contacts (Figure 2-6).

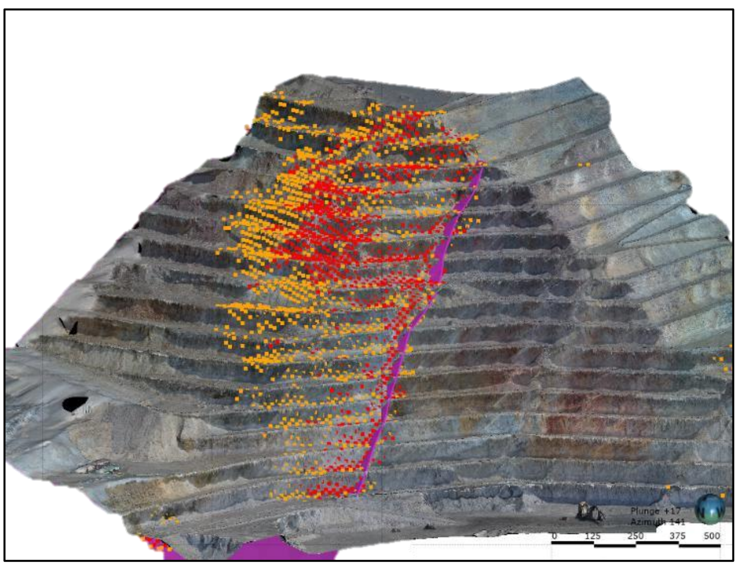

Figure 2-6 Draping georeferenced radar data over 3D photogrammetry model identifies the controlling fault on the right side of the instability.

- Using prism and GPS data to get movement vectors and show these on the geotechnical model (Figure 2-7). Vector orientation at the slope toe can help determine the instability mechanism and what remedial measures may work e.g. if upward deformation is observed at the slope toe, a buttress may be effective.

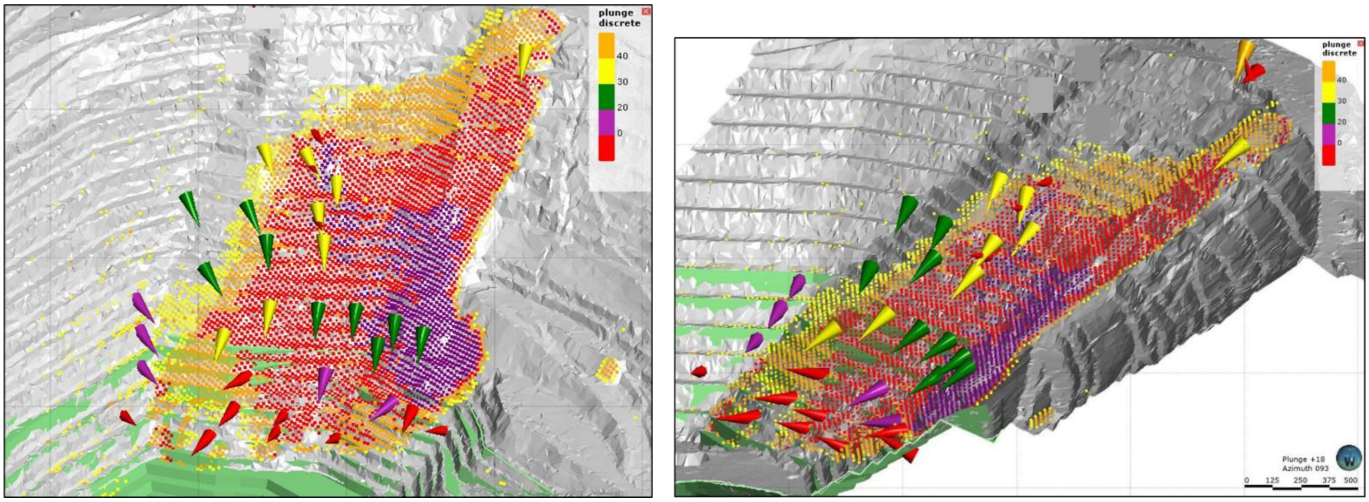

Figure 2-7 Prism and GNSS 3D displacement vectors (cones) and radar data displayed on a pit shell for a large instabiltiy. Most of the movement is downwards, but heave is evident at the slope toe (red vectors).

- Draping InSAR over 3D georeferenced model, looking at both total displacement and up-down displacements. InSAR may show heave at toe.
- Plotting shear surfaces (from sub-surface instrumentation) onto cross sections and the 3D geotechnical model. Check if shearing corresponds to existing structures. Are previously known structures being activated or should new structures be added to the structural model?
- Surveying surface cracking and checking alignment with structural model and radar data.
- Collecting additional geological, geotechnical and hydro-geological information and incorporating new observations into the refined geotechnical model.

2.4.2 Determine the “Response Zone” or Critical Zone

The “response zone” or “critical zone” is the area at the slope toe where mining and blasting causes a direct slope response. Beyond this zone, mining can continue, and slope movement does not occur.

This area is determined by evaluating slope response to blasting and mining.

The Critical Zone extents may be different for excavation than for blasting. They may also change from bench to bench as the mining sequence changes and the slope gets higher.

To determine the Critical Zone the process is as follows:

- **Blasting**: Review plots of deformation with time and include blasts taken and where they were taken relative to the instability. Note the magnitude of deformation from the blast, the time taken before the slope goes regressive, and if velocity after the blast was the same as velocity before the blast. Noting the blast size and confinement is valuable. Reducing confinement can have a significant reduction on slope response. Further details on blast data collection and blasting controls are given in Section 3.5.
- **Excavation**: Review plots of deformation with time and review tonnages removed from slope toe and where they were removed.
  - Slope response may be extremely sensitive in some areas during excavation. This may indicate daylighting of a key structure.
- Consider the slope failure mechanism when defining the response zone.

Important: It may not be clear-cut exactly where the response zone is. High rainfall or snowmelt can make mining responses more challenging to differentiate.

Furthermore, when defining the response zone, slope movement associated with an instability will have to be differentiated from general slope relaxation.

- **Obtaining a benchmark understanding of typical regressive movement rates seen from an excavation response is essential to define the response zone.**

Engineering judgement will be required here, which carries with it a degree of risk acceptance.

2.4.3 Numerical Modelling

Developing a numerical model of the instability mechanism can be a valuable tool to:

- Assess the potential impact of continued mining below an instability
- Evaluate the effectiveness of remediation options such as step-ins, buttresses, unloads, change in slope angle/configuration
- Evaluate the effectiveness of a potential depressurisation strategy

Slope monitoring data should be used to achieve a well calibrated stability model. The advantage of a moving wall is that the model can be back analysed to an SRF/FoS of about 1.0.

The challenge when using numerical modelling for forward predictions of an already pseudo-stable pit wall is that the SRF/FoS numbers will likely be at or below 1 and therefore provide limited value i.e. we know the slope will move but we don’t know if it will collapse or not. It may be almost impossible to determine from a model if a slope will collapse catastrophically or continue to deform. That said, looking at the change in FoS as the proposed mining cut progresses may give an indication to the likelihood of recovering the ore from the cut.

Note: most numerical models cannot handle large deformations i.e. the models stop converging.

Numerical modelling can be very valuable in designing and choosing suitable mitigation options. Mitigation options which can be analyzed numerically include step-ins, buttresses, unloads, and depressurization.

Remember that depressurization may look effective in a model, but there remains a degree of uncertainty as to how effective it will be in the actual slope, until it is tested in the field.

Suggest plotting FoS/SRF for different stages, or elevations of the mining cut. If a significant FoS/SRF reduction is only observed in the last say 1-3 benches, this could be a strong argument for progressing with the current design. If significant reductions in FoS/SRF are seen with immediate advances in the cut, this may support investigating a design change.

Another approach can be to plot simulated plastic displacement at various benches vs. time to look for steady vs. accelerating displacement trends.

The following table provides general guidance for FoS/SRF vs observed slope behaviour.

FoS/SRF Value	General slope behaviour
<1	Slope acceleration. Progressive behaviour
1	Constant deformation
1.0-1.10	Regressive behaviour
1.10-1.20	Tension cracks. Deformation seen in long-term trends. Note that tension cracks do not necessarily mean slope failure is imminent.
>1.2	Stable slope, little to no movement observed

Important: Using the results of a numerical model to set TARP triggers is not recommended.

Questions to ask at this stage:

1) How well do we understand the failure mechanism?
2) Has the geotechnical model been updated with the new slope monitoring data?
3) What design changes could be made to reduce the likelihood of collapse?
4) What operational controls can reduce the chance of collapse?
5) If the slope does collapse where will the failed material end up?

2.5 Economic Assessment – What is the likely consequence of a collapse?

The economic consequences of a slope collapse need to be considered. These consequences will help determine the best path forward for the mining operation. Consequences may be:

- Ore loss
- Ore deferral
- Ore dilution
- Infrastructure damage
- Loss of access to ore
- Loss of access to critical areas such as portals
- Damage or loss of equipment

2.5.1 Runout Analysis for Economic Assessment

Runout analysis should be conducted to evaluate the economic consequences of a potential collapse. The process for doing this is shown in Figure 2-8.

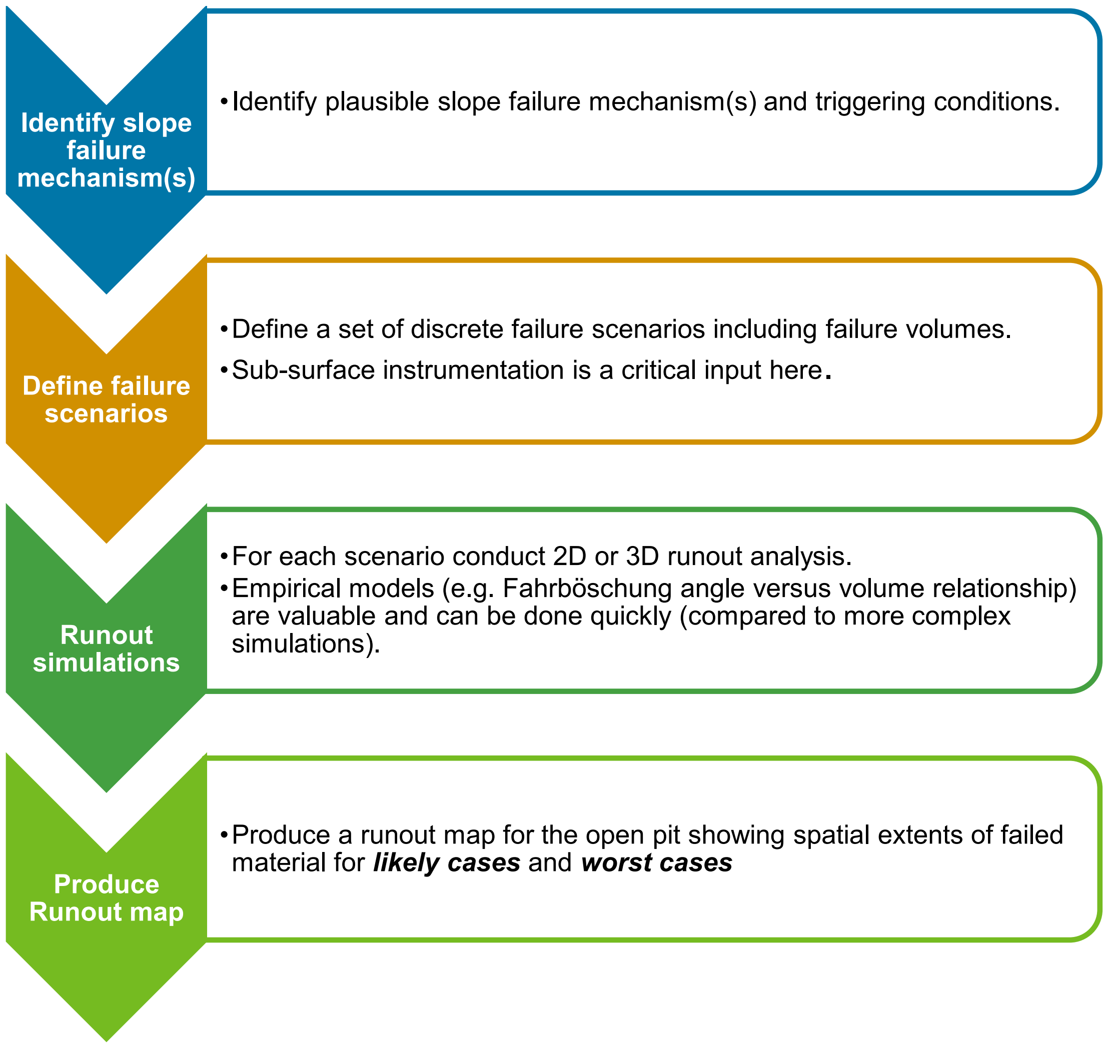

Figure 2-8 Example process flow for conducting a runout assessment.

Evaluate the options available to manage the instability

Before deciding how to proceed with the mine plan, it is necessary to understand the options available to manage the instability. The options under consideration may be:

- **Do nothing**
- **Design change** - Mitigation plan to reduce or eliminate slope movement
- **Implement Operation Controls** – continue mining on, or close to, current design. This involves keeping slope movement rates within manageable limits.
- Or, **more likely, a combination of design changes and operational controls.**

These options are discussed in the following sections.

Using a cost-risk analysis approach (Section 5) is valuable in evaluating the options and defending any decision to undertake slope mitigation and/or implement operational controls.

2.6 Mitigation options

In areas where it is not considered safe or cost-effective to progress the cut on design, or if a collapse has occurred, it may be necessary to mitigate the instability.

Mitigation involves a design change that aims to do some, or all of, the following:

- Bring the safety factor up above 1, and ideally closer to the design acceptance criteria, such that slope movement stops.
- De-couple the slope and prevent movement continuing as mining progresses
- Reduce the slope velocity to manageable rates allowing toe mining to continue with minimal delays.

The mitigation method chosen will depend on several factors including cost of the mitigation option, the operational capability and operating procedures, volume of the instability, depth to failure surface and the instability failure mechanism.

Mitigation options are discussed in the following sub-sections.

2.6.1 Mining Out the Failure

Mining out the failure is an option if the failure occurs along a specific structure and there is more competent rock behind the structure.

If the instability is occurring along rock fabric and through intact rock, mining out the failure may be less preferable since another instability may form behind.

Other considerations for mining out the instability include:

- If access is available from the failure crest to get behind the shear surface.
- Size of the area to be remediated such that the cost and time for remediation does not become uneconomical when assessed against other options such as a step-out.
- Sufficient working area exists at the toe to load out the material
- Need for breaking of oversize boulders to be loaded out and the associated cost of material rehandle.
- Any operational risks which may exist such as working on narrow platforms or below walls with limited catchment as the cut progresses.

Mining out of slope instabilities or failures can be done in the following ways:

- Cut out the failure from the top down (Figure 2-9), typically done using dozers where failed material can be pushed and ripped. In stronger, blocky rock masses, secondary blasting or use of rock-breakers may be required. For remediating smaller instabilities, it may be necessary to first dump in a buttress or "platform" to build a stable work area before cutting out the failure. As the material is pushed downwards it is then loaded out from the toe. It is important to note that as talus material is built up against the slope, surface monitoring here may not be possible and the operation must have controls in place to manage this risk.

  - Careful interpretation of monitoring data is required to differentiate what is related to mining spillover, rill settlement and what could be potentially deeper-seated movement.

- Where a slope failure has occurred in poor quality rock, one option is to cut out the failed material at a temporarily steeper slope angle then dump in better quality material with a higher friction angle. This can allow the slope to remain on design.
- Dig at the toe and have the failed material gradually feed to the shovel or loading equipment. Careful planning of equipment position and layout is required to minimize exposure. Use of remote equipment should be considered even though this may take longer to complete the project. In steeper pit slopes with blocky rock masses this option may not be possible due to excessive rockfall risk. This approach may be preferred if there is no access to the crest of instability.

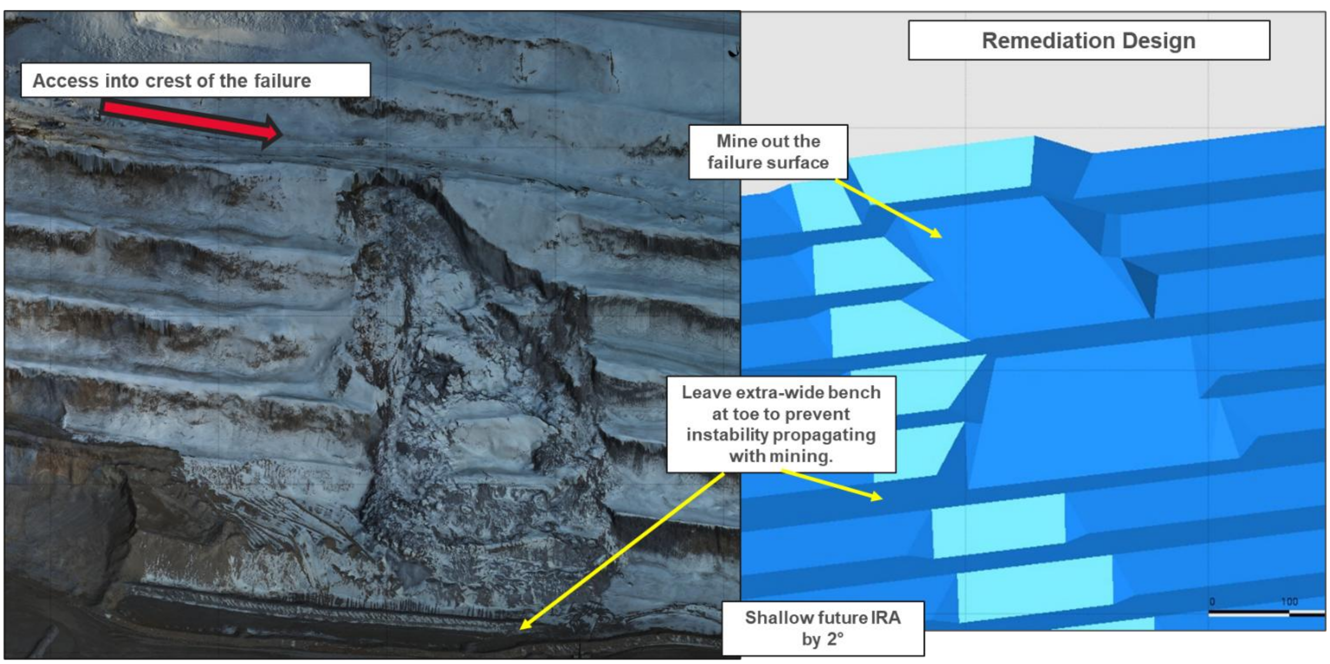

Figure 2-9 Example of slope failure remediation done from the top down. Access is available at the crest to cut behind the failure surface. Additional width is left at the failure toe to prevent instability propagating with mining. The inter-ramp angle in this example is reduced by 2° for rest of the phase to reduce likelihood of similar instabilities occurring.

