

# Transitioning from mine operations to closure: the dilemma of differing geotechnical design acceptance criteria perspectives

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## Abstract

*For open pit mining, understanding and managing slope performance is critical for both operations and closure. Towards the end of mine life, achieving reliability of slope performance in operations often necessitates real-time implementation of active slope stabilisation controls. This situation changes significantly towards closure, when production economics are no longer the priority, and resources for field monitoring control and active slope management diminish. The risk profile also shifts to a greater focus on stakeholder needs, including the environment and social acceptance, as land use changes. Although risk profiles will shift, the safety goal of ‘zero harm’ needs to continue to be achieved through all phases.*

*Historically, most final pit slopes were not designed for closure. Rather, they tended to be optimised for production efficiency and thus were typically too steep for long-term reliability. The key question then becomes – what happens when the controls that have been put in place for maintaining their stability are decommissioned for closure? With sufficient understanding gained during operations, it may be possible to adequately forecast behaviour and define a Design Acceptance Criteria appropriate for the slope, for post-closure, once operational controls are decommissioned.*

*This paper is hoped will help address this dichotomy and provides suggestions to meet industry objectives. It is also intended to promote discussion on this transition, such that industry and regulator perspectives can be accommodated alongside each other within the forthcoming Large Open Pit (LOP) Guidelines for Mine Closure handbook publication, currently in preparation under the auspices of the LOP initiative.*

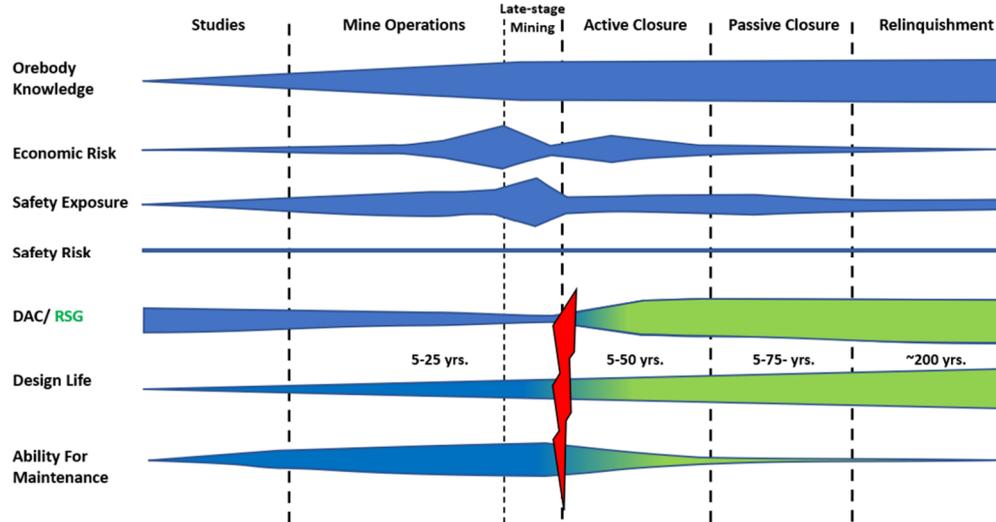
**Keywords:** *design acceptance criteria, relative stability guideline, target stability reliability, geotechnical design, geotechnical risk, slope stability, as low as reasonably possible, post mining land use*

## 1 Introduction: evolving conditions and requirements

Understanding the key factors that control pit wall stability inherently evolves over time during the development of the pit, through increased orebody knowledge and appreciation of anticipated design life and safety and economic risks. All of these directly influence the design acceptance criteria (DAC) that need to be followed, which ultimately then influence the mine’s ability to undertake slope stability maintenance and/or incident response.

In early project planning stages, initial pit development and final closure objectives must align with community desires and permitting requirements; similarly, in closure. By contrast, during operations, up until the start of

passive closure, the mine has much greater control over each stage of the evolutionary process, albeit always ensuring compliance with appropriate legislation. Figure 1 conceptually illustrates this evolution of characteristics throughout the typical lifecycle of planning development and closure for an open pit mine.

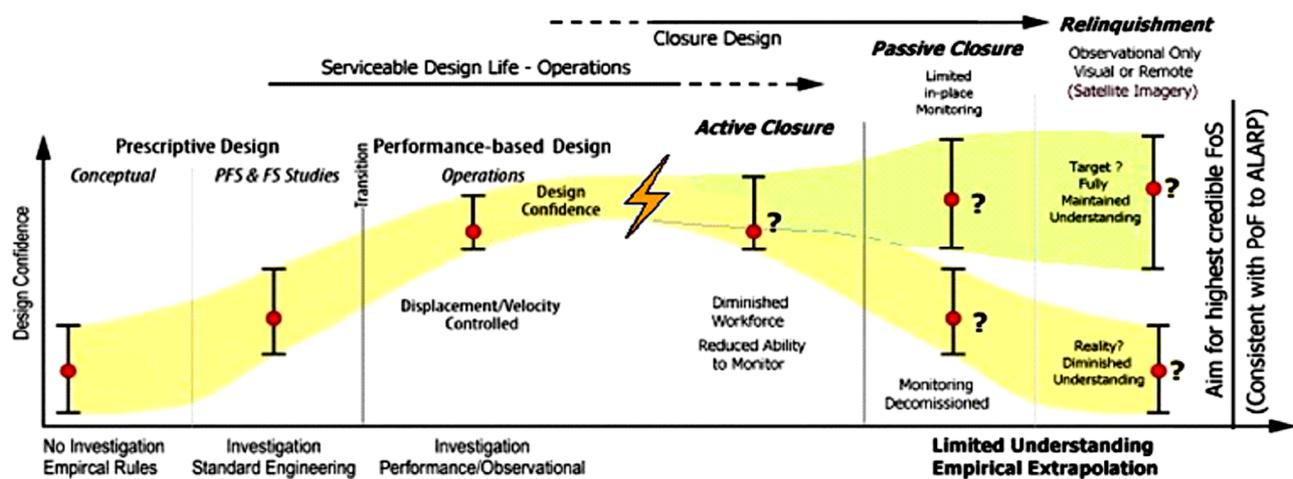


**Figure 1** Evolution of several characteristics throughout the mine lifecycle. Lightning bolt marks the point where operations-focus design acceptance criteria (DAC) must change to a closure-focus relative stability guideline (RSG)/target stability reliability (TSR)

## 2 The challenge

The dilemma for the closure planning team is how to transition an operations focus planning approach back to a community and public perception focus. Economically-optimised final pit slopes at the end of operations are not designed for closure, and thus are typically too steep for long-term stability reliability into relinquishment. This is particularly the case where extensive engineering measures to achieve active stability improvement have been put in place to ensure that late-stage production operations objectives are met. The key question then becomes – what happens during the closure phases when implemented slope stabilisation control measures are decommissioned or no longer can be maintained?