2.6.2 Step-In

Leaving a step-in, or extra wide "geotechnical berm" may be required in the following situations:

- To de-couple the slope and prevent the failure mechanism progressing with mining and increasing in size
- To maintain toe support if the mechanism is a non-daylighting wedge.
- If it is considered unsafe to continue mining below a moving wall e.g. there is a risk of rapid acceleration such that evacuation cannot be done in a timely, safe manner.
- If an existing failure, or slumping has occurred which prevents the current design being achieved.

Unplanned step-ins are likely to have a negative business impact in the form of deferred or lost ore resulting in NPV reduction. Consequently, the design width must be optimized as much as possible to manage the risk but to also minimize the business impact. Where the step-in is used to de-couple the slope, the width will be highly dependent on the depth of the failure surface, and this must be understood through sub-surface instrumentation and detailed mapping if the failure is more structurally controlled. Use of a backfill buttress, constructed on the step-in, may reduce the step-in width required; however, this requires that the repose angle of the buttress materials is steeper than the inter-ramp slope angles being mined. It may be possible to steepen the wall below the step-in and remain on design if an instability is not expected below.

2.6.3 Buttresses

Buttresses can be placed at the toe of the moving slope to provide additional resisting forces and help stabilize the instability (Figure 2-10). They are typically built of rock fill sourced from waste material or low-grade ore that would normally go to waste dumps or stockpile. Buttresses are most effective when the mining cut is close to exposing the failure surface. Use of slope movement vectors are valuable in determining the effectiveness of a buttress. Where vectors are inclined upwards at the slope toe (typical of an active-passive type mechanism) the use of a buttress may be very effective (Figure 2-11). Detailed understanding of the failure mechanism is required to determine the size and particularly the required height of the buttress.

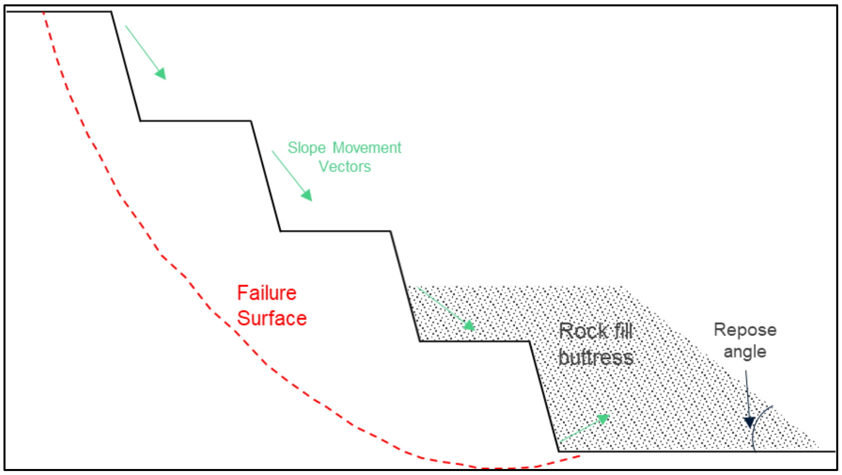

Figure 2-10: Use of buttress may be favorable where upward slope movement (green vectors) exists at the toe of an instability.

Buttresses will likely require a step-in for construction therefore the economic impact is similar to that of a step-in discussed in the previous section, plus the construction cost. However, additional mining delays will also likely be experienced while the buttress is being constructed.

A key consideration before implementing a buttress is: will mining continue below the buttress and does the geotechnical model suggest another instability may exist below?

A buttress provides toe support to an instability above, but adds driving load to any potential instability below.

With continuous review of slope monitoring data during placement of a buttress; it may be that a smaller buttress is required to satisfactorily reduce slope movement than originally designed for. That being said, the time required to construct the buttress (i.e. the mining pause) may be sufficient to allow the slope movements to go regressive, rather than the buttress itself.

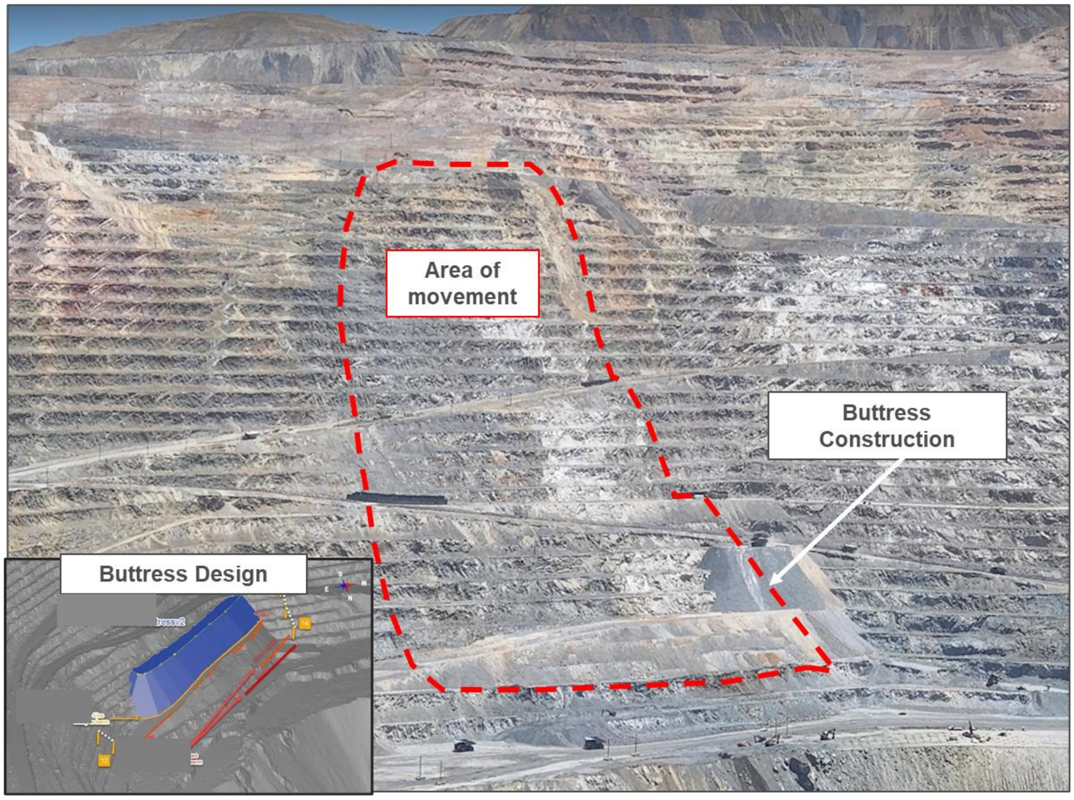

Figure 2-11:Buttress construction at the toe of a large moving wall to stabilize the area above.

Step-in or build a buttress?

The big question is always whether to step in or buttress.

Leaving the intact rock in has some advantages:

1. It is going to be more effective (i.e. stronger) than the buttress material,
2. It avoids the risk of placing the buttress while the slope is moving above.

If the step-in is in high grade then there would be a business case to try and take it and replace it with waste rock. So, the mining and geotechnical engineers have to weigh the risks with the costs. With a step in there may also (or most likely) be more ore left behind in the lower benches. So if the buttress can keep the slope "on design" then it would make the most sense. This is likely determined by the design IRA and the repose angle of the buttress materials.

2.6.4 Unloading

The idea of unloading an instability is to remove the driving forces and thus increase the factor of safety. One must understand that, in doing so, if the instability has a large frictional component, then some frictional resisting forces are also lost. Unloading a failure can be extremely impactful to an operation both in terms of additional cost and reduced productivity. When deciding if an unload is justifiable, stability modelling can be valuable as a guide to look at any FoS difference an unload may provide. The stability model may help decide the volume of material to be removed.

If operating at the toe of a deforming slope, an unload may make the mass more manageable. That is, slope velocities are reduced, and the time taken for velocities to return to safe operating limits after a period of acceleration (perhaps from a blast, mining or weather event) is much less; thus reducing mining delays. However, quantifying this benefit from a design perspective is extremely challenging and may be difficult to then assess the benefit against the cost and production impacts.

Figure 2-12 Unload of a deforming slope to mitigate the instability (photo courtesy of Lauren Shyluk).

To safely carry out a slope unload in practice, clear operational controls and planning limits need to be built into the mine plan and communicated to all teams. These may include:

- Bench-by-bench release limits (or “gate checks”), based on slope displacement or velocity thresholds from monitoring data.
- Toe exclusion zones during the first stages of unloading until slope movement rates reduce to within acceptable TARP levels.
- Controlled blasting practices to prevent accelerations, or a collapse of the unstable mass below.
    - *Note: It may not be possible to unload an instability if it is particularly sensitive to blasting*.
- Re-entry criteria, especially after blasting. Criteria may be clear regressive behaviour and/or velocity within a specified limit. Pauses following a blast should be built into the mine plan.
- Controlled excavation rates (for example, limiting tons mined per shift) to prevent sudden loss of confinement along daylighting structures.
- Ongoing FoS review of the calibrated stability model after each major unload stage to check how the balance between driving and resisting forces is changing. Slope unloading can be coupled with toe mining to maintain a target factor of safety and keep observed movement (Figure 2-13) within tolerable limits (dictated by the TARP).

Important: Pushing material over the slope crest during an unload can limit surface monitoring. Every effort should be made to load material out from the crest.

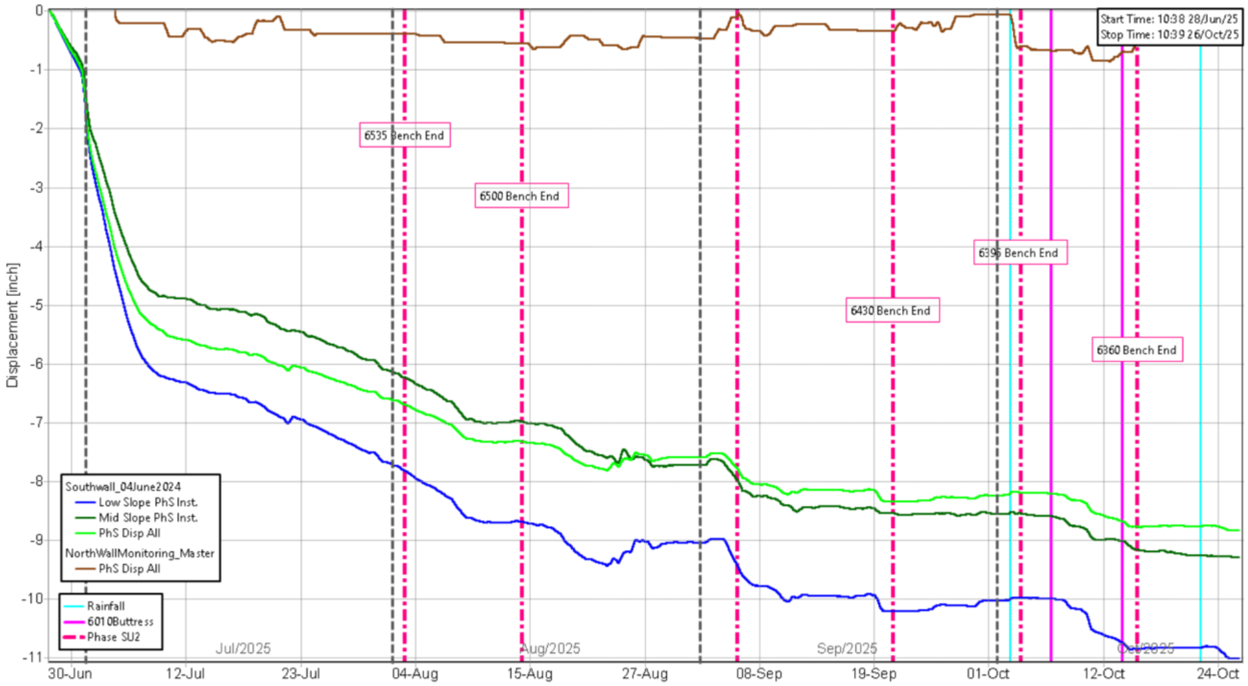

Figure 2-13 Radar displacement data showing regressive slope behaviour following each bench removed (pink lines) during an unload (Figure courtesy of Lauren Shyluk).

3.0 OPERATIONAL MINING CONTROLS

Operational mining controls are implemented to:

- Reduce the magnitude of deformation and potentially reduce the likelihood of a collapse
- Keep slope velocities within manageable rates such that it is safe to operate below them and sufficient warning is maintained such that personnel can be evacuated.

When deciding to progress mining below a moving wall the Business must:

- Have sufficient confidence in the slope behaviour that ***continued deformation is expected*** rather than a catastrophic collapse
- Be able to safely manage the risk of a slope collapse. Remember that by mining below a moving wall, more demand is placed on geotechnical teams.
- Understand and accept the additional costs (often in terms of production delays) associated with implementing the operational mining controls.
- Understand and accept the economic risk(s) of a slope collapse.

The controls discussed here are beyond those considered as standard good mining practice.

From a risk perspective, these controls can be thought of as **reducing the probability of a slope collapse**.

3.1 Depressurization

Depressurization measures may well already be in place as part of standard geotechnical operating procedures at the site.

Additional / targeted depressurization may be required to reduce slope movement for mechanisms which are particularly sensitive to increases in pore pressure.

Targeted measures may include:

- **Horizontal drain drilling**. Fan drilling at multiple locations every bench to continually relieve pressure as mining progresses. In hydro-geologically complex environments it is often better (greater chance of success) to have a thorough, systematic drilling program rather than try targeting specific areas.
    - Horizontal drain drilling can take up space on the operating bench and may cause production delays. It needs to be built into the mine plan.
    - When slope velocities are high, it may be unsafe to drill horizontal drains. This limitation should be considered. A targeted drilling program may achieve more holes in the summer months when slopes are dry.

  - Sometimes it is beneficial to drill drains from the stable side of the slope and target structural features defining the instability, especially if water perches on these structures.
  - **Remember, slope movements may shear the horizontal drain holes rendering them ineffective.**
- **Vertical drains** may be an option where sub-horizontal low permeability horizons exist e.g coal mining. By drilling vertical drains this can relieve pressure below the pit floor by piercing the low permeability bed or seam.
- **Surface water management**. This may need targeted focus or effort if surface water management is not already well controlled. Every effort should be made to direct water away from the potential instability.
- **In-pit and ex-pit pumping wells**. These can be very effective if the hydrogeology is well understood. They are costly to install and require permanent infrastructure. There may also be significant lead time to drill and commission these wells.
- **Drainage adits** – These would likely be considered more Mitigative than an Operational Control since the capital spend and time to install would be significant. If there is good confidence in the hydrogeology model and their reliability can be demonstrated then this might be an option implemented in extreme cases.
  - Another advantage of adits is that you can drill drainholes into the slope from behind. In cold climates the drainholes in the adit won’t freeze up. There is a big advantage having the drainholes working year-round as opposed to just in the warmer months when the outside temperatures allow outflows.

Pore pressure data from VWP’s installed in the transient zone should be plotted against slope movement and rainfall data to assess the potential effectiveness of depressurisation for managing the instability. However, it can be challenging to decipher the results (Figure 3-1) because as the slope deforms and the rock mass dilates this can release pressures in some areas but allow water pressures to build up in other areas.

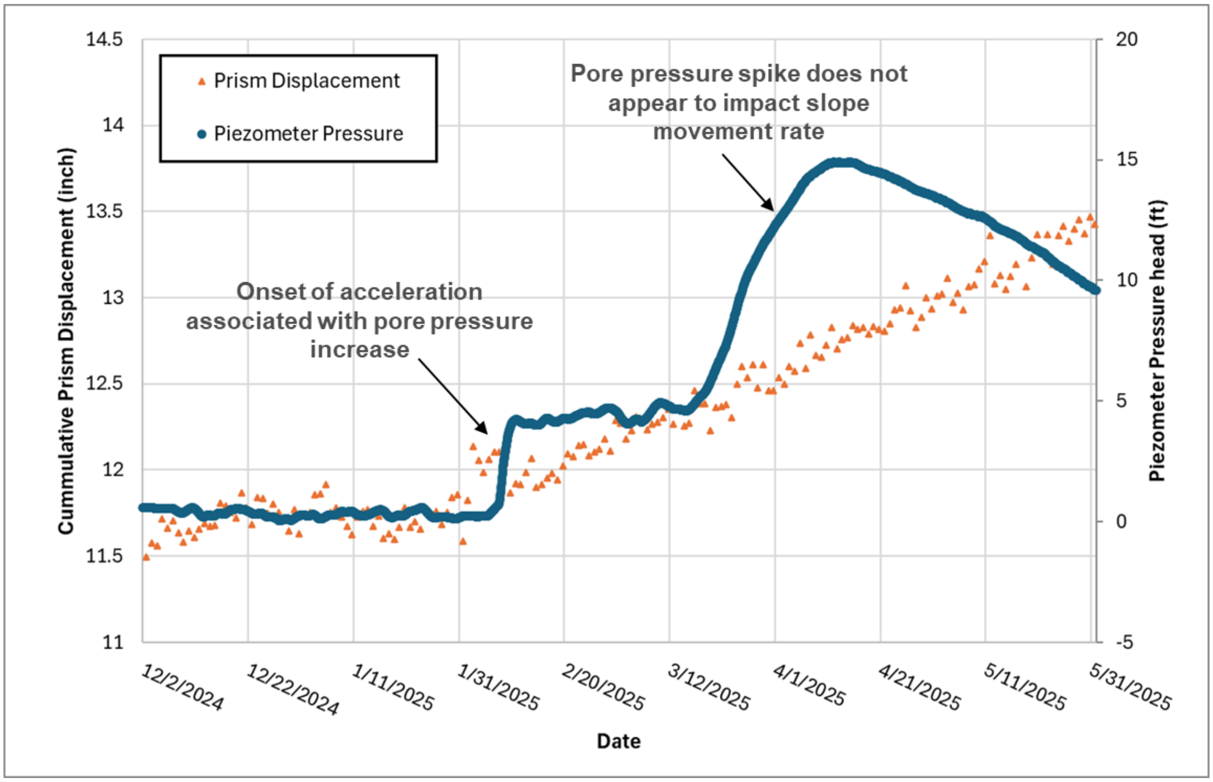

Figure 3-1 Slope displacement (prism data) plotted with piezometer data. The onset of acceleration appears to coincide with water pressure increase. However the later spike in pore pressure does not have a material impact of slope displacement.

3.2 Reduced Excavation Rates

Where a pit slope is sensitive to excavation at the toe, limiting the excavation rate (i.e the tons mined per shift, or per week) can allow the slope to respond more gradually and reduce the chance of progressing to a collapse. While restricting tonnage will obviously hinder production, it may be favourable to numerous TARP delays or a slope collapse. The goal here is to limit the excavation rates such that the slope velocity remains within manageable limits.

Determining a suitable excavation rate is very challenging and should evolve bench-by-bench as understanding of slope behaviour increases. Dig rates could be given as a 12-hour cap, a 24 hour cap or a multi-day rolling average to allow flexibility in the daily mining plan. Continued review of slope response to excavation is required.

3.3 Mining Pauses

In addition to reducing the dig-rate, it may also be necessary to incorporate mining pauses into the mine plan to allow slope movement rates to reduce. Figure 3-2 shows slope response to high excavation rates followed by a mining pause and then implementation of reduced dig-rates to keep slope velocity manageable. Developing contingency plans for alternate ore supply in case of extended pauses (e.g. stockpile feeds) is recommended.

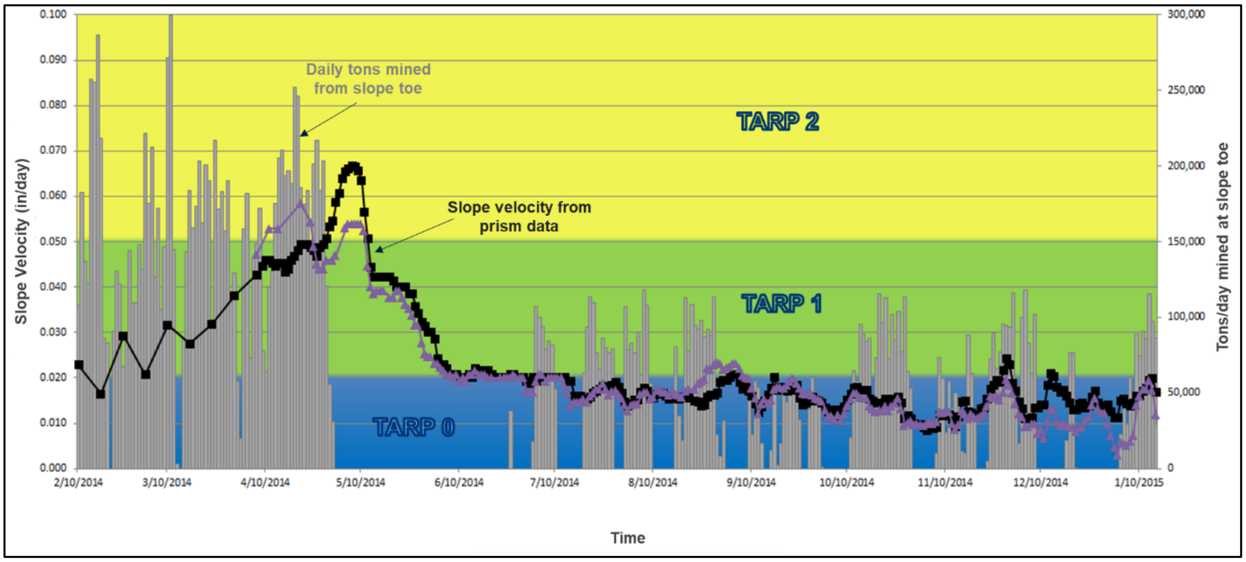

Figure 3-2: Slope velocity plotted against tonnage mined from slope toe. A mining pause followed by reduction in dig-rate maintains the slope below TARP 2 rates.

Ongoing review of slope performance against blasting and excavation spatially is critical for determining where tonnage restrictions and blast controls need to be applied. In many cases it may not be necessary to implement these controls across the entire bench, rather just where a slope response is observed. Identifying this “response zone” can help optimize the mine plan.

3.4 Free Digging

If the rock is weak enough or fractured enough it may be possible to free-dig the bench at the toe of the moving wall without blasting. This may be preferable to blasting as it will result in little to no damage to the slope. Furthermore, it may reduce production delays if the slope does not accelerate beyond a certain threshold used to trigger evacuation. If free digging is planned, it may be sensible to drill out the blast pattern beforehand so if the shovel cannot free-dig all the intact material, the remaining block can be loaded and shot without incurring production delays. Free digging is unlikely to be preferred from an Asset Management or equipment maintenance perspective but any incurred additional maintenance costs must be evaluated against the benefit of limiting slope damage and slope response.

3.5 Wall Controlled Blasting Below or Above an Instability

Blasting near, below or above, moving (or potentially unstable) pit walls requires careful controls and strategic planning to ensure the safety of personnel and equipment, and the integrity of the wall. Blasting below pseudo-stable walls may result in:

- Immediate slope collapse.
- Slope acceleration which then results in collapse.
- Slope acceleration followed by regression, but resultant movement rates are faster than those pre-blast.
- Slope acceleration followed by regression to original movement rates.

Subsequent blasting below a moving pit wall may see slope responses take longer to regress, and the magnitude of progressive-regressive cycles increase (Figure 3-3). In both instances this is an indication of rock mass dilation and further reduction in stability.

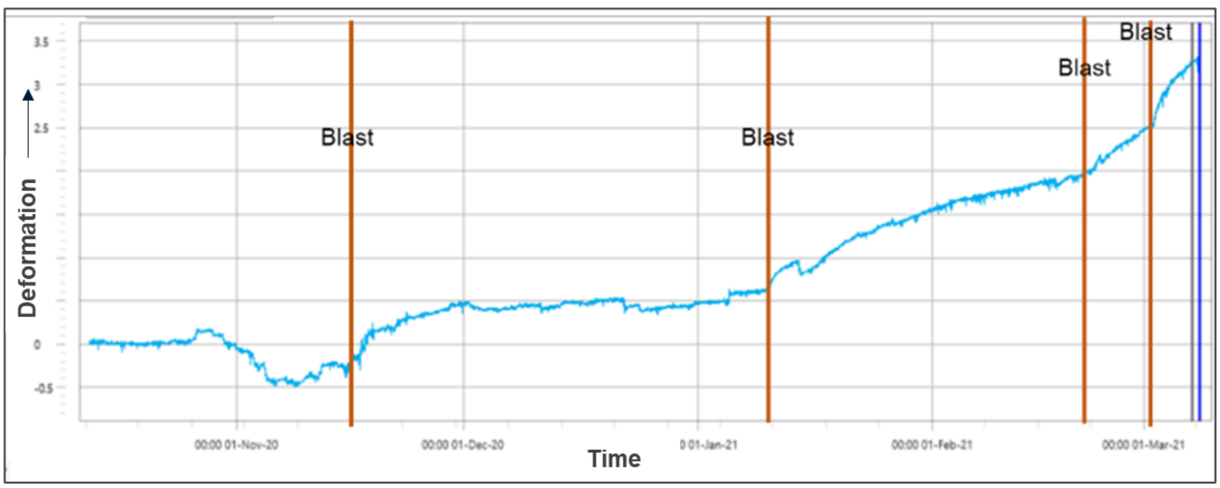

Figure 3-3: Radar data showing increased magnitude of progressive-regressive cycles following multiple blasts.

Blasting at the toe of a pseudo-stable wall may exacerbate slope movement due to one, or several, of the following:

- High PPVs.
- Blast vibration causing the slope to resonate at, or close to, its natural frequency.
- High ground displacement.
- High acceleration, above which slope deformation occurs.
- Excessive blast damage into the rock mass at the toe such that slope acceleration occurs. This may also be progressive i.e. occurs continually on every bench exacerbating, or even causing, an instability.

- Rapid removal of toe support as the blast breaks up the rock mass causing slope acceleration.

When designing the blasts it is critical to understand the failure mechanism and which of the factors above contribute to slope displacement. Detailed comparison of slope monitoring data (both surface and sub-surface) together with seismograph data and the blast design is required. Radar data with fast scan times are the likely preferred option for analyzing slope response from blasting.

Seismographs should ideally be placed at the toe, center and crest of the instability; and if possible, in the same location for every blast to ensure consistent data collection.

Remember to bury the seismograph (typically more than 8-10 inches in the ground and cover and compact with fines such as drill cuttings), or anchor it to a concrete pad. The seismograph needs to move with the ground and not become "de-coupled" from it.

Data collected as part of a blast assessment should include:

- Radar responses including: velocity ratio, velocity after the shot, acceleration, and response time i.e. how long before slope returns to pre-blast rates.
- Attenuation curves (site laws) should be developed for blasts at the slope toe. If blasts are significantly different in design, especially regarding confinement (e.g. production blasts vs trim blasts) then site laws should be developed for different blast types.
- Signature holes to determine resonant frequency of rock mass.
- Develop a database showing which values of frequency and PPV cause a slope response. The site law(s) can then be used to guide suitable charge weights per delay to keep PPVs below the required threshold.
- Plot Z-curves (PPV vs Frequency) of blasts and colour each blast red, orange or green depending on the level of blast response. This can provide guidance as to which PPVs at which frequencies cause a slope response.
- Record the high/low ratio on FFT plots i.e. % of energy above and below a specified frequency.

Blasting controls to minimize slope response may include:

- Reduce size of shot.
- Deck the pattern to provide vertical relief. Use delays of 250-500ms between decks. Ensure inert deck is sufficient that sympathetic detonation (top charge detonates the bottom charge) does not occur. For 8inch diameter holes the inert deck should be > 10ft.
- Limit the number of holes per delay.
- Limit confinement through steep, clean free faces and ensure good face burden to provide horizontal relief.

- Change blast orientation and timing design relative to critical geological structures such as faults. Avoid shooting up-dip of critical structures.
- Develop frequency controlled blast timing designs.
  - *Note: Pit slopes will have certain frequencies which they "naturally" resonate at (typically from 5-80Hz). Softer rocks will have lower resonant frequencies compared to stronger, massive rocks.*
  - *If the slope's resonant frequency is similar to the dominant frequency from the blast then the effects from the blast are amplified causing higher displacement levels and potentially more slope movement.*
  - The goal with frequency controlled timing is to concentrate the blast energy at higher (or lower) frequencies than the resonant frequency of the slope and cause less displacement.
  - Having simple blast shapes will make it easier to implement the timings. i.e. it is easier to simulate and develop timing designs for patterns with consistent number of rows across the pattern.
  - Placement of seismographs to compare actual blast vibrations with those predicted is critical for blast assessment and refinement. Figure 3-4. shows an example of seismograph data for blasts with and without frequency controlled timing.

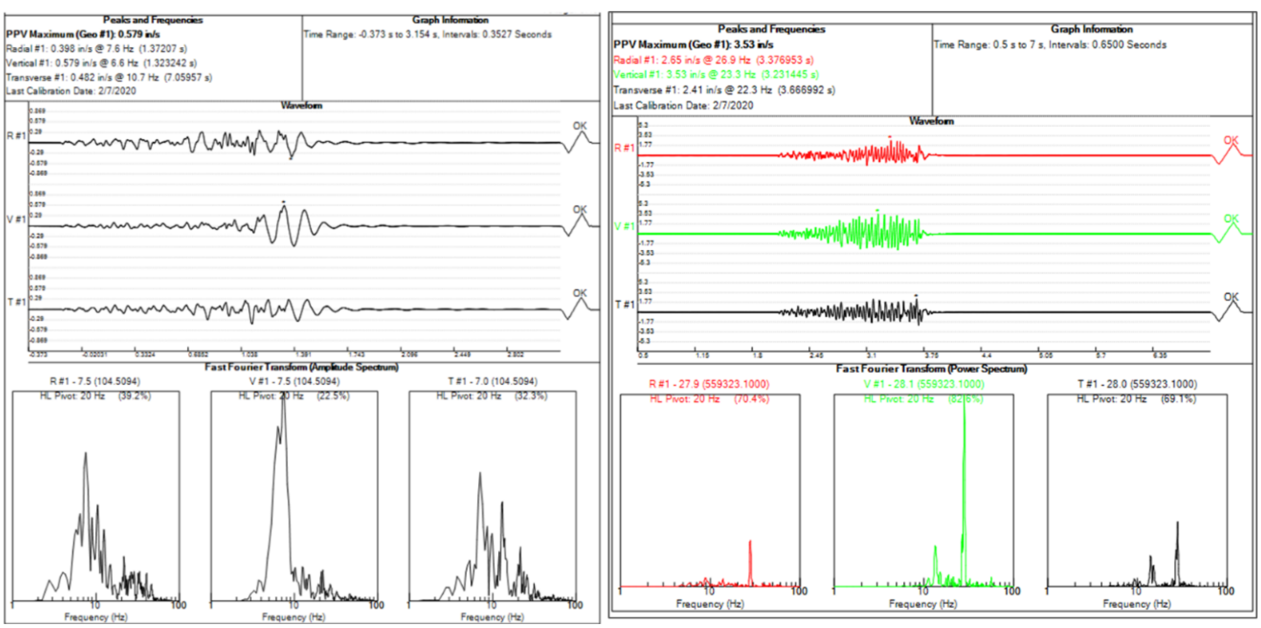

Figure 3-4: Seismograph data for blast without frequency controlled timing (left) and with frequency controlled timing (right) where the majority of energy is concentrated around 30Hz, with a smaller amount at 15Hz.

Safety controls are required when blasting below a moving wall, which include:

- Live monitoring review of slope behaviour prior to, and during, drilling and loading of the pattern.
- Extend isolation at crest and toe during blast in the event of a collapse.
- Stand-down, or mining pause, after the blast while the Geotech Engineer reviews the slope monitoring data. The pause duration should be planned ahead of time. Access to slope toe and crest can be granted once clear regressive behaviour is observed and slope rates are within the desired TARP levels (Figure 3-5). These pauses should be built into the mine plan.

Figure 3-5 Example of blast response shown on velocity-time plot with the TARP levels displayed in the background. If access to the slope toe is allowed at TARP 2 that could be tolerable from a production standpoint. If the TARP states that access not permitted until TARP 1 that could be extremely detrimental to production.

Performance of each blast should be assessed against agreed upon success criteria. Such criteria will likely be slope response time, amount of acceleration observed, and mining delays incurred. An example is shown in Figure 3-6.

Ideally, combining more data on one graph can give a comprehensive record and data set. An example is shown in Figure 3-7 which combines radar data, seismograph readings, rainfall, and frequency limit for the site.

As with all blast designs, a continuous feedback loop must exist for designs to be continually optimized.