This dilemma of differing perspectives is illustrated in Figure 2, expressed in terms of changing degrees of understanding and confidence in pit wall stability through various stages of mine life.



**Figure 2** Conceptual level of mine life geotechnical understanding with indications for possible range of understanding at relinquishment, based on slope behaviour in post-operations close-down and decommissioning, as well as long timeline forecasting into passive closure (adapted from Macciotta et al. 2020); Lightning bolt symbolises change in focus: operations to closure)

### 3 Knowledge base

Before the time that active closure is to be implemented, a comprehensive site-specific geotechnical database of key information must be made available to the closure planning team. The reliability of the geotechnical closure design will largely depend on the accuracy and quality of this knowledge base and the extent to which it has been developed and maintained over the phases of mine life. Often, particularly in legacy or smaller operations, there is little documentation available to the closure team on slope performance. By contrast, for larger, longer-lived operations, the opposite problem frequently faces the closure team, namely winnowing out salient facts from the wealth of available information. More often than not, though, there still remain data gaps in geographical, health, safety, environment, community and social baseline data as well as on the operational performance history of the slopes. Resolving such data gaps must be a priority in late-stage planning for closure.

If a high degree of confidence in the geotechnical knowledge base has been achieved during operations, it may be possible to adequately forecast behaviour and establish an appropriate sector-specific target stability reliability (TSR) that will be in compliance with overall relative stability guideline (RSG) thresholds. These TSRs may, but not always will mirror the DACs established for mining operations. Like DACs in operations, these reliability targets can be defined in terms of Probability of Failure (PoF) or Factor of Safety (FoS) values appropriate for the slope at closure, considering the consequences of failure once operational controls are decommissioned and considering the closure scenario and vision agreed to by all stakeholders.

In some of the best monitored pits worldwide, where adequate understanding of slope characteristics is available, it may already be known that decommissioning of the active in-place engineering measures may compromise stability. Such measures may have to be maintained in perpetuity or ensure that access to hazardous slopes is actively prevented (as required by the selected closure scenario) to keep risks within tolerable limits. In other cases, where there may be marginal probability of future instability, a programme of long-term slope performance monitoring may be the best path forward until design confidence can be increased. The best cases are those where detailed closure planning has been built into latter stage thinking during mining operations. In such cases often there is good understanding and assurance that the slopes can be left as-is, even moving into full relinquishment, requiring implementation only of as-needed surficial drainage and vegetation measures as erosion controls.

Planning for closure must therefore establish appropriate stability reliability requirements for the envisaged post-mining land use (PMLU) vision, including considering effects of extreme events (seismicity and precipitation), so that practicable risk tolerability associated with the selected closure vision can be assessed. This may necessitate FoS or PoF of final slopes be re-examined as part of final closure planning with mitigation measures duly considered, (such as flattening or buttressing), so as to achieve satisfactory TSR compliance.

It should be the aim of a good closure plan to minimise uncertainty when establishing the actual level of stability of the various slope segments existing around a pit at the end of mine life. For example, as discussed in Carter (2014, 2019), many of the failure cases examined for development of the scaled span concept used in assessment of surface/underground mining interaction (crown pillar) stability, commonly lack knowledge of key factors pertinent to failure mechanisms. For open pit closure design, (which must consider low recurrence hazards with potential high consequence outcomes), appreciation of control mechanisms is critical to minimise expenditure on ineffective mitigation measures. Data reliability and the level of understanding of underlying site-specific geotechnical information must thus be commensurate with the level of identified risk, and this should then dictate the extent of engineering analysis needed. Stakeholders must also be kept apprised of reliability gaps in the knowledge base and be educated that without sufficient data reliability, modelling of scenarios at more than an empirical or conceptual level will not add value to the closure plan.

In Figure 2, the changing error bars in prediction accuracy over time (based on lack of reliability) reflect not only uncertainty due to database gaps, but also changing uncertainty perception due to the differences in perspective between late-stage mining operations where an aggressive economic optimisation viewpoint dominates slope design thinking, versus relinquishment objectives, where long-term stability requirements

dominate. During operations, monitoring and reactive intervention remedial measures are possible. At relinquishment, final slope geometries must be in harmony with long-term material strengths and pore pressure conditions to not only ensure sufficient stability but also to achieve as much reduced risk as practicable, consistent with the closure vision. The knowledge database must in turn, thus include geotechnical data relevant to long-term issues.

Database gaps that can affect sensible decision-making on the specification of appropriate RSG/TSRs for closure (constituting the *de facto* DACs), must be avoided. Checks that adequate data exists are needed in early operations when money and time is still available to address knowledge shortfalls. Mine planners need to understand that into closure, intervention to manage adverse slope performance is no longer an option. Often, more stringent deformation limits, well below levels considered normal during operations, become the requirement at closure to mitigate potential disruption. A staged approach to implementing an effective, yet robust remote deformation detection monitoring system with appropriate trigger action response plans (TARPs) may be required.

## 4 Design for closure

### 4.1 Design service life

The level of understanding, evaluation, and management of geotechnical slope stability risk for open pit slopes should match the anticipated design service life. For operations, this is relatively straightforward, but establishing a design service life for mine closure is challenging with little agreement on an absolute number of years. There is a contentious array of views; some stakeholders venture aspirational ‘in perpetuity’ targets or ‘until the next ice age’ defined as 1,000 years; others offer more modest science-reliability-based periods in the order of 350 to 1,000 years. Key industry reference guidelines are notably silent on this fundamental time estimate (ANCOLD 2012; ICOLD 2017; Australian Government 2016; Asia-Pacific Economic Cooperation 2018; International Council of Mining & Metals 2019).

The definition of a closure design service life can have a significant impact on perceived or implied closure acceptability, public expectations, design options, and ultimately on closure costs. In some instances, costs may be so high as to preclude owner appetite for meaningful closure practice.

Hadnutt (2020) suggests that design service life is the “assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance, but without major repair being necessary”. This can be simplified to ‘lifetime to first major repair’. In the context of mine closure, this definition aligns with the ‘active closure management’ period (i.e. ability to effect remediation), however, for ‘passive closure’ with an expectation for full relinquishment (with limited or no maintenance), the definition might be considered problematic. It is thus critical that stakeholder performance expectations are well defined for the agreed ‘design service life’ that is incorporated into closure requirements.

Application of performance-oriented risk-based approaches can be effective in helping move a closure plan towards achieving a ‘walk away’ or ‘passive care’ outcome. The philosophy of performance-oriented thinking is to consider the final closure landform set within the adjacent ongoing evolving geomorphological landscape surrounding the property. They will both ultimately be subject to the same natural events such as slope instability, surface erosion, groundwater level fluctuation, or fires. Risk levels should thus be considered equally between the property area and the surrounding landscape. Zero risk does not exist in the natural environment (OSTDC 2014) nor for constructed landforms. Targeting zero risk for closure planning is thus an unrealistic objective; however, one would expect the caveat (and agreement with stakeholders) must be that significant risks are appropriately managed and align with as low as reasonably possible (ALARP), consistent with the adopted closure vision. In this context, once the open pit has transitioned to an equivalent landform, its ‘design service life’ would then be expected to be dictated by landform evolution processes applicable to similar natural features, rather than by any consideration for revised levels of designed stability.