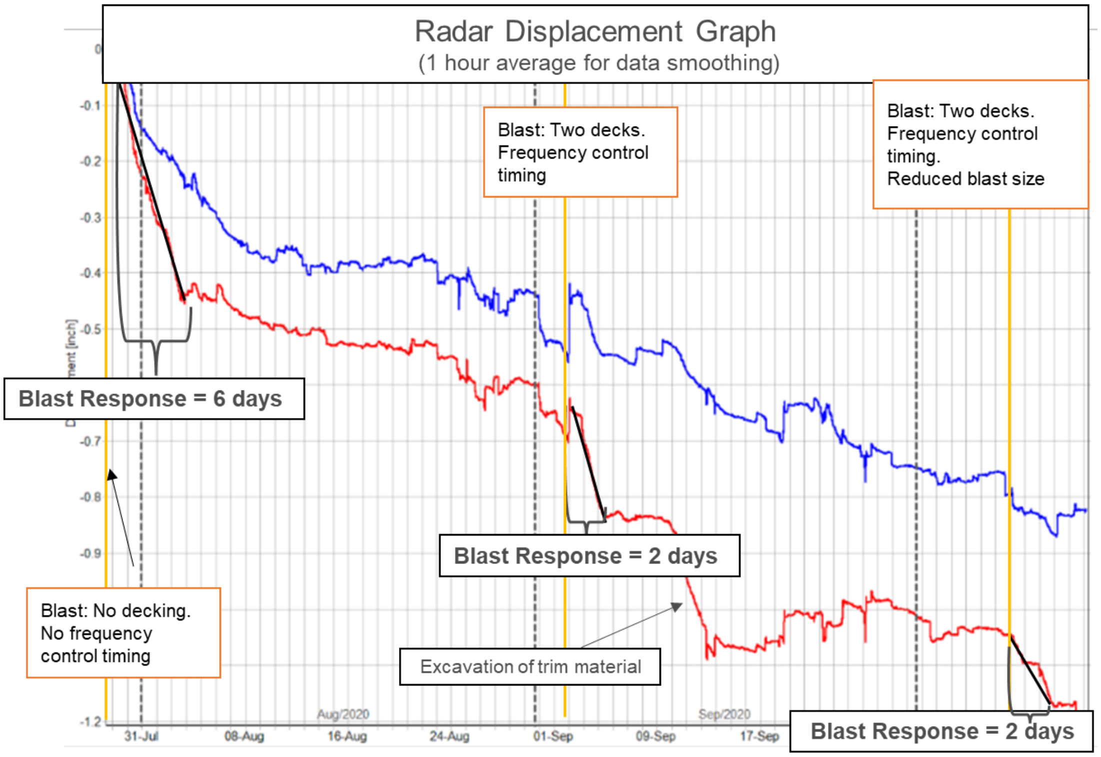

Figure 3-6 Using ground-based radar to review slope responses to blasts (orange) and excavation on a Displacement vs Time plot. The red time series shows reduced deformation as blast design improves.

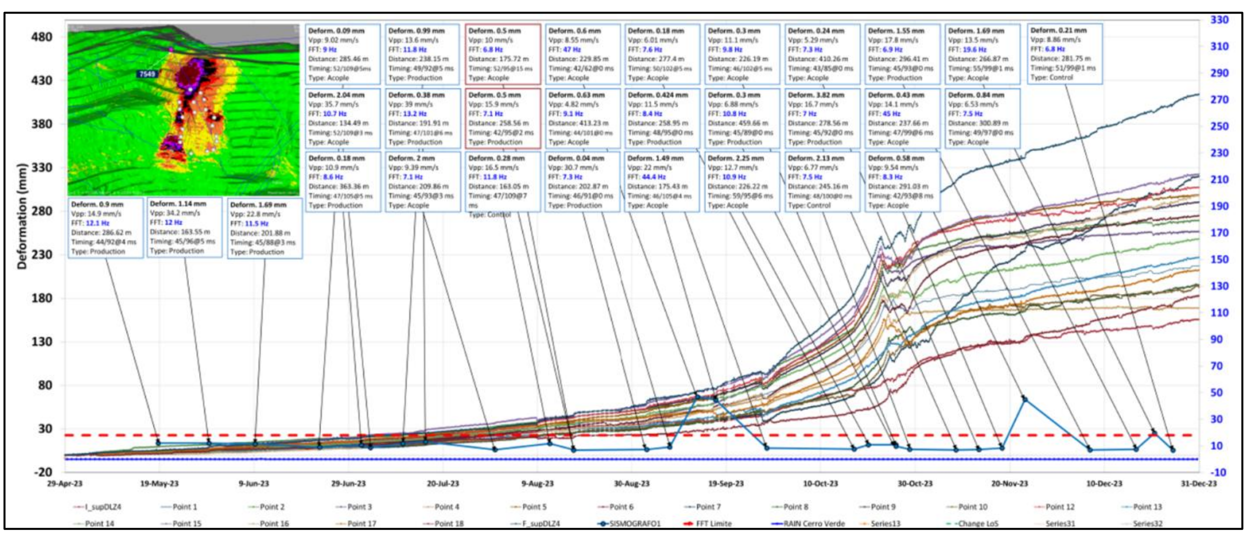

Figure 3-7 Radar data combined with sesimograph readings (cyan), rainfall data (blue) and site frequency limits (red dashed line). Image courtesy of Luis Tejada.

Remember, even with excellent blasting controls, the slope may respond to blasting. This is likely due to rapid removal of toe support. The slope then moves and relaxes in response.

3.6 Ground Support

In very specific cases, ground support may be implemented to improve stability and keep the slope on design. This approach is likely to be only cost effective when the instability is relatively small, such as a multi-bench wedge. Using ground support to stabilize an inter-ramp or overall slope-scale instability will likely be cost (and time) prohibitive except in extreme cases.

In stronger rock masses, ground support may involve post-tensioned anchors, installed sufficiently far behind the failure surface and tensioned to mobilise the shear strength along the failure surface.

In weaker rock masses, ground support may be required to increase stability of the rock mass itself, as well as mobilizing shear strength behind a potential shear surface. Tighter spacings and fully grouted rock bolts may be applicable here. High tensile mesh, cable strapping and shotcrete may also be incorporated into a ground support design system.

Using ground support to stabilize critical infrastructure such as a haul road or areas below a conveyor system may well be justifiable.

A few comments when considering the use of ground support:

- Installing ground support requires considerable time, money and effort.
- Bench turnover (mining rate) may be significantly impacted while ground support is installed.
- Contractors used for the work should be experienced and become part of the Mining Team. They should be involved in mine planning meetings and understand where their work fits into the weekly and monthly mine plan targets.
- Undertaking installation of ground support can create an elevated risk for personnel if not well-managed.
- There may be a perception by Upper Management and non-geotechnical personnel that the installation of ground support guarantees the slope will not fail. Obviously this is not the case, and the level of risk must be understood and well communicated.
- A detailed ground support design and geotechnical analysis combined with a cost-risk approach will be required to evaluate if ground support is the preferred option over slope shallowing or other mitigative options. The decision to then proceed with ground support should be made by Upper Management, not the Geotechnical Engineer in isolation.

3.7 Flexibility in the Mine Plan

Having a flexible mine plan with contingency built in is critical when operating below a moving wall, or when instabilities are expected. Plans must be in place in the event of a slope collapse, and in the event of extended mining delays due to movement rates being too high to safely operate below the moving wall. The following list of contingencies has proven successful in open pit mining operations:

- Provide multiple access to the ore faces and pushbacks.
- Ensure availability of stockpile ore (noting that in many cases stockpiles will provide lower grade ore).
- Establish additional ore faces before instability occurs.
- Plan wide pushbacks for improved production rates.
- Provide for failure costs into schedules and budgets.
- Build geotechnical delays into mine plans. These delays may be from blasting pauses, slower dig rates, high TARP levels, etc.
- Build contingency for slope remediation into mine plans and budgets, an example is shown in Figure 3-8.
- Ensure multiple access roads exist into the pit to de-risk the operation should a haul road be impacted by slope instability. That being said, providing multiple access and planning wide pushbacks requires additional stripping; and this must be weighed against the consequences of failure if these precautions are not taken.
- Avoid, where possible, stability impacting critical infrastructure. This may not happen in reality, and in such cases, the cost-risk analysis approach (Section 5.0) is very valuable in deciding the best course of action.

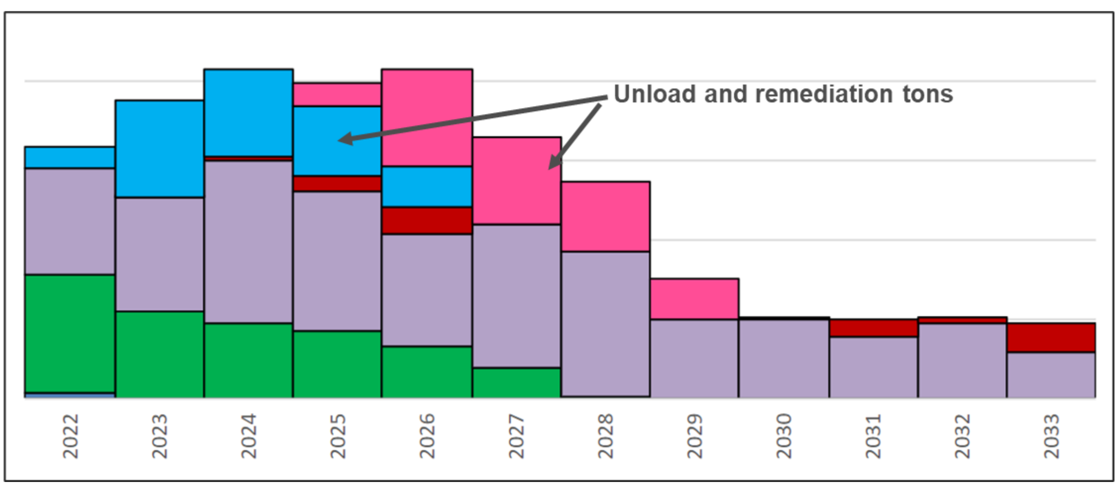

Figure 3-8 Example of mine plan with allocated tons each for "geotechnical contingency" such as failure remediation and unloads.

Once the adjustments to the mine plan are made, the new forecast and economics can be estimated.

3.8 Mining Cost Implications

All operational controls come with cost implications for the operation. Most of these costs are in the form of a reduction in mine productivity which may

- Reduce free cash flow year on year
- Reduce overall NPV
- Create a risk of an “ore gap” between two mining cuts. i.e. if the rate of mining a cut in waste is reduced and does not reach ore before the current ore cut is depleted.

The cost of progressing below the instability should be evaluated against the cost of mitigative options. This will facilitate a decision making process.

Remember, the safety risk is a critical factor in the decision making process. Mining a moving slope carries a higher safety risk than if the instability is designed out (mitigative option).

How to evaluate the safety risk and evaluate the best option for dealing with the instability is discussed in Section 5.

4.0 TARP DEVELOPMENT AND TARP EFFICACY

The Trigger Action Response Plan (TARP) should describe all the aspects of both safety and economic management of a deforming slope. It must include the Operational Controls being used to manage the instability. The TARP required cannot be a generic one. Instead, it must be specific to the instability failure mechanism, the slope behavior and the business risk.

- The TARP is a critical control for how an instability is managed. This control sits on both sides of a bow-tie risk diagram.
- In the context of safety-risk and overall cost-risk analysis (Section 5), it is critical to think about TARP Efficacy
- ***TARP Efficacy is the likelihood the pit floor is evacuated before failure occurs.***
- TARP efficacy impacts life safety
- TARP efficacy may also impact the probability of slope collapse (because it includes the controls to reduce slope movement).

4.1 Considerations when building a TARP

Before developing TARP triggers, the operation should consider the following:

- **What is the ability of the operation to respond to evacuations**. How often does evacuation occur? Are teams well versed in such procedures? How much equipment needs to be moved, and how long will this take? This is important when considering how far ahead of time to evacuate.
- **Economic Risk of a Collapse**. Can a slope failure be tolerated? Is a design change preferable to a collapse? In these cases, tight trigger thresholds may exist for lower TARP levels allowing mitigations such as unloads or buttresses to be designed and executed.
- **Collaboration**. How interactive is the Geotech team with the Operations team, Mine Dispatch, Mine Planning teams, etc.? The TARP will involve response from many groups on site and perhaps other teams in corporate roles. Are all teams in agreement with the approach chosen to manage the instability?
- **Geotechnical Team capability and capacity**. Is the team capable and sufficiently staffed to monitor and manage potential instabilities? Does the level of experience exist within the team to make difficult decisions under pressure? Is there an on-call system in place, or even better, a Monitoring Centre with dedicated day shift and night-shift personnel. Is staffing sufficient to cover absences from vacation, sick leave, parental leave, etc.? Is staff turnover high on site or is knowledge retention good?

- **Monitoring coverage and redundancy**. Is there sufficient monitoring coverage on the slope? What happens if equipment stops working or communications is lost? Is there are team of Geotechnicians able to fix it quickly? Would coverage be lost if certain elements of monitoring equipment went offline? And if so, how long can the Operation continue without coverage?
    - Remember: additional monitoring units such as radars make the Geotechnical Engineer's life busier not simpler! But ignorance is not bliss!
    - There will need to be a compromise of too many vs too little radar units with real time alarms.
- **Risk tolerance**. Does the Operation understand the risk it is undertaking and is the risk brought to a satisfactory level by the TARP? See Section 5 for guidance on Safety Risk and Tolerances.

Geotechnical Capability – Why are slope movements not detected when using radar?

A critical part of TARP efficacy is the ability of the Geotechnical Team to identify slope movement using radar data.

There are common reasons why failures are often not detected. These are:

1. Setting up alarms incorrectly within the software.
2. Using stability models to guide alarm levels e.g. "the model said we'd get 2m of displacement so that's what we set the alarm at"
3. Insufficient evaluation of existing data when choosing alarms. It's important to ask: Are the thresholds suitable? Did we miss anything historically and why? Do we have too many alarms?
4. Staff turnover "the alarm was like that when I got here". And a lack of training for new staff.
5. Masking and geocoding i.e. slight misalignment of the DTM with Radar data. This is particularly relevant for large pits and/or when radars are shooting long distances. It is important not to get too precise with masking out areas that may be more sensitive to slope movements (e.g. slopes close to haul roads).
6. Consultants or third parties setting very tight alarms to cover for liability. These cause too many false alarms which then just get turned off or ignored.
7. Lack of capacity in the on-site monitoring team to conduct data analysis, work overload, too many instruments, lack of analysis tools, human distractions and fatigue.
8. Radars are line-of-sight. There may be no suitable position, or a reluctance at site, to place the radar in an appropriate location to see the instability (where movement direction is generally downwards).

4.2 Developing Effective TARP Triggers

Triggers should be developed based on a detailed review of the slope behaviour from monitoring data.

- Data from all available monitoring should be plotted and compared with:
    - Other monitoring equipment data for cross-validation.
    - Blasting events,
    - Weather events,
    - Mining progression.
- Reviewing slope response to mining shows where the “Critical Zone” is. Beyond this Critical Zone, mining can continue without a slope response. This zone will be some distance in front of the slope toe and some distance laterally.
- TARP must be updated regularly and as new information is available, and/or slope mechanism changes, or business risk changes.

Once the TARP is developed it should be continually reviewed and updated as new information is obtained and more is learned about the slope.

Review by external parties such as Corporate Geotech, External Consultant or Review Board is recommended.

4.2.1 TARP Levels

Most TARPs will have around 4-5 levels. Broadly speaking, TARP levels 1 and 2 will be economically focused; that is the triggers are tight and related to early detection. The responses for TARP levels 1 and 2 will likely involve understanding the failure mechanism and then implementing controls and/or design changes to prevent a collapse.

TARP levels 3 and 4 relate more to safe management of a slope deformation that is trending to collapse. While collapse is never the desired outcome, it is absolutely critical that an effective TARP is developed for this scenario.

A broad example of each TARP level is as follows:

- TARP 1 – an area of concern is first identified. Operational mining controls in place.
- TARP 2 – movement rates have increased very slightly and action is required to reduce the likelihood of the slope progressing to a collapse. Response may include mining pauses, unloads, step-ins, buttresses, plus adding more monitoring equipment.
- TARP 3 – collapse may be developing, isolate areas for safety. **Important to note that acceleration to collapse could be quick and TARP levels might be bypassed, or not spend very long in TARP 3 for example (Figure 4-1).**

  - Strategically staging equipment to regain access and start mining again upon slope collapse should be considered at TARP 3 (or perhaps TARP 2).

- TARP 4 – failure imminent. For large failure masses critical areas should already be evacuated. Evacuation extents may increase.