The Asia-Pacific Economic Cooperative (APEC) Mining Task Force, (2018) recommends splitting consideration of design life reliability into different time horizons:

- Design life for the overall closure system.
- Design life for a specific closure components (e.g. concrete used in a spillway, etc.).
- Average recurrence interval for a design event (e.g. a 1 in 200- or 1 in 1,000-annual exceedance probability storm).

Each of these ‘design lifetime horizons’ could be different for a given closure plan. APEC (2018) outlines current best practice as follows: ‘*mandates for design life should consider both the limits of engineering practice and our institutions*’, noting that the fundamental challenge for design life reliability definition is inability of even the best science-based ‘crystal ball gazing’ to make reliable predictions of internal and external loading conditions over an indefinite future. Benchmarking long-term slope stability performance of surface mines is particularly challenging due to lack of precedent experience. In fact, engineering science for large excavations is limited to evidence-based design periods in the order of 100 to 200 years only, while predictive excavation performance models for closure periods over 1,000 to 10,000 years are well beyond real world calibration experience. Added to this, very few governmental, and even fewer commercial institutions have endured more than a few hundred years, so expectations for enduring oversight and ongoing management need also to be tempered by this reality.

One pragmatic legislative example, balancing the limits of engineering practice, is the US Uranium Mill Tailings Radiation Control Act (Federal Government of the United States 1978) which mandates closure measures be effective ‘*for up to 1,000 years to the extent reasonably achievable and, in any case, for at least 200 years*’. According to Logsdon (2013), this environmental protection guideline was formulated to cover the ‘*periods over which climatological and geomorphic processes could reasonably be predicted, given current knowledge of earth sciences and engineering.*’ The 200-year period can be seen as being reasonably within reach of analytical or predictive engineering approaches, while the 1,000-year time span enters the realm of qualitative evaluations.

Table 1 provides an example of how design life could vary according to closure vision, constituting a proposed guidance framework to aid appropriate geotechnical design life decision-making.

**Table 1 Example guidance for proposed design life considerations for geotechnical and hydrological analysis\* (developed based on recommendations by Logsdon 2013; Federal Government of the United States 1978; ICOLD 1987)**

Aspect of performance	Active closure**	Passive closure
Design life of overall facility (landform erosion)	25–300 yrs	300–1,000 yrs
Slope/dump stability with material degradation	25–100 yrs	100–200 yrs
Water quality/pit lake models	>500 yrs	>1,000 yrs
Annual exceedance probability of design events:		
• Storm flood	1 in 100	1 in 10,000
• Seismic	1 in 100	1 in 10,000

\* Local jurisdiction requirements may be more onerous.

\*\* Criteria may be lower with agreed shorter active/managed closure period, or on relinquishment to new land use with associated performance maintenance.

## 4.2 Design reliability

Closure design to ALARP reliability criteria requires a change in perspective from the commonly applied ALARP-based DACs utilised in open pit slope design for operations. Not only is this change in thinking

necessary to encompass longer extreme event average recurrence periods; but also because most FoS and PoF guidelines considered applicable for operations might not be adequate for closure. Typical operational DAC for open pits outlined in Read & Stacey (2009), are built around FoS and PoF criteria based on precedent operational experience, each operator’s risk profile, and framed within typical regulatory requirements. Furthermore, they are generally predicated on active risk management, thus allowing mining to be undertaken to the steepest slopes possible. By contrast, a more conservative approach is taken in the ‘Guidelines for Mine Waste Dump and Stockpile Design’ book by Hawley & Cunning (2017), reflecting a heightened degree of failure consequence and lower achievable risk management for dumps, as compared with pit slopes.

Another issue of concern for directly applying typical FoS criteria recommended for operations for defining mine closure completion acceptance thresholds is that such FoS limits, particularly where data uncertainty is high, cannot reliably be directly interpreted as an indication of PoF. This has been shown by Macciotta et al. (2020) for operating open pit DACs, where data reliability will likely be higher than for closure, where greater longevity is required, and hence where assessing more extreme value statistics becomes a necessity.

The dilemma from a closure risk exposure viewpoint is also that risk during operations can be actively managed, while for full pit relinquishment, a demonstration that risk will be sufficiently (passively) mitigated that public exposure is reduced to within tolerable limits, is required. To address these changes in perspective of how slope instability risk for pit slopes needs to be managed, a series of suggested design confidence and stability reliability guidelines are summarised in Table 2.

**Table 2 Example slope stability design acceptance criteria expressed as a function of mining stage\***

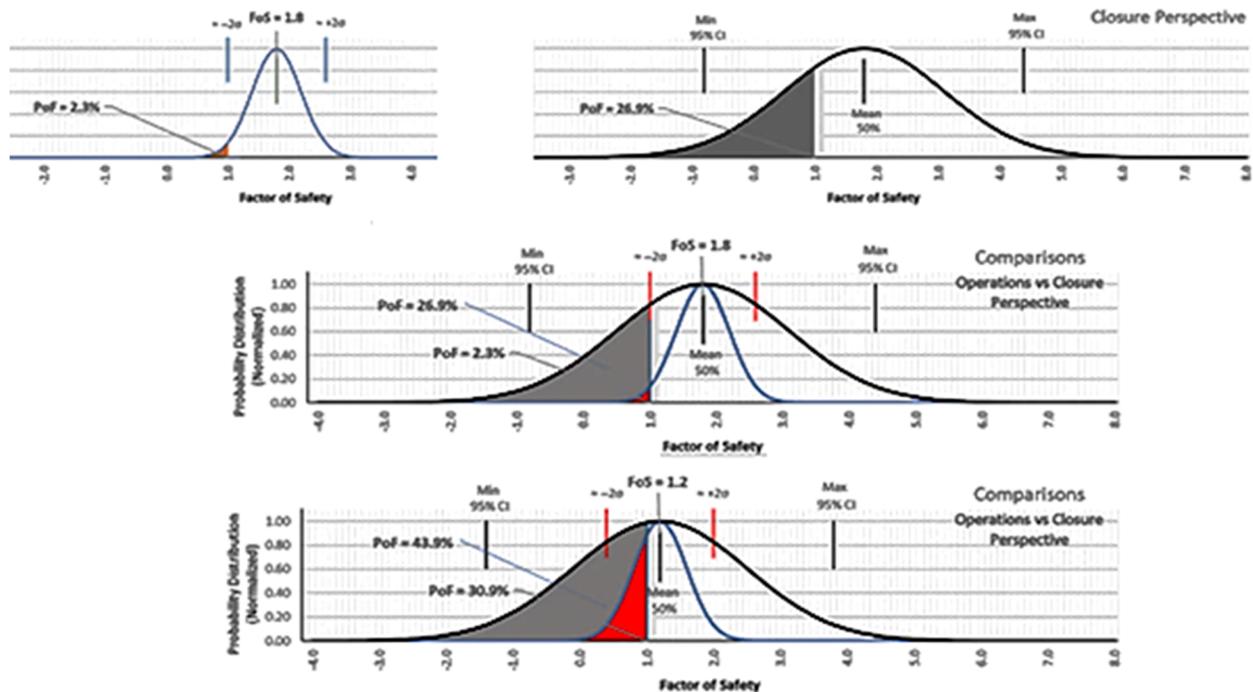
Safety and environmental risk profile	Design stage	Slope performance goal		Stability reliability
		Acceptability criteria	Design conf.	
Natural hazard environmental risk management	Green field site	Ensure pit layout whittle pit shells (at 45°) economically viable. Assuming good rockmass	Moderate	Very high
	Concept stage	Establish slope angles viable for rock conditions identified by early investigations	Low	Moderate
	Early pre-feasibility	Improve slope designs with additional data and sensitivity assessments	Low	High
	Pre-feasibility	Test design confidence through data checks wrt most aggressive slope design layouts	Low	Very low
	Feasibility stage	Verify data to finalise bench, inter-ramp and overall slope designs for optimised extraction	Low	Moderate
Operational risk management	Early operations	Implement conservative slope designs in weathered upper zone	Moderate	High
	Initial production	Ramp up to full production - steepen slopes away from final walls	Moderate	High
	Mature operations	Optimise slopes to maximum angles to minimise stripping ratios	Moderate	High
	Late stage operations	Steepen bench geometry to maximum achievable IRA in final cuts	High	Very high
	Transition to closure	Transition short term operations slopes to stable long-term geometries	Low	Very low
	Active closure stage	Implement active stabilisation measures to achieve stable long-term geometries	Low	Low
Natural hazard environmental risk management	Passive closure	Achieve final vegetated stable slopes with no maintenance needs	Moderate	High
	Relinquishment	Achieve regulatory approval for same level of public access as natural hillslopes	Moderate	Very high

\*Note this table would only be applicable to certain closure scenarios and contexts and is presented solely as a guide to aid the development of project-specific criteria. The last column corresponds to target reliability in stability analyses given typical levels of design confidence for a consistent level of risk

It is important to note in Table 2 that the two right-hand columns attempt to categorise design confidence and associated target reliability only for the actual physical stability calculations, viewed from the perspective of each mining stage. This discussion focuses principally on the evolution of the safety and environmental risk, starting with the inherent natural hazard risk associated with the environment and landscape as routinely managed by farmers and government agencies (supplemented with exploration safety controls),

through active operational risk management during mining and closure implementation, and ultimately reverting to natural hazard management. In the study phases, the mine owner’s business risk is managed through improving ore body knowledge confidence, applying conservative assumptions (grade, performance, etc.) with conservative slope DAC (as illustrated in Figure 1).

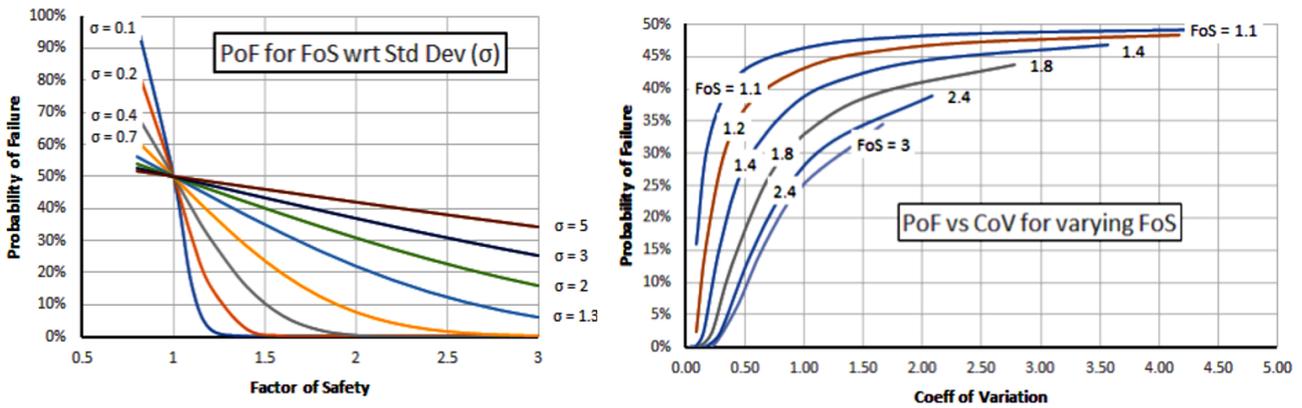
Calculated stability reliability based on the earliest geotechnical models and subsequently improved through operations may, however, differ markedly when viewed from an operations versus a closure perspective. This divergence in viewpoints can conceptually be seen by comparing the two probability distributions of FoS between operations and closure as shown in Figure 3.



**Figure 3 Differing viewpoints between short- and long-term slope stability uncertainty**

The left top graph in Figure 3, illustrates the typical narrow spread of uncertainty existing for managed risk at the end of most open pit operations. By contrast, the right top graph in Figure 3 views the same slope condition, but from the viewpoint of an increased uncertainty of instability under the influence of unmanaged events such as extreme precipitation or seismicity. The FoS of 1.8 remains identical between the two plots but the uncertainty, expressed in terms of the 95% Confidence Interval (CI) range, i.e. approximately two standard deviations either side of the mean, changes dramatically. In consequence, the PoF also increases from approximately 2%, viewed with a short-term operations focus (left diagram), to more than 25%, viewed from a long-term closure and relinquishment perspective (Figure 3 – top right diagram). This perceived dramatic increase in failure likelihood is perhaps even clearer when the plots are overlaid, as shown in the composite lower two diagrams – the upper one for the same FoS = 1.8 as in the two separate plots, and the lower one for FoS = 1.2 for the same 95% CI ranges. Note: all these plots are normalised with respect to PoF to allow direct comparisons of relative changes in the computed PoF.