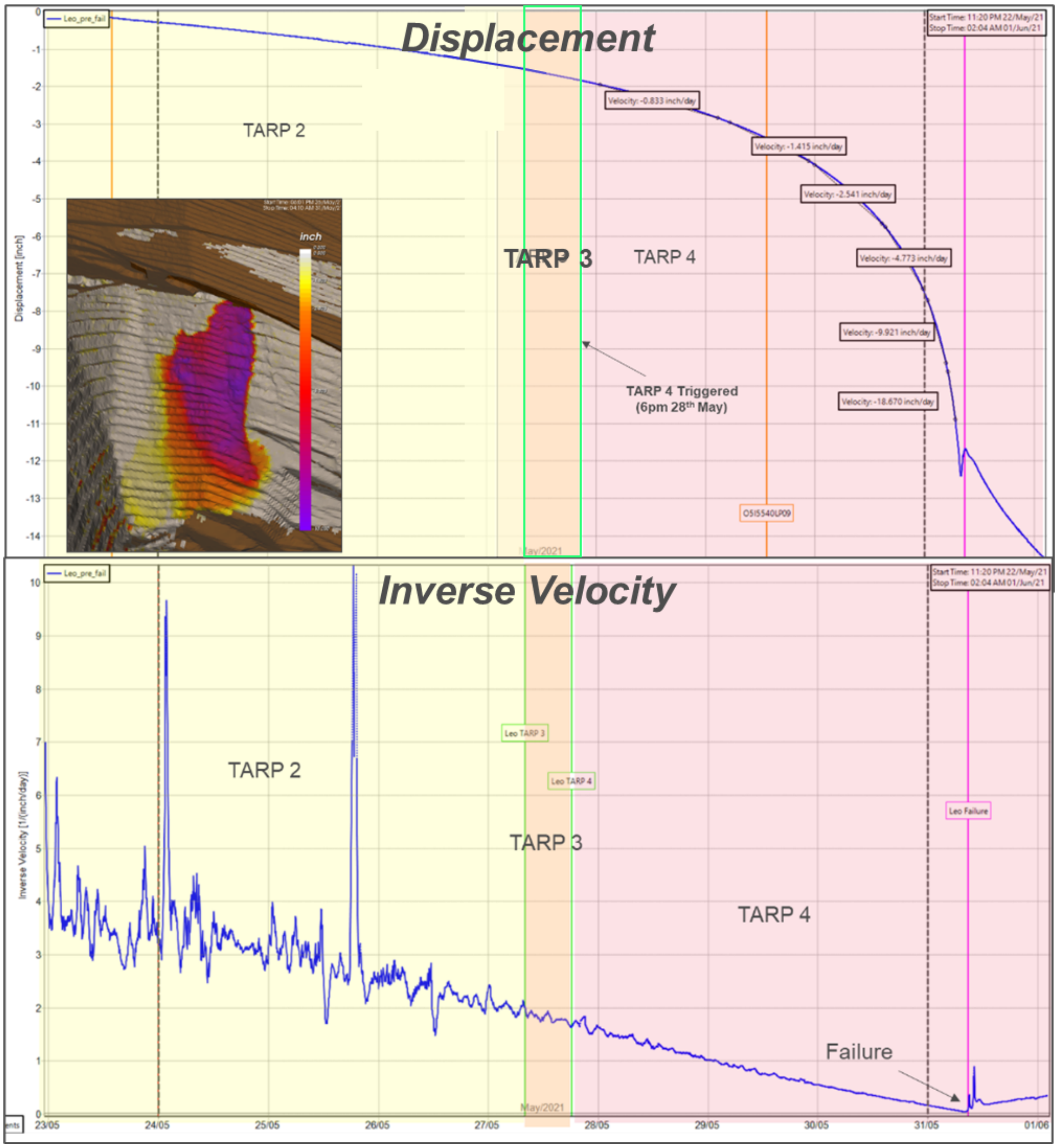

Figure 4-1 Radar data for 7 days prior to collapse of large brittle instability. Note that TARP 3 only lasted for about half a day before TARP 4 was triggered. The trigger for TARP 4 was that failure expected within three to four days.

4.2.2 Types of triggers

The advantages and limitations of the different available triggers are listed below. Suggested TARP triggers and rock mass behaviour is sketched out in Figure 4-2. It is critical that triggers used are site specific.

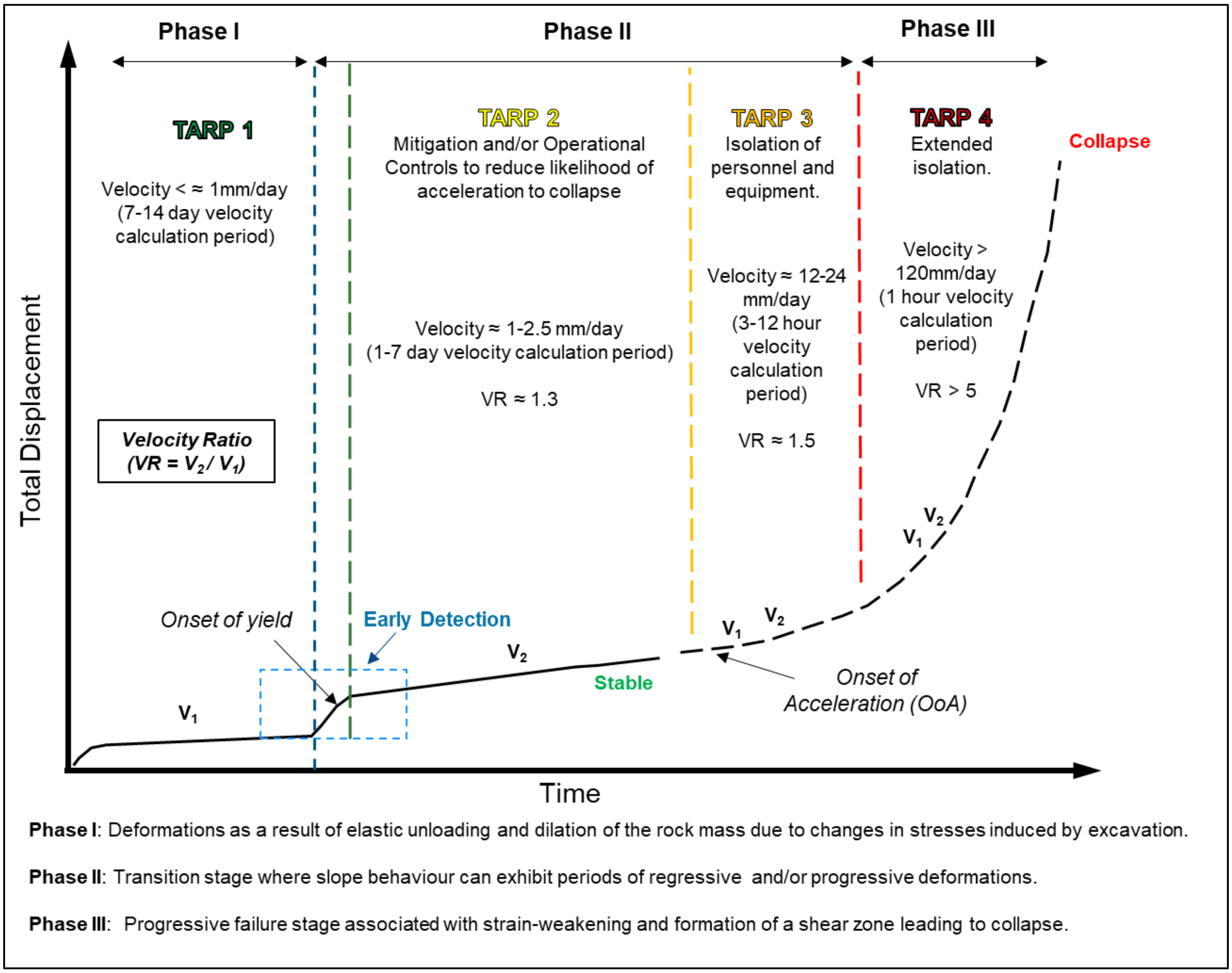

Figure 4-2 Sketch of rock mass behaviour, with suggested TARP levels and triggers.

- **Displacement**. It is very difficult to predict how much displacement a rock mass can withstand before it collapses. This will be extremely dependent on the rock mass quality, joint stiffness and overall failure mechanism. Using displacement as a TARP trigger may add limited value.
    - **Displacement is a relative parameter** because it depends on the reference point or starting point chosen. For example, stating that "TARP 2 should be triggered at a displacement of 20mm" is meaningless.

  - **Displacement trends can be valuable for small brittle failures where the time from Onset of Acceleration to collapse is too short to use other approaches reliably.** Some operations have used this approach successfully. A dedicated monitoring team constantly looking at the time series data is required.
- **Velocity**. May be difficult to specify values without benefit of hindsight or a good historical dataset of the instability. Some slopes can experience very high rates of movement without collapsing. That said, the following recommendations are made based on industry experience:
  - Determine the baseline or minimum measurable velocity of the instrument. A value just above baseline is good trigger for TARP levels 1 and 2 (early detection).
  - Velocity of 1.5mm/day to 2.5mm/day (0.05 - 0.1 inch / day) may be a good starting point as a trigger for pausing mining and assessing mitigation options; before irrecoverable deformation occurs.
  - Once velocity reaches > 5-10mm/hour slope collapse is likely imminent. However, this must be used with caution and not as an evacuation trigger by itself. The amount of strain a slope can withstand prior to collapse will depend on characteristics of materials, size of instability and the failure mechanism.
  - **The velocity averaging time or velocity calculation period used must be understood as it will impact what the user sees and can respond to.** Pros and cons of different calculation periods are given in Table 1**.**
- **Velocity Ratio**. This is defined as the current velocity divided by the previous velocity. A VR>1 indicates progressive slope behaviour i.e. the slope is accelerating. VR is an extremely valuable trigger. It helps identify the onset of acceleration (Figure 4-3).
  - The time period over which the VR is calculated should be specified e.g velocity over last 6 hours divided by the velocity over previous 6 hours. Or velocity over last 24 hours divided by the velocity over previous 24 hours. However, remember that if calculating VR over a longer time window this risks “missing” a rapid acceleration.
  - Preliminary rules of thumb for velocity ratio are:
    - Use multiple time calculation periods to view the data
    - VR can be calculated from prism, GPS, sub-sampled radar or high-precision radar data and used as part of Early Detection.
    - For a TARP 3 trigger, or trigger for when to start evacuating, using a VR of 1.2-1.4 averaged over 1-6 hours may be a good starting point.

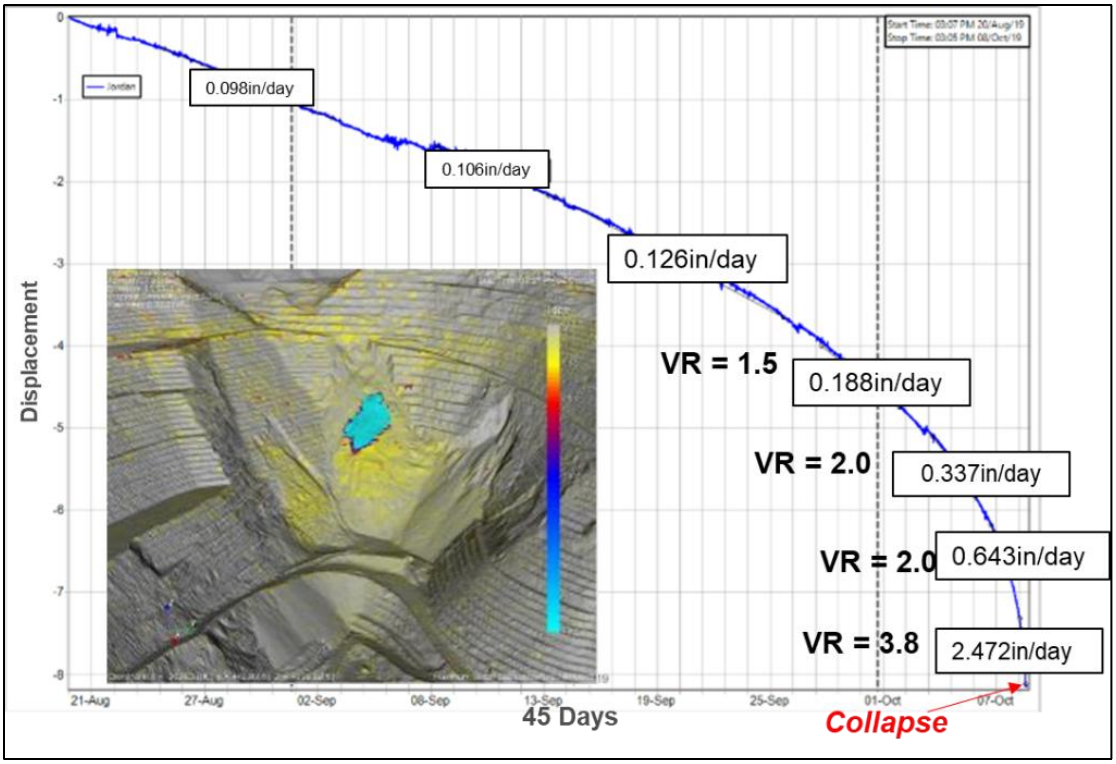

Figure 4-3 Velocity ratios (shown in bold text) for a progressive slope collapse.

- **Inverse Velocity**
  - Commonly used as a trigger at TARP levels 3 and 4.
  - Generally good for predicting slope failures in the days prior to collapse
    - Important: there are also many examples where inverse velocity predictions have not worked.
  - Can be successful for greater time periods but with much less confidence
  - Becomes valuable when the inverse velocity plot “cleans up” and shows a clear trend i.e. the slope is accelerating.
  - **Do not get too precise when predicting collapse using inverse velocity extrapolation. Inverse distance plots can be curved i.e. Actual time of failure is sooner than predicted time of failure (Figure 4-4).**

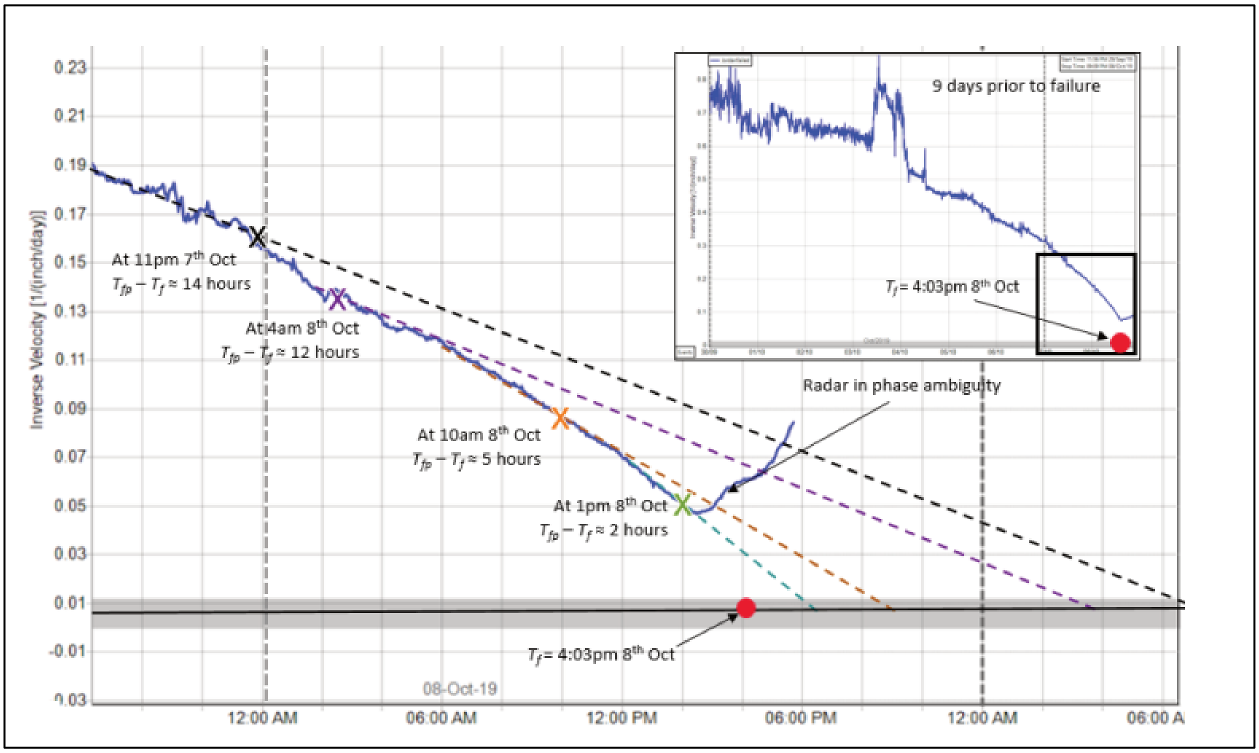

Figure 4-4 Inverse velocity plot from radar data. The inset shows the trend nine days prior to actual collapse time (red circle). Main image shows four time-to-failure predictions (Tp) in the 15 hours prior to collapse. The actual time of collapse is sooner than the predicted time. The predictions become more accurate the closer to actual time of failure. Note that phase ambiguity occurred about two hours prior to collapse.