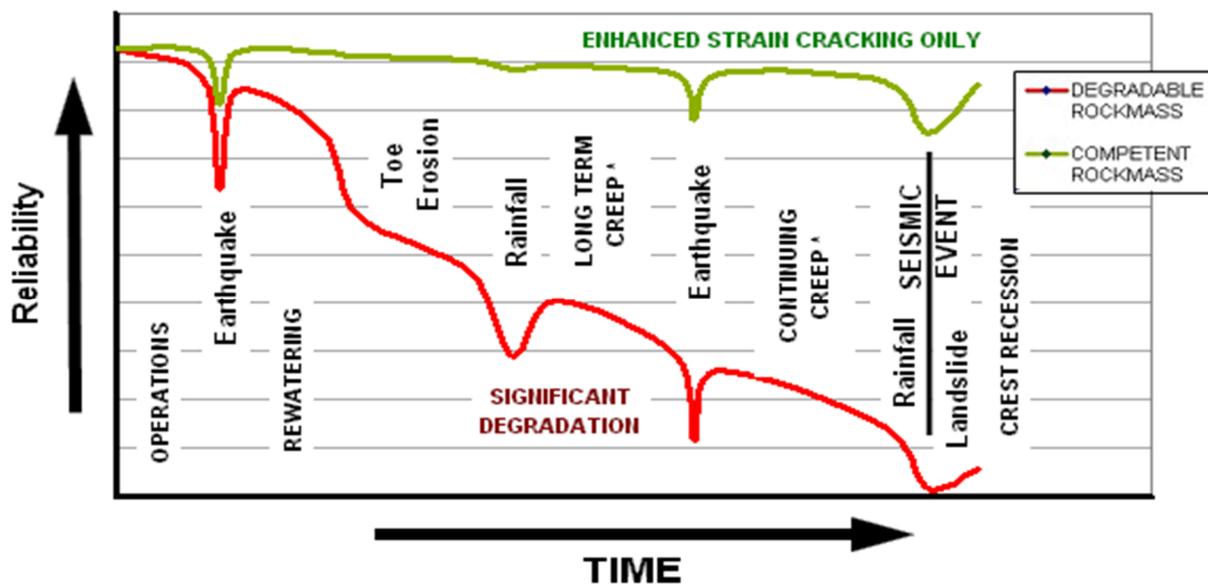
As graphically illustrated in Figure 3 above with respect to a normal distribution of FoS analysis uncertainty, and, as summarised in Figure 4 for normal distribution variance parameters ( $\sigma$  or  $\sigma^2$  and Coefficient of Variation, CoV), only for a FoS value of unity is there agreement between FoS (1.0) and PoF (50%). Yet, as Duncan (2000) notes: “Through regulation or tradition, the same value of safety factor is applied to conditions that involve widely varying degrees of uncertainty. This is not logical”.



**Figure 4 Characteristic relationships between Probability of Failure and Factor of Safety for differing analysis confidences (reliability)**

As shown in the left plot in Figure 4, without constraint a PoF value often depends more on degree of uncertainty than on actual values from analytical or numerical calculations. A high FoS does not necessarily therefore always equate to a lower PoF. In addition, because PoF values are often found more influenced by uncertainties in geological models and in parameter values than in the underlying analysis methods, PoF inter-relationships with FoS, as demonstrated by Pine & Roberds (2005), also typically cannot be directly tied to standard statistical measures of variance and/or confidence, based solely on computed FoS values.

Important as these issues are in affecting confidence in reliability calculations, it must also be appreciated that even without deliberate excavation geometry changes, a slope’s FoS will physically not remain constant over time but will vary with ambient field conditions; this is a key consideration relative to establishing closure period and relinquishment criteria. Transient conditions (such as rainfall-induced porewater pressure increases and seismic loadings), as well as longer term permanent changes to material strength (due to weathering and strain softening effects), must be expected to alter over time (Figure 5).



**Figure 5 Influence of time-dependent and temporal changes on slope stability (\*long-term creep active throughout, but rate assumed to accelerate with increased degree of rock mass degradation)**

The effects of varying post-closure environmental conditions on different competence rock masses are conceptually portrayed in Figure 5 by the two trend lines in an attempt to highlight one of the thorniest problems of closure engineering. Namely, that a myriad of widely divergent, quite different post-closure pit slope stability scenarios exist for the same series of field condition changes. In this example, the two extremes

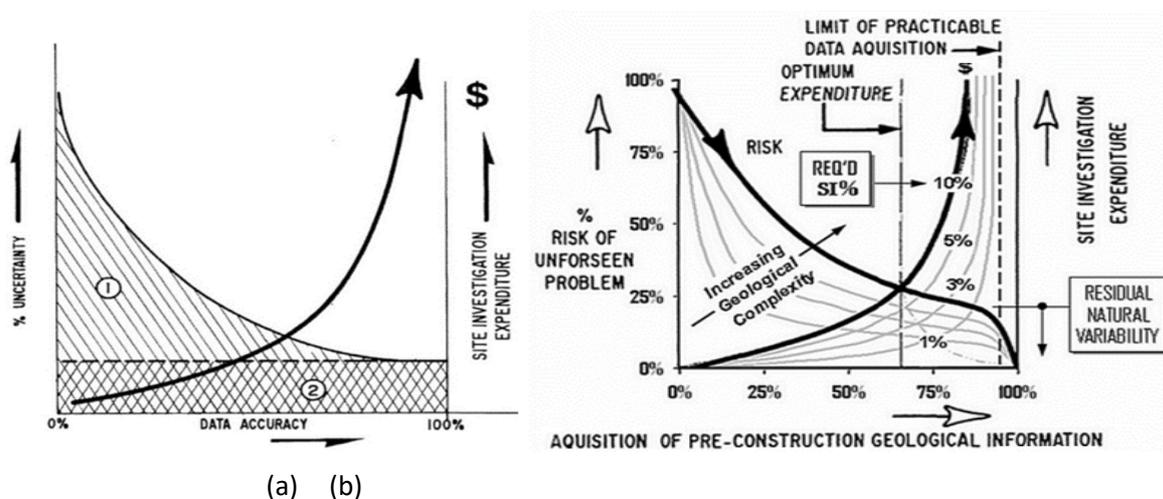
have been plotted – a competent rock mass that does not change appreciably even when subjected to extreme events, and a weak rock mass that is susceptible to significant deterioration under these same changing field conditions. For these two pit slope cases, one survives unscathed through a variety of adverse events; the other fails due to strength degradation affecting the weak rock mass. Closure RSG/DACs need therefore to be flexible enough to encompass dealing with the full gamut of possibilities between these end member scenarios. However, as outlined by de Graaf et al. (2019), up until now, no generalised industry-accepted guidance for mine slope stability closure DACs exists. The proposed Large Open Pit (LOP) Project Mine Closure Guidelines are now attempting to address this (de Graaf et al. 2021).

Historically, closure DACs have been based on a combination of designer’s experience, perceptions of uncertainty and likely consequence of failure in addition to the level of risk tolerance acceptable to mine management. More recently, consideration for confidence in input models and design parameters, along with the scale of instability and consequence of long-term failure, have become recognised as important factors to adjust DACs in accordance with reducing residual risk to ALARP levels. Quantification of relative stability is, however, not a measure of ALARP suitability, i.e.  $DAC \neq ALARP$ . Consequently, for closure, the concept and terminology of a DAC should perhaps be dropped entirely; as the implication is that once a DAC has been achieved, then all expectations are then satisfied, which creates another dichotomy of opinion.