- **Remember: If a slope is moving quickly at a constant rate then the warning time between an acceleration and collapse will be very short (Figure 4-5)**

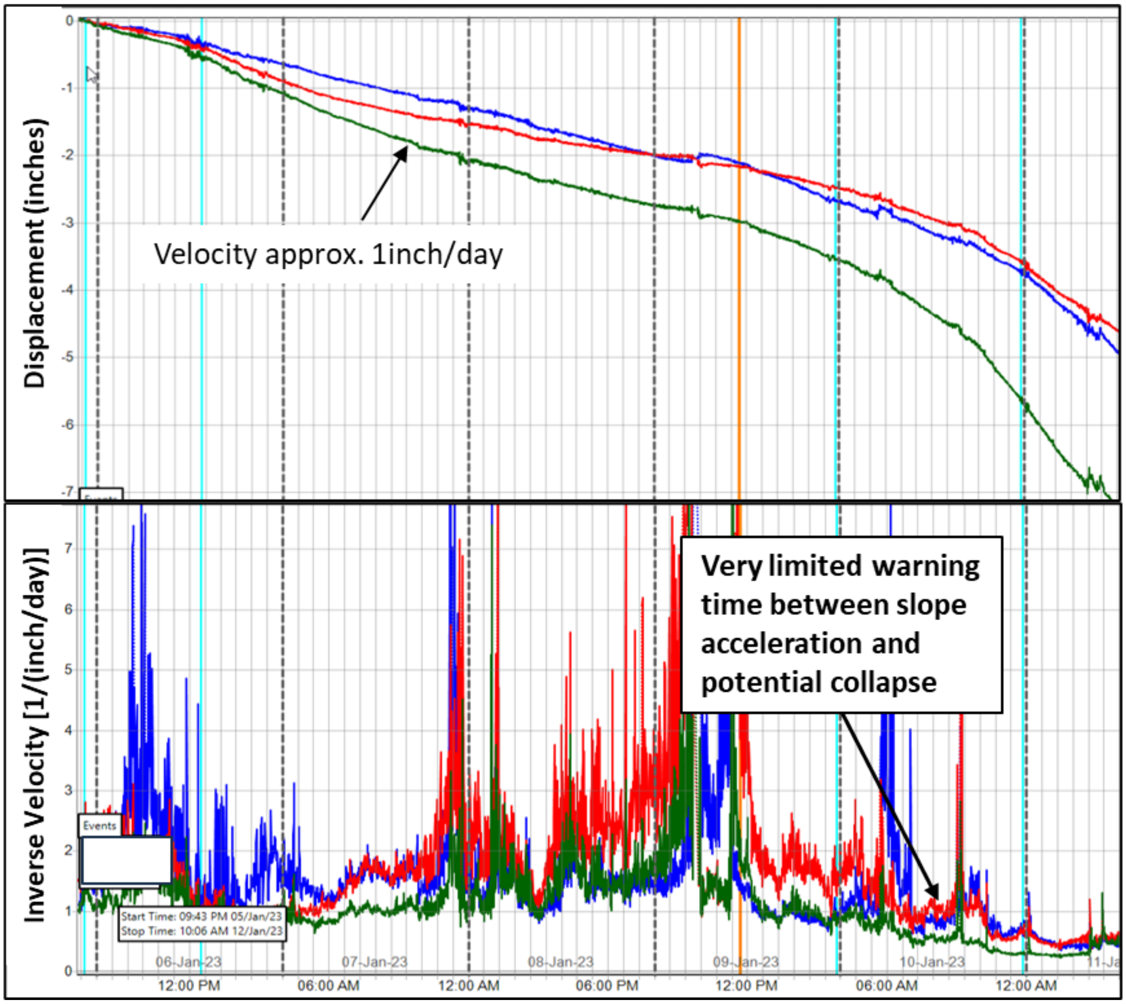

Figure 4-5 Radar data for a large, fast-moving slope. A constant velocity of 1inch/day may provide insufficient warning of a collapse when using the Inverse Velocity method, especially if a large number of personnel and equipment need to be isolated.

- **The velocity averaging time or velocity calculation period over which inverse velocity is displayed is extremely important (Table 1). Examples are shown in Figure 4-6.**

Table 1 Advantages and disadvantages of choosing different velocity calculation periods (modified from Cabrejo, A., 2013).

Calculation Period	Advantages	Disadvantages
Short Velocity Calculation Period	• Faster response is observed in the plots upon changes in the behavior of the rock mass • More accurate collapse forecasts using Inverse Velocity • More accurate short-term slope behavior indicator • Optimal for rapid developing failures • Optimal for tracking changes — shorter the VCP, the earlier detection of changes • Optimal for tracking critical operations, i.e., mining in proximity to excavations • Optimal for brittle, structurally controlled mechanisms	• Noisier velocity and inverse velocity plots • 'Blind' for some period if the sample rate is too short • For slow movement rates, the plot could be noisy and not show trends at all. Might not be able to detect long-term creep • Higher impact of atmospheric changes • Less time for filtering and smoothing • Sub-optimal for rotational failures with long deformation time • Requires high sampling rate to detect consistent trends due to noise
Long Velocity Calculation Period	• Easier to identify small scale movements • Smoother velocity and inverse velocity plots • Easier to detect trends in the velocity plots • Easier to distinguish between linear, regressive, and progressive movements • Developing operational strategies, e.g., long developing rotational failures and creep	• Later collapse forecast (predicted time of failure) compared to shorter VCP • Might be 'blind' to responses upon sudden changes in the behavior of the slope • The response in the inverse velocity plots is highly susceptible to changes which could be misread and may provide collapse forecast related to atmospheric changes

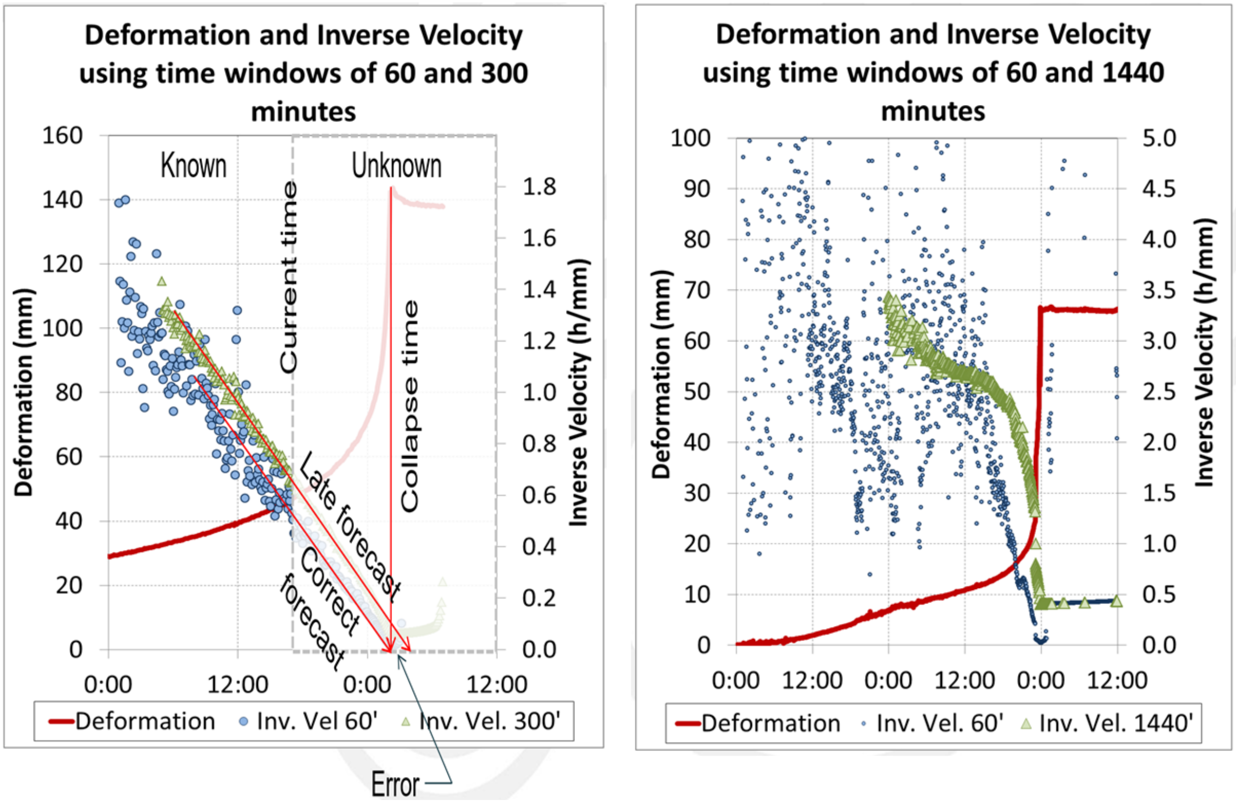

Figure 4-6 Examples of inverse velocity plots using different time windows (60 and 1440 minutes). These show how trends develop sooner when calculating over longer time periods (green dots) but are often less accurate (i.e. later forecast) when predicting collapse time.

- **Coherence** of pixels from radar data must be sufficiently high to provide good quality data usable for slope monitoring. Having a response in the TARP should radar data become incoherent is highly recommended.
    - Rainfall, mining operations, significant rockfall etc can result in incoherent data.
    - Pixels may become incoherent in the minutes prior to a slope collapse.
    - Coherence is sometimes used as a complimentary TARP trigger at higher TARP levels, but remember it may provide little to no warning time of a collapse.
- **Weather triggers** must be included in the TARP. These may include:
    - Precipitation. Specify how many mm (or inches) of rainfall in a certain period trigger a TARP escalation.
    - Temperature – especially important for when warming temperatures cause rapid snow-melt
    - Reviewing existing slope movement trends with rainfall and temperature plots will guide how to set the TARP triggers.

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 regarding 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 critical equipment must have taken place well before phase ambiguity 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 Figure 4-7.

Ensure phase ambiguity is no longer occurring before re-entering the isolation area.

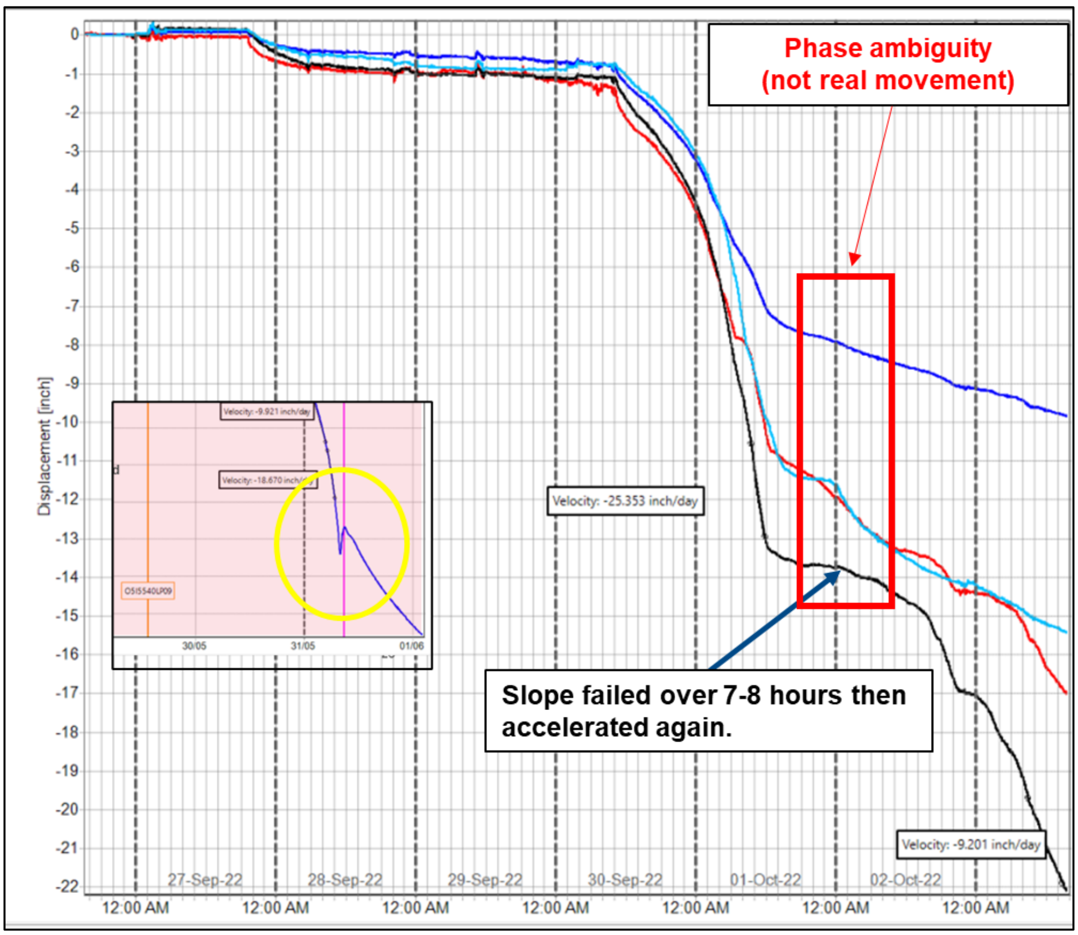

Figure 4-7 Examples of phase ambiguity in radar signatures. The insert is a typical example and easy to identify. The larger figure shows what could be interpreted as slope deceleration but it went into phase ambiguity (failed) then continued deforming at a slower rate.

4.2.3 De-Escalation

Clear de-escalation criteria should be added to the TARP. These specify when the TARP level can be reduced.

Consider having the de-escalation threshold to be well within the escalation trigger. For example: If the trigger for a TARP 2 is a velocity of 0.07 inches/day (over a 24 hour period). The de-escalation criteria might be 0.05 inches/day (over a 24 hour period). This helps reduce ambiguity in decision making and reduces chances of constantly bouncing between TARP levels which can be frustrating for mine operations and reduce credibility of the geotechnical team.

Recommend having a sign-off process for de-escalation such that experienced geotechnical engineer(s) are able to review and decide when to re-enter or start mining again in an area. Having such a decision site with junior team members can result in pressure to start mining from Operations Teams.

4.2.4 Runout Analysis and Evacuation Plans

- Runout analysis is required to **guide evacuation plans** and **look at economic consequences of a potential collapse**.
- Failure depth from sub-surface instrumentation is very valuable in defining estimated failure volumes which are directly related to runout estimates.
- Using the Fahrböschung angle approach provides a simple, empirical 2D guideline to runout distance. Effective empirically-based runout estimates are calibrated to site-specific experience and have the advantage of being implemented probabilistically. Remember, the best-fit through an empirical tool is the 50th percentile. In the case of empirical runout estimates, this means there’s a 50% chance the event will run farther than the best-fit estimate.
- A detailed 3D analysis using software such as DAN3D can provide a more accurate runout estimate accounting for the influence of topography and allow sensitivity analysis to be run. These programs require calibration to previous events and careful consideration of which historical event is most similar to the event under consideration. The engineer should consider a “base case” and a “worst case” scenario. The worst case scenario should be used when guiding isolation extents for personnel (Figure 4-8).

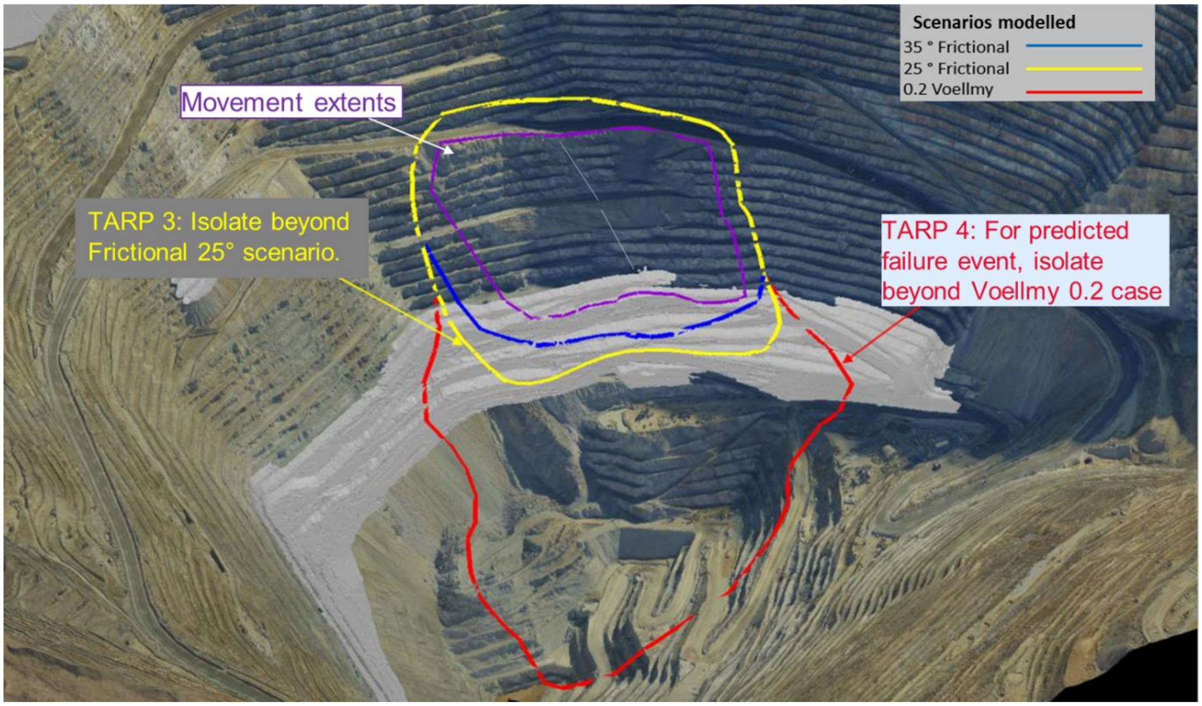

Figure 4-8 Example of 3D runout analysis used to guide isolation extents.

- More sophisticated 3D runout analysis tools are being developed. The challenge is that is almost impossible to calibrate such models until after a collapse. However, such analysis can be valuable in guiding isolation extents.
- The choice of extents for equipment or other infrastructure should be discussed with the Business risk team.
- **A large amount of contingency must be applied when defining actual isolation extents to be used in the TARP.** Runout models are to be used as guidance only and there will always be a degree of unpredictability. **No value can be gained by being too aggressive with a personnel isolation plan.**

4.2.5 When to evacuate

Evacuation will likely take place at either TARP level 3 or 4 or a combination thereof.

When to evacuate will depend on

- The isolation extents (guided by the runout analysis, with large amounts of contingency added)
- The amount of personnel to be moved and how quickly they can be moved

- The amount and type of equipment to be moved and how quickly it can be moved. Large amounts of slower moving equipment will require more time. This must be accounted for in the TARP.
- Slope mechanism – a brittle mechanism can accelerate from low movements to collapse very rapidly. Evacuating at a lower TARP level (e.g. TARP 3) provides a greater safety net.

Important: for a large pit wall collapse, a successful evacuation should be a relaxed procedure which occurs with plenty of time prior to a collapse.

Making the decision to evacuate an area is a high-stakes decision which is often required to be done with limited data, a degree of uncertainty, and with limited time.

The time between evacuation and collapse (if the slope does collapse) will feel very long and stressful.