It is suggested that a risk-based ‘RSG be utilised’. The objective of proposing a different acronym, than DAC or directly using PoF or FoS terms, is that it is hoped that this RSG concept will prove more effective than current approaches as a means for communicating degree of relative stability and make the criteria more transparent for stakeholders. It is to be hoped that the approach will gain more traction once appropriate RSG thresholds have become more extensively benchmarked against other key geotechnical guidelines (dams, crown pillars, tailings etc.).

In concept, for developing a RSG for a specific closure plan, all the same key factors influencing DAC decisions on design analysis for operations would first need review e.g. ALARP selection, and consequence and reliability assessments. Each must then be considered with respect to the closure scenario agreed to by principal stakeholders. Project timeline changes must also be examined, as many aspects have the potential to change substantially throughout the various project development phases into closure as the knowledge base is developed and improved. As illustrated in the left-hand diagram in Figure 6, uncertainties may be of two types – epistemic (1) or aleatoric (2):

- Epistemic: Uncertainty due to lack of knowledge, which can be reduced through investigations.
- Aleatoric: Natural randomness of a property or loading condition that cannot be reduced.



**Figure 6 (a) Postulated relationship between uncertainty due to data inadequacy (1) versus inherent uncertainty due to natural variability (2) as a function of level of understanding. (from Carter & Miller 1995); (b) Conceptual reduction possible in data uncertainty and hence project risk through enhanced site investigation (from Carter & Barnett 2021)**

Given that natural variability most likely will be greater in a complex geological setting than a simple one, investigation expenditure and the density of data collection in early project stages and into operations right up to the active closure stage should be tailored to the level of perceived geological complexity, as conceptually illustrated in the different curves included in the right-hand diagram of Figure 6. Lack of appreciation of key geotechnical conditions in early project stages could in complex geology result in such significant differences as to make closure estimates prepared for the permitting process completely invalid for the actual reality of final closure. Effort must therefore be placed early on towards developing an increased understanding of the degree of possible natural uncertainty on a site-specific basis, and then improving this with increasing focus on geotechnical domain characterisation throughout mine design life.

Guidelines for differentiating between natural geological variability and uncertainties due to data inadequacy related to level of required understanding by project stage are outlined in Carter & Barnett (2021) based on assessment of domain modelling reliability, which ideally will increase to the right in the graphs in Figure 6.

Clear and simple communication of these concepts is also needed to all stakeholders. It must be transparent to all that if inadequately quantified models are generated, these cannot be expected to be suitable for effective design or risk management. Miller (2019) noting this as a common problem of many, even quantitative, risk assessment models, particularly when 'quantified' with unlimited magnitudes, wrote "Data and QRA models are often inherently flawed, unscientific, lack transparency, contain numerous assumptions and omissions that cannot be checked or verified so the results are easily manipulated and highly deceptive". Another train of thought is that experience has shown (Silva et al. 2008; Macciotta et al. 2016) that even when using approximate numbers, a defensible risk assessment can prove useful as a risk management tool. The aim for undertaking any risk assessment should be however that each scenario is extremely well understood, and that all considerations, uncertainties, and credible sensitivity ranges are properly defined, and the process clearly documented.

Transparency in defining such uncertainties in design evaluations is even more important to be widely understood by all stakeholders if the design analysis includes reference to only FoS criteria. This, however, can be rectified either by adding some PoF guidelines, invoking a relationship between FoS and PoF, such as shown in Figure 4, or by following a path of undertaking sensitivity assessments on each design scenario to verify uncertainty ranges. Applying sensitivity assessment approaches in such circumstances also has additional merit as an aid to helping designers to thoroughly review and optimise their designs through an iterative process. If undertaken sequentially as a project matures, applying these types of approach will inevitably help facilitate an increased understanding of key hazards while also raising confidence in the underlying knowledge base, thus leading generally to more effective mitigation of risks for a given DAC/RSG.

The minimum RSG needed at each stage of project development will be different for various elements of a project's facilities. This is dependent not just on perceived consequence, but also on the actual level of geological, geotechnical and hydrogeological understanding achieved to that point. The authors recommend setting RSGs to reflect the worst reasonably foreseeable consequence, so as to set the bar sufficiently high so that unrealistic overly optimistic aspirations are negated as early as possible. This approach is in accordance with ALARP requirements to mitigate reasonably foreseeable outcomes.

Regardless of the assessed level of risk tolerance, the selection of RSGs must be demonstrated to be consistent with stability reliability values ( $\beta$ , FoS, PoF) appropriate to each stage of project maturity. If consequences are low and understanding of uncertainty is high, a lower FoS is defensible. Nevertheless, high levels of consequences and uncertainties require a higher benchmark or other measures such that ALARP is met. Of utmost importance, and on which emphasis must also be placed, is proper identification of potential failure modes in analyses conducted for sensitivity assessments. However, if selected appropriately and executed to a reasonable level of rigour, sensitivity types of design assessment can be viewed as probabilistic, particularly when design loadings (seismic and hydrologic) also reflect occurrence probabilities.

## 5 Design tolerance

In the context of geotechnical closure risk management, there is a requirement that the design analysis methodology and underlying decisions as to what is tolerable and acceptable, must be both unbiased and defensible, as well as being aligned with the closure strategy. Furthermore, the (risk) decision-making process should be logical, consistent, and capable of clearly identifying trade-offs between economic and social equity (CDA 2013).

A decision as to whether a geotechnical design's residual risk is ALARP in the closure context must be made also on a case-by-case basis in consultation with stakeholders. If a proposed outcome cannot be justified or accepted by all stakeholders, this should trigger a review of all the closure scenario options to either improve design reliability or reduce the expected consequences. Typical examples would include minimising exposure by increasing exclusion zones, re-profiling slopes, buttressing, or backfilling the pit void. Given that such mitigation measures would likely change both risk and cost outcomes, these types of changes likely would also trigger adoption of more comprehensive risk assessment methods (i.e. more quantitative approaches).

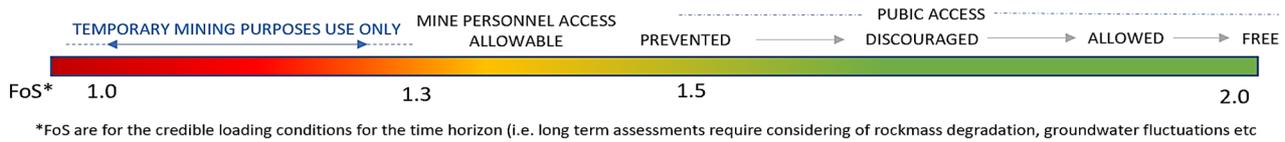
While it is generally agreed that targeting zero risk is unrealistic, particularly for the very long design service life needed for closure, there is still a need to appropriately examine all foreseeable risks, but with particular focus on managing catastrophic and/or high safety risks consistent with the ALARP principle. Given that at the end of production, a philosophical shift must be made away from the operator's typical as high as viably possible (AHAVP) approach of managing risks, usually by implementing effective intervention measures, closure planning must be based on considering the new post-operations condition where successful interventions are no longer an option to manage risk, since typically no workforce exists.

Reliability in analysis and data utilised to assess, for instance, the two different stability reliability scenarios outlined in Figure 5, however, needs to be identically measured. For both extremes, sufficient reliability must be achieved through acquisition of appropriate investigation data, extending knowledge gained during operations, to ensure that parameter assessment is accurate, so that stability analyses can be relied upon, and decision-making can be executed based on reliable data. In this context, the active closure stage should be utilised to undertake slope performance measurements to gain understanding and knowledge regarding initial response behaviour of final closure designs. The principles of increasing adequacy of geotechnical understanding with investigation and design maturity remain identical into these closure stages of the project timeline. It is only the option to manage risk that differs between the operations and the closure perspective.

Unfortunately, lack of reliability in input data and in slope assessment models often cloud correct interpretation of absolute stability state. Where this is suspected there may be a need to undertake independent verification. Oftentimes this can be most effectively achieved by engaging subject matter experts (SMEs) to review base data and the engineering fundamentals involved, including undertaking, if necessary, additional deterministic or probabilistic assessments to conclude such verification.

## 6 Stability evaluation

The ranges of typical FoS constituting DAC/RSG targets to be applied for closure consideration, as diagrammatically outlined across Figure 7, have been formulated based on engineering judgement, precedent industry experience, international standards, and stakeholder expectations. As such, these typical values are supported by the preceding process of failure consequence assessment based on credible failure modes informed usually through a potential failure modes analysis (PFMA) and a robust hazard identification process. However, at the transition from the end of operations into final closure, as encapsulated in the diagrams in Figures 1 and 2, there is a need to change perspective from managed risk at the left end of the diagrammatic scale in Figure 7 to responsible stewardship at the other end of the scale. Obviously, major adjustments are needed to make these two extremes anywhere near compatible.



**Figure 7 Comparative scale of Factor of Safety in operations versus closure**

While the requirement for personnel safety remains constant, the key differentiating factor where one is situated along this scale is in the controls that can be implemented. Mining operations install robust monitoring systems and ensure their workforce is well trained in geotechnical hazard management, such that TARPs can be implemented to allow mitigation of safety exposure. Economic consequence to the operator becomes then the key factor allowing lower FoS to be tolerated.

In the post-closure environment, at the right-hand end of the scale in Figure 7, robust monitoring controls are usually diminished, and stakeholder expectations, including access requirements become the key control factors, (Table 3). Keeping risks within ALARP can then only be met for the selected closure design, by minimising exposure to slopes with lower reliability and/or achieving a higher slope reliability for slopes where exposure of people is expected to be high. These controls can be explained in a stability reliability sense by requiring lower PoF and higher minimum FoS values that together can be considered tolerable by all concerned stakeholders. Consequence, however, will drive stakeholder opinions, with any safety exposure outside of an actively managed area likely requiring high FoS thresholds. However, as shown earlier in Figure 3, PoFs may not be the same for a given FoS, and furthermore not all FoS will be comparable sector to sector or site to site. Design reliability must therefore be the yardstick for determining what stability requirement is tolerable given the potential consequences for a given slope situation.

This concept is not new and is discussed in a study and operational context in many references, including Adams (2015), Hawley & Cuning (2017) and Macciotta et al. (2020). Nevertheless, because of the significant difference in perspective between operations and closure and the typical complexity of most large pit slopes, as schematically illustrated in the left diagram in Figure 8, significant inherent variability must be accounted for as potentially existing throughout the slopes. Closure design must account for such variability, as rarely will slope conditions around the full perimeter of a large pit shell be identical. Differences will exist, not just because of geological variability, but also because of varying operational DAC applied to different sectors – for example, pit slopes with ramps, may have been mined to a more stable geometry than other slope sectors or domains. Such factors should be considered when ranking stability reliability for each different domain around a pit shell, as shown in Figures 8 and 9, and as detailed subsequently in Figures 10 to 12 and Table 4.

Figure 8 shows a hypothetical pit at the end of mining, with variable wall performance conditions and different neighbours around the pit shell. This will be used as an example for illustrating the proposed RSG ranking approach relating confidence, consequence and required wall condition (related to PMLU). It will be noted that the NE sector (Domain E) has proven much more problematic than was envisaged as significant slope instability has occurred here, whereas slopes in other sectors have shown good performance behaviour. However, at closure, Domains A, B, and F will remain with higher consequence potential due to adjacent land use requirements. An escalating mine closure RSG criterion is thus needed to account for these differences and help transition operating criteria to better marry with the chosen closure vision.

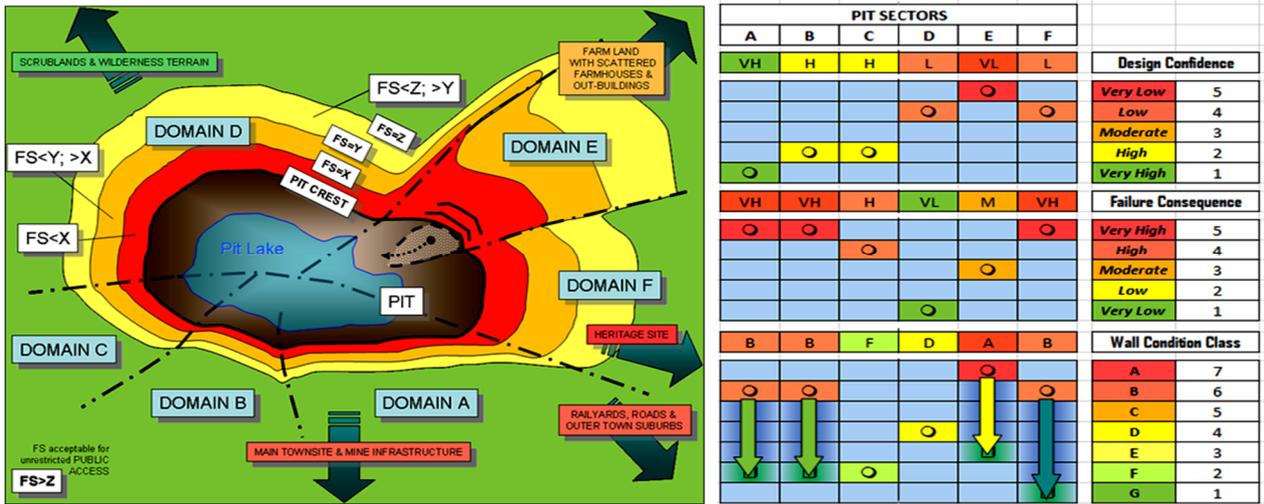


Figure 8 Suggested approach for ranking design confidence, failure consequence and slope class for post-mining land use relative stability guideline checks (Note: Table 3 definitions used for wall class ranking)