Be prepared to respond to pressure from many groups in the Business with questions such as:

- **"Why are we evacuating now?"**
- **"Can we just finish the shift?"**
- **"It still hasn't collapsed, when can we go back in?"**
- **"Can we just quickly send a few people in to the isolation area to grab some equipment?"**

Stick to the TARP, the isolation plan and your geotechnical knowledge. It is better to debrief afterwards and look for improvements rather than risk a fatality.

It is critical that the Geotechnical Team is constantly assessing and dissecting all parts of the monitoring data:

- **Constantly look for changes in the slope behaviour**
- **Divide the movement area up into many sub-sectors and analyse each individual smaller area. There may be a critical "block" which fails first and then the rest of the slope follows.**
- **Do not just look at one time series plot for the overall instability. The distribution of stresses can evolve with time. Complex, sequential failures involving multiple shearing and strain localised zones are more common than we as an industry probably understand.**

Remember – if a slope does collapse Upper Management will be glad it happened without fatality, injury or damage to equipment. They are unlikely to want a few extra tons mined before it collapsed.

TARPs – How precise and prescriptive should they be?

Should the final TARP be such that it is/can be followed precisely if/when movement or collapse occurs? How much should be left to the geotechnical engineers' discretion?

This is a common challenge. On the one hand it is not advised to change the plan in the hours, or even days, prior to a collapse. But what if the slope behaviour changes or an unexpected scenario presents itself?

The following suggestions are made:

- The TARP should be as simple to follow as possible for all personnel involved.
- How the triggers are calculated should be simplified and clearly defined for the geotechnical team to follow. Avoid subjectiveness of manual measurements to determine TARP levels.
- Sufficient contingency should be built into the TARP such that safety is not compromised. Refer to the discussion above on Inverse Velocity, Isolation Extents, and When to Evacuate.
- All that being said, some discretion or "engineering judgement" may be inevitable, and in some cases beneficial.
    - Identify a suitably qualified and experienced Geotechnical Engineer who can make decisions under pressure often with limited monitoring data available

An example of a thorough TARP for a potentially brittle slope with high economic consequences is provided below.

Example TARP - Large potentially brittle instabiltiy with significant economic consequences

TARP Description	TARP Level	Triggers (Wall Behavior)	Responses (by Team)				
			Mine Execution	Mine Technical	Geotech, Production and Scheduling	Loss of Monitoring System Response	Communications/ Security/Upper Management
Low levels of movement detected **Observational mining required for wall protection and to limit further movement**	**1**	***Monitoring Data and Observations:*** **Live Radar Data** - background movement with no meaningful trends, stable conditions. **Subsampling Data** - Stable rates – velocity trend less than 0.02 inches/day over 30-day average showing stable or regressive movement. ● **Prism/GPS Data 3D Displacement** - **Less than 0.05 inches/day over 7-day average using prism and GPS data**	• Mining within Critical Zone as follows: ○ **South East Wall**: 50ktp 4-day rolling average; 60ktpd max within critical block. *****Tonnage caps and critical zone extents may be adjusted based on wall performance observed during mining operations.** • Blasting pauses as necessary within Critical Zone • Wall control blasting – may be required beyond critical zone. • Continue implementation of approved surface water/dewatering/depressurization plan. • Evaluate electrical and water infrastructure and potential impacts should failure occur.	• Design blasts as needed to minimize vibration/damage to critical zones. • Detailed geological and structural model review and update. • Develop area/wall-specific stability model • Evaluate split cut mining option or similar. • Perform runout assessments to provide isolation guidance for failure scenarios • Review monitoring data and incorporate key learnings into models for validation • Develop and evaluate ore delivery contingency plans should toe mining require an extended pause or remediation action.	• Develop clear monitoring plan and report movement and mining rates daily. • Read sub-surface instrumentation weekly. • Complete Gate Checks after every bench mined. • Continual placement of surface and subsurface monitoring instruments as mining progresses. • Review Critical Zone extents and modify as appropriate.	If full monitoring coverage lost, 12-hour grace period before critical zone mining must stop	• Normal Security Activities • Normal internal and external communications • GM sign off on observational mining decision
Clear, measurable deformation beyond background levels. **Stop mining in critical zone to allow regressive slope behavior.**	**2**	Geotech will assess the TARP level daily based on a combination of performance data that may include, but is not limited to: **Prism/GPS Data 3D Displacement** - **Movement > 0.05 inches/day over 7-day average using prism and GPS data** **Sub-sampled Radar Data –** Distinct velocity ratio > 1.5 identified over more than 7 days. **Live Radar Data –** >0.05 inches per day and detectable trends in monitoring shapes of broad area and size. **Field performance:** Observable signs of deformation **De-escalation to TARP 1**: • Requires approval from Accountable Person for Monitoring, Manager, GM, and Geotechnical SME • Requires ***clear regressive trend*** and ***rates clearly below 0.05in/day*** for both prisms and GPS 3D Displacement.	• **Pause Critical Zone Mining (blasting and excavation)** • With Geotech review, drilling and support/preparation work may continue in critical zone where needed. • OK to continue mining non-critical zone • Distribute level 3 & 4 Isolation zone maps • Prioritize approved surface water/ dewatering/depressurization plan. **Preparation for failure remediation:** • Ensure availability of remote equipment fleet and trained operators aligned to estimated failure tonnages. • Evaluate remediation strategy, consider location of equipment prior to failure in order to ensure rapid re-entry to pit bottom **Develop Evacuation plans** • Develop and distribute Level 3 and Level 4 evacuation zones, and produce TARP isolation maps, based on real time Geotechnical Monitoring, and Run-out Assessments **Develop rescue strategy for pumping infrastructure.** • Execute rescue plan towards upper end of TARP 2; but before TARP 3 is triggered.	• **A decision will be made on mitigation option(s) to prevent further acceleration e.g.:** **1) Evaluate option of buttress.** **2) Evaluate option of unload.** **3) Split cut mining** • Run scenarios to understand value stream impacts. • Review blast impacts from production faces (outside of critical zone) on slope movement.	• Report movement and mining rates daily • Read sub-surface instrumentation weekly. • Complete Gate Checks after every bench mined • Develop plans for post failure equipment placement for potential remediation efforts. • Geotech to review TARP triggers and thresholds as required. • Ensure radar redundancy exists (minimum two IDS radars and one GP with good line of sight)	If full monitoring coverage lost, 6-hour grace period before critical zone activities must stop	● Normal Security Activities ● Normal internal and external communications • Prepare company wide statement and media release
Wall acceleration Area isolation for safety	**3**	Geotech will assess the TARP level daily based on a combination of performance data that may include, but is not limited to: • **Radar and/or Prism Data 3D Displacement:** **Greater than or equal to 0.5 inches/day** • **Velocity Ratio: 1.2 calculated over 48 hours** (today's velocity/yesterday's velocity). Only applicable where velocity clearly exceeds instrument noise (>0.2"/day) **Field Data:** Observable signs of failure development along potential release structures – field indicators of cracking and dilation. **De-escalation to TARP 2**: • Requires approval from Accountable Person for Monitoring, Manager, GM, and SME. Requires ***clear regressive trend with velocity ratio <1.0*** and ***rates clearly below 0.5in/day*** for live radar, prisms and GPS 3D Displacement	• **Remove personnel and Isolate TARP Level 3 area** • **Remove all equipment from isolation area** • **Strategically place excavation and support equipment for potential remediation efforts per plan developed in TARP 1.** • Deploy spotters/sentry to ensure isolation in place and for rapid alert to any changes in behavior • Establish non-emergency incident command • Prepare for TARP 4 response by communicating TARP 4 isolations lines	• Develop a short term (1-5 days post failure) recovery plan • Value Stream to plan for ore interruption	• Test radars daily • Report rates twice a day • Ensure radar redundancy exists (minimum two IDS radars and one GP with good line of sight)	If loss of monitoring occurs; evacuate Level 4 area immediately.	● Communicate movement rates daily ● Notify Review Board of change in response level ● Update to MSHA ●Updates to Upper Management ● Only Mine External Relations is to release information to Media
3 days until expected failure	**4**	Geotech will assess the TARP level daily based on a combination of performance data that may include, but is not limited to: • **Radar and or prism data:** Statistically strong trend toward failure **within 3 days** • **Inverse velocity:** Forecasting failure **within 3 days**	**Prepare for failure event** • Establish Incident Command • Remove personnel and Isolate TARP Level 4 isolation area • Remove equipment from runout area as needed. • Geotechnical incident to be raised • Isolate personnel from Slice 2 at 12-hours before the predicted failure event.	• Develop a short term (1-5 days post failure) recovery plan • Value Stream to plan for ore interruption	• Test radars daily • Continued update and reporting of rates to all teams. • Ensure radar redundancy exists (minimum two IDS radars and one GP with good line of sight)	Evacuate level 4 area immediately.	● Communicate movement rates daily ● Notify Review Board of change in response level ● Update to MSHA ● Daily updates to Senior Leadership Team (SLT) ● Only Mine External Relations is to release information to Media.
Unexpected failure	**5**	● Unexpected active failure	● Establish Incident Command ● Evacuate pit ● Mine-wide headcount ● Operations stopped		• Incident Command (IC) response communicated to Mine personnel	Radar monitoring is required to access designated TARP Level 4 areas	● Access to the Mine (Leaving and Arriving) only by authorization of incident command ● Interface with MSHA on site ● Update MSHA ● Only Mine External Relations are to release information to Media
De-escalation		Geotech will assess the TARP level based on a combination of performance data that may include (but is not limited to): Failure has occurred and or all monitoring shows a clear regressive trend ●Evaluate failure and risk based on current conditions ● Movement shows steady or regressive trend over hours	●Communicate TARP de-escalation to work force.		Movement rates must be confidently below Level threshold to de-escalate. De-escalation requires approval from Geotechnical nominated Communicate TARP level to Mine Execution Teams	Multiple monitoring sources are required to support a de-escalation decision. De-escalation requires reliable data	● Communicate current TARP level

Special Weather Trigger/Response (if Level 2 or greater)

Triggers:
- 1" of Rainfall recorded in a 24-hour period
- Observed rapid snowmelt in the vicinity of the Revere as determined by the Mine Hydrology Group

Response to Weather:
- Option to Increase TARP response by a level at discretion of Geotech Team
- Evaluate TARP level after 24 hours

TARP Notes:

* Radar data refers to actual rate of movement, not to include atmospheric interference. Engineer judgment may be necessary.

* * Inverse velocity methods are more consistent when movement rates are high and can be erratic at lower levels. Therefore, inverse velocity is only considered as a TARP trigger for Level 4

* Mine Management and the Geotechnical Team reserve the right to edit the TARP based on wall behavior.

5.0 COST-RISK ANALYSIS

A cost-risk analysis approach is an extremely valuable tool which can help with the following:

- **Logical and defensible decision analysis**. Evaluate if the cost-risk of proceeding with a mining cut below an instability is preferred, or should mitigation be undertaken?
- **Communication.** Help the Business understand the risk it is accepting and if this risk is tolerable.
- **Control Effectiveness**. Understand the effectiveness of any controls implemented to manage the instability.
- **Understand the capacity and capability** of the operation. Is it able to safely manage an instability?
- **Understand alternative design options**
- **Identify knowledge gaps (sources of uncertainty)** in design mitigation options or understanding of the failure mechanism.

A cost-risk model framework should evaluate both safety and economic risks together because, for example:

- Advancing below an instability may be favourable economically but carry an increased safety risk that is not tolerable to the Business.
- Such a safety risk could potentially be reduced to tolerable limits with additional controls, but these controls are so significant in terms of cost, time and effort, that advancing below the instability becomes unfavourable.
  - An example here might be using a remote shovel in the dig face to load remote trucks. This would reduce exposure of workers. However, the cost of procuring, buying, setting up and maintaining the equipment, together with reduced productivity could well make this option uneconomic.
- Conversely, a mitigative option, such as an unload, may be more costly from a production standpoint (out of plan capital spend and significantly adjusted mine plan), but reduce the safety risk to within tolerable limits and be the preferred option.

Both mitigation and operational controls to mine below an instability carry costs (in terms of money, time and effort).

The operation must work out which is the preferred option(s) given that safety must be within a tolerable limit.

5.1 Life Safety Risk and ALARP

Mining below a moving pit wall increases the safety risk. The decision to proceed should not be taken lightly.

Most businesses have a very low risk tolerance for instabilities which could present a safety risk to mine workers, the public or the environment. The level of risk tolerance will vary from business to business.

The decision to proceed mining below an instability should not be taken by the Geotechnical Engineer alone.

Before mining below a moving pit wall, the Business should:

- Evaluate if the risk of fatality or serious injury to personnel is within a tolerable limit (Figure 5-1). This limit should be defined by the Business or operating jurisdiction and communicated to the designers and operators to allow informed risk tolerance decisions to be made.
  - *Note: Operators should avoid using simple 5x5 risk matrices for evaluating complex, high consequence events like slope collapse.*
    - *Risk estimation methods using matrices often do not encourage a deep exploration of uncertainty, or highlight opportunities to reduce uncertainty and risk.*
    - *Many corporate risk matrices assign 'high' or 'very high' risk to any scenario with the potential to cause a fatality, irrespective of estimated likelihood.*
- Determine if such risks have been reduced to As Low As Reasonably Practicable (ALARP).

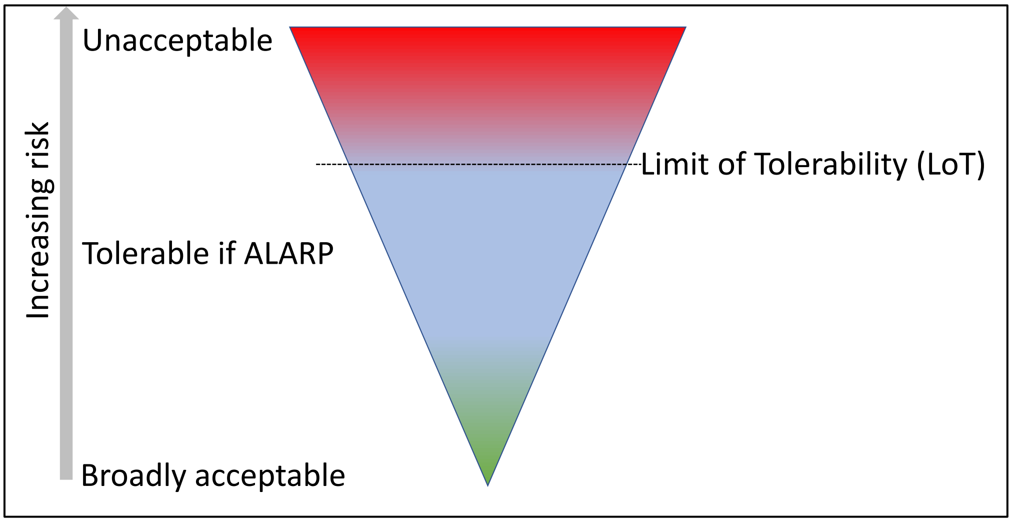

Figure 5-1 Risk and tolerability limits. Those risks sitting in the ALARP region must be driven As Low As Reasonably Practicable. Good practice alone is not sufficient. For risks plotting above the Limit of Tolerability work cannot continue.

The ALARP principle involves accepting that

- No engineered structure or pit slope will ever be completely safe or risk-free, i.e., there is no such thing as “zero risk”.
- There is a limit to the extent of any risk that the public or workers can be expected to tolerate.
- The tolerable limit needs to be defined by the Business, and the risk in question driven as far below it as is reasonably practicable.

For risks falling in the ALARP region, they are considered to be tolerable only if the duty-holders demonstrate that the risk is significant in relation to the sacrifice (in terms of money, time, or trouble) required to avert it and that there is a **gross disproportion** between the cost and benefit to further reduce the risk. Good practice alone is not sufficient.

Conducting an ALARP assessment requires a well-facilitated workshop of Subject Matter Experts. **How to undertake and ALARP workshop is beyond the scope of this Guidance Note.** However, the principle can follow a simple semi-quantitative risk assessment (SQRA) (Figure 5-2).

By attempting to assign likelihoods to each step, the Business will start to develop an understanding of how well the mechanism is understood, how well the runout analysis is understood, how effective the TARP is, and how exposed personnel may be.