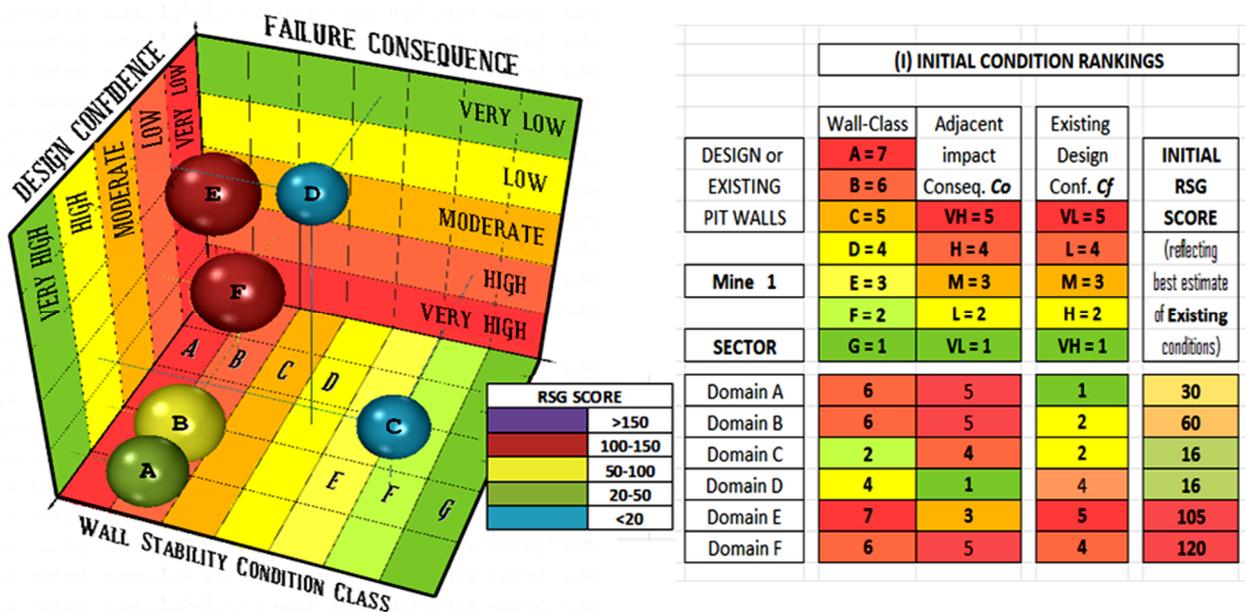


Figure 9 Conceptual results of relative stability guideline assessments for hypothetical example open pit configuration and sector geometry shown in Figure 8

**Table 3 Suggested screening classification table for benchmarking open pit slope wall conditions and probable significance for slope failure risk (modified from Carter & Miller 1995; McCracken & Jones 1986; Kirsten & Moss 1985; Priest & Brown 1983; Pine 1992; Cole 1993)**

Existing pit wall condition class	Existing pit wall likely Probability of Failure %	Existing pit wall likely Factor of Safety*	Assessed existing wall reliability index*, β)	Existing pit wall likely long-term reliability*	Indicative stakeholder position on closure strategy	Suggested Controls	
						Public Access	Operating Surveillance
A	50 – 100	<1	<0.1	Effectively zero	Totally Unacceptable	Forbidden	Ineffective
B	20 – 50	1.0	0.5	Quasi-stable Slopes	Not acceptable	Forcibly Prevented	Continuous sophisticated monitoring
C	10 – 20	1.2	1.0	Unvegetated slopes with uncontrolled rockfall risk and undesirable risk of failure	High level of concern	Actively prevented	Continuous monitoring with instruments
D	5 – 10	1.5	1.2	Standard design reliability, slopes w/rockfall control	Moderate level of concern	Prevented	Continuous simple monitoring
E	1.5 – 5	1.8	1.5	Good design reliability, unvegetated slopes, but w/rockfall protection	Low to moderate level of concern	Discouraged	Conscious superficial monitoring
F	0.5 – 1.5	2.0	2.5	Design reliability to routine civil design standards, incl. rockfall protection & berm drainage	Of limited concern	Allowed	Incidental superficial monitoring
G	<0.5	>>2	>3	Extremely high reliability, controls far exceed credible hazards (vegetated slope to full highway design standards)	Of no concern	Free	No monitoring required

\*For closure loading conditions considering material degradation & longevity events.

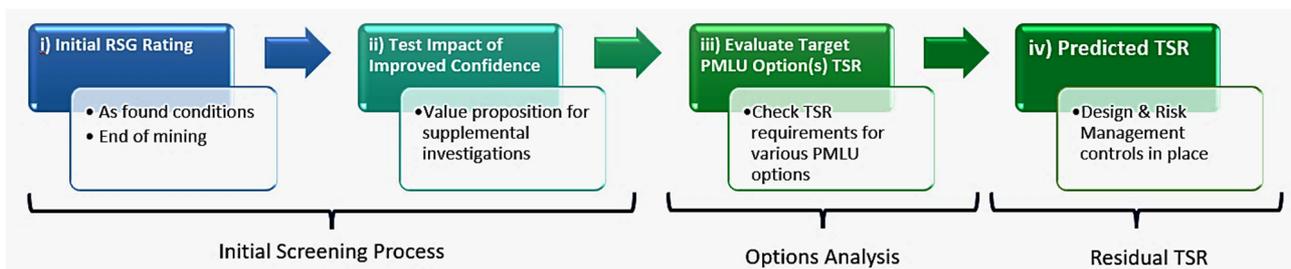
Note  $\beta \approx \log_{10}(PoF)$ , where  $PoF = p(FoS < 1.0) = p(SM < 0) \approx 10^{-\beta}$  (after Pine 1992).

As shown schematically in Figures 8 and 9, a traditional hot-to-cold three-scale ranking of confidence, consequence and slope/wall condition is proposed for establishing sector-specific RSG scores. This approach is suggested not only because it provides a relatively accurate, yet open and transparent method for qualitatively screening end of mining (inherent) closure slope failure risk per sector, but because it can also be used to provide the base case for then evaluating closure risk and potential for remediation or enhanced exclusion mitigation measures, by identifying where gaps exist between ‘as found’ and required slope class.

In viewing the tabulation on the right-hand side of Figure 9 with the wall condition rankings derived from Table 3, it should be appreciated that the FoS, PoF and β scales included in Table 3 are provided solely for guidance in helping in formulating thoughts on appropriate ranking levels commensurate with potential long-term slope degradability likelihood (per Figure 5 concepts). Given that the FoS and PoF value ranges, which can each be linked through the reliability index β column, have been predicated based on utilising a normal or log-normal distribution for FoS (see, for example Christian & Urzúa 2009), it is intended that Table 3 be used as a tool for assessing likely future stability state of a given slope in a closure scenario, based on its condition at the point of closure of the mine, or as it might be considered to degrade to in a PMLU context (using as a guide the descriptions in the centre of the table). When used in this manner as a guidance