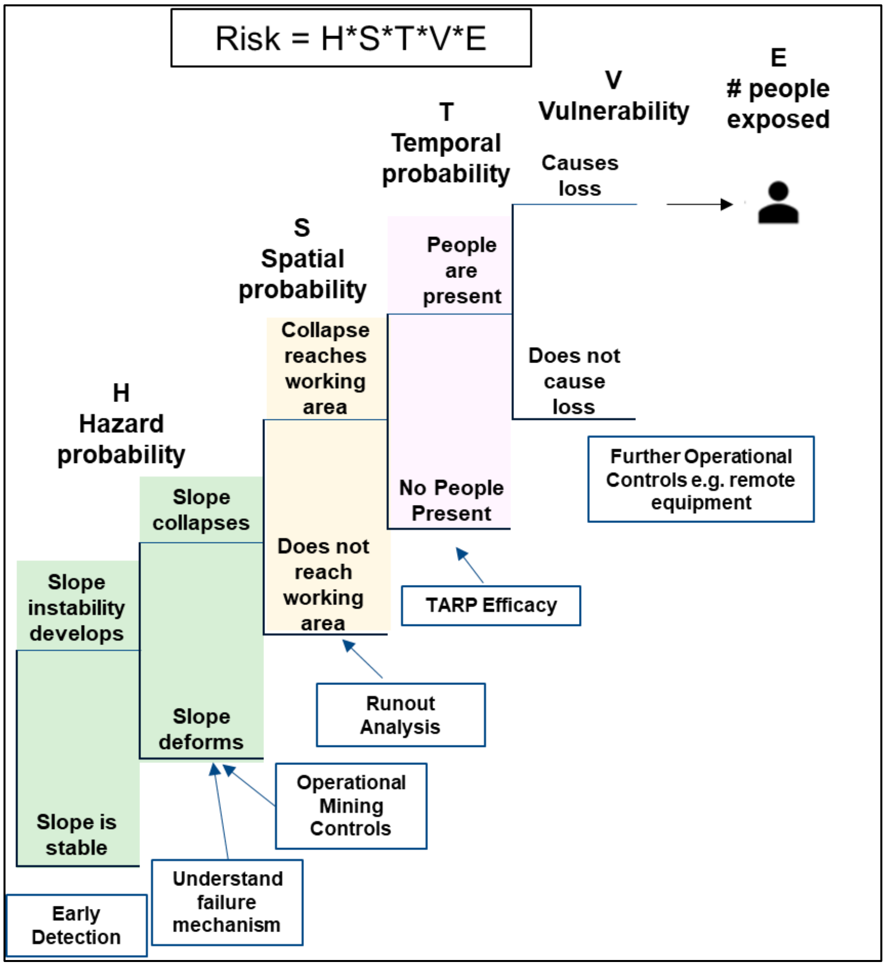

Figure 5-2 Example of an SQRA to evaluate safety risk. Some of the key inputs required at each step are shown.

Outcomes of the ALARP assessment could be one of the following:

1. **Existing risk is confirmed to be ALARP and mining can continue.**
2. **Risk would be ALARP after implementing specific action(s) or controls. Examples include:**
    - Implementing a geotechnical Monitoring Centre with dedicated night shift and day shift to improve TARP efficacy i.e. less likelihood of alarms missed.
    - No queuing trucks and no auxiliary mining equipment below instability to reduce worker exposure.
    - Less time between scans of radar units to detect onset of acceleration sooner.
    - Purchasing of additional slope monitoring units for redundancy.
3. **The confidence level for the risk result is low, such that additional studies are required before an ALARP conclusion. For example,**

- The slope mechanism and behaviour are not sufficiently well understood
- Failure depth is not well understood such that failure volumes and runout cannot be estimated with confidence.

4. **ALARP is not possible, and mining below the potential instability should not be undertaken. For example:**
    - Brittle slope instabilities where there is very little warning time may simply have a risk level that is considered intolerable (Figure 5-3). If this is this case, mining at the toe cannot continue and a step-in, unload, or mining out the failure altogether may be required.
    - An effective TARP cannot be demonstrated by the site.

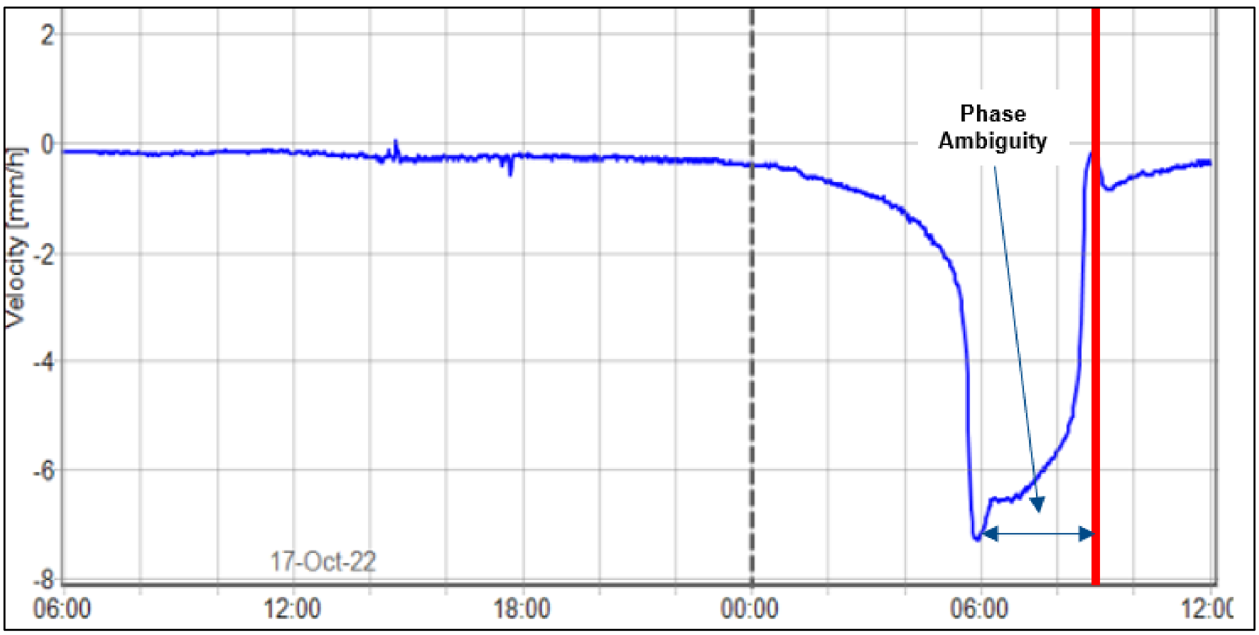

Figure 5-3 Velocity time series showing example of brittle failure with limited warning. Mining at the toe of such mechanisms may be considered intolerable.

Remember, ALARP is not static. It should be reassessed periodically or when changes occur to the mine layout, slope instability, etc.

"Reasonably practicable" and the ALARP concept

The ALARP (As Low As Reasonably Practicable) principle was initially developed within UK Health & Safety regulation and has now been replicated in several country's regulations (e.g., Australia), initially for the oil and gas industry but has since been applied to other industries.

Ensuring a risk has been reduced to ALARP is about weighing the risk against the resources or effort needed to further reduce it. The risk reduction measures should be implemented unless it can be demonstrated that implementing the risk reduction measure would be grossly disproportionate to the benefits achieved. As such, the process is not one of balancing the costs and benefits of measures but, rather, of adopting measures except where they are ruled out because they involve grossly disproportionate cost or effort.

Extreme examples adapted from the UKHSE illustrate the point as follows:

- To spend $1M to prevent five staff suffering bruised knees is grossly disproportionate, but
- To spend $1M to prevent a major explosion capable of killing 150 people is proportionate.

The term 'reasonably practicable' indicates a narrower range than all physically possible risk reduction measures. If the cost of a risk reduction measure, whether in terms of "money, time or trouble", can be demonstrated to be grossly disproportionate to the risk reduction gained from the measure, (taking account of the likelihood and degree of harm presented by the hazard), then implementing the measure may not be required. The higher the level of risk, the greater the degree of rigour that is required to show that risks have been reduced to ALARP.

Key Points:-

- Risk must be reduced unless the cost is grossly disproportionate.

- Good practice alone is not sufficient

- Documentation is critical for defensibility and transparency and requires agreement from the Business.

5.2 Cost-Risk Framework

Developing a cost-risk model or framework is recommended to evaluate the best option for the Business where a significant geotechnical instability exists.

An example of a such a framework is shown in Figure 5-4. It is likely that a specific cost-risk framework will be required for each site and each specific instability. However; the broad approach will be similar.

The example in Figure 5-4 takes the following approach:

1. Estimate the costs for the Operation Controls or Mitigation options. These need to be considered in terms of money and time. E.g. pauses after blasting will impact delivery of ore tons and therefore free cash flow.
2. Estimate the likelihood of a slope collapse.
3. Given this likelihood of collapse, determine if the risk is managed to ALARP. What controls need to be added and what are the costs of these controls? If the risk cannot be reduced to ALARP the option cannot be considered.
4. Assess the economic consequences of a slope collapse vs no collapse (continued deformation).
5. Decide if any additional controls or actions should be included to reduce the economic consequences. E.g. relocate critical infrastructure
6. Re-evaluate the likelihood of a slope collapse given the controls added and the effectiveness of these controls.
7. Multiply out the scenarios and evaluate the cost-risk for the different cases.

Considerations when doing this exercise:

- Assigning a likelihood of collapse or “probability” will be extremely subjective. Broad agreement (say within 10-20%) between Subject Matter Experts in the workshop is just as defensible as complex, expensive, time-consuming probabilistic analysis.
    - When considering this, remember that probability of failure is not like rolling a dice which can be repeated indefinitely to generate a statistical distribution. The slope will either collapse or it will not.
- The actual likelihoods themselves are not what this exercise is necessarily about. What adds value is looking at which controls and process improvements can be added, how effective they are considered to be, and the relative change in likelihood of collapse as a result.

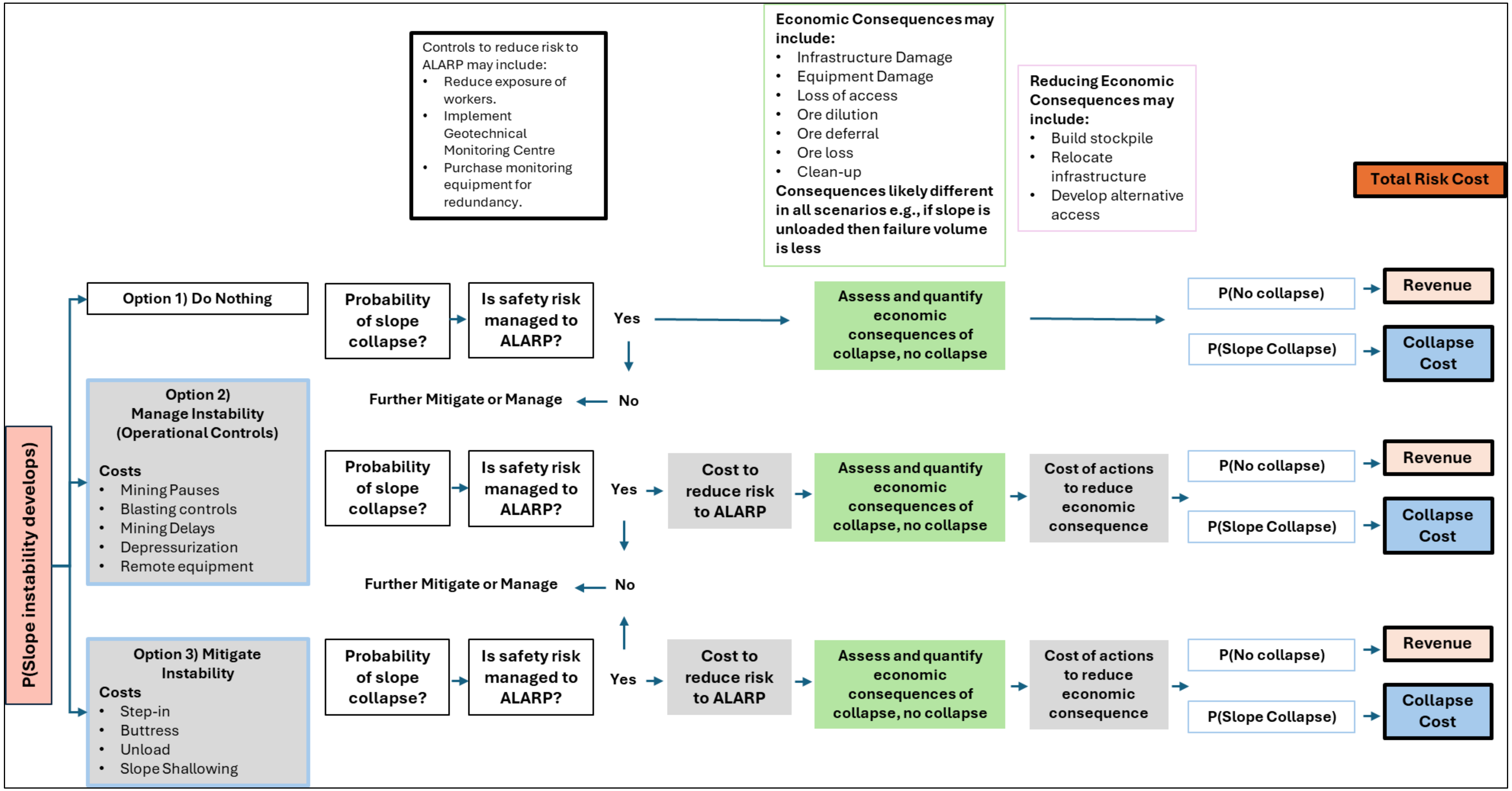

Figure 5-4 Example of a cost-risk framework for how to best manage an instability.

6.0 COMMUNICATION AND APPROVAL

Communication is a critical part of Observational Mining and managing an instability.

Communication will need to take place with:

- Upper Management – Mine Manger(s), Managing Director(s) CEO's, Board of Directors, etc. (depending on the organisation structure).
- Peers – other team members who will be critical to implementing the plan to manage the instability. Mine Planning (short range, mid-range long-range), Drill and Blast, Operations, Hydrogeology, etc
- Workforce – this is the operation teams on the ground. They must know what is being done, and what is expected of them under different TARP levels.

6.1 Upper Management Team

The decision to mitigate and/or operationally manage the instability must be approved by the upper management team.

Depending on process in place within the Business there will likely be an approval system commensurate with the risk and change in NPV (or free cash flow) i.e. a significant change to the mine plan will need approval from high levels within the organisation before mining can start. They will likely want to know:

- All options considered and the cost-risk of each one.
- Why the preferred option is being recommended to them.
- The cost of this option presented in NPV, free cash flow (year on year).
- Key assumptions used in the revised mine plan e.g. cost per ton for an unload; and/or time required for an unload.
- Economic risks that the preferred option still carries e.g. risks of slower production from operational controls, risk of slope collapse.
- Degree of confidence and uncertainty and what this means for the Business. How material is it? What additional actions are being carried out to add stability to the mine plan?
    - Be fully transparent throughout this. Geotechnical designs will always carry uncertainty, and the proposed solution may not perform as desired. It is important not to hide this. Information should be shared truthfully, even if it's difficult. This builds trust and credibility.
    - Safety factors and similar numbers (e.g. PoF, SRF) which indicate a degree of stability must be presented with extreme caution and audiences must understand

that even for the best “calibrated” models a degree of uncertainty remains. A moving slope can still have an FoS>1.

Safety risk must also be clearly understood by Upper Management. The management team must know that safety is being fully managed.

By using the ALARP process discussed above, this provides clear guidance on:

- What the risks were
- The controls being implemented and their effectiveness
- The new safety risk and that this risk is being managed to ALARP.

Use of the Cost-Risk analysis provides a transparent way to communicate all this information and the assumptions made during this process.

Risk-based discussions between the Geotechnical Engineer and upper management must be held in a manner which is clear, intelligible, well-documented and fully understood by all those involved.

In many cases, such stakeholders will not be familiar with geotechnical principles. Mining company Executive Committees, for example, are increasingly coming from non-mining backgrounds but are required to make significant business decisions impacted, in some cases, by geotechnical risk at an operation.

6.2 Operational Workforce

Key points to communicate:

- Geotechnical safety risk(s) and how the risk(s) are being managed. Noting that new risks or instabilities may develop as the surface operation changes.
    - Explain ***why*** things are being done and specific decisions have been made.
- TARPs and what everyone’s roles and responsibilities are for the different TARP levels.
- What support is required from the workforce to manage geotechnical risks.

Operational superintendents and managers must be involved in the decision making process to manage an instability. They bring valuable operational insights that may get missed by purely technical teams.

6.3 Technical Peers

These teams will be critical to managing an instability. They must be involved throughout the process in deciding how the instability should be mitigated and/or operationally managed.

Key points to communicate:

- Implementation requirements to achieve design, e.g. wall control blasting, surface water management work; horizontal drain drilling work. Present the value of these or the business risk reduction.
- Risks to the Mine Plan (annual, quarterly, monthly and weekly)
- Acknowledge the conflicting interests while everyone works towards the same common goal(s)

A note on incident investigation. What happens if the slope collapses?

Should a collapse occur with either harm to people or material business impacts, then deeper levels of investigation will be conducted. Such an investigation will likely involve external (to the Business) and internal (but external to the site) Subject Matter Experts. Depending on the consequences of the collapse legal teams and insurers may also be involved.

Being involved in incident investigation is often stressful and challenging as there will be many questions and varying responses from stakeholders. Some notes are outlined for guidance in such situations:

- Understand the purpose of the investigation. Investigations will follow a pre-established methodology to suit the severity of the event (e.g. Essential Factors™, fishbone diagrams, etc). Familiarise yourself with the methodology being used and consider if it is appropriate for the situation.
- Note that Engineers are expected to exercise the degree of care, skill, and diligence reasonably expected from a person having their knowledge and experience, and in comparable circumstances at the time in question.
- **Good incident investigations aim to identify root causes and prevent recurrence, not to assign blame**. Internal policies should emphasize that investigators and relevant parties keep an open mind and focus on facts, not fault-finding.
- Maintain thorough documentation of slope design, assumptions, ground management plans, key decisions, and methods chosen to manage risk during operation. The more robust the slope management framework and documentation, the easier the investigation will be and the better a site will be able to demonstrate due diligence (vs negligence).
- Gather relevant information and present in a factual manner. Avoid speculation.
- Remain calm, curious, and cooperative. Understand that SMEs on the investigation panel may take time to understand the site; but that they also bring valuable different perspectives.
- Avoid defensive language, behaviours and maintain respectful and psychosocially safe environments.

- Remember, good investigations are focussed on learning and prevention – your input matters. The investigation team want to deliver actions which produce change for the better and promote learnings.

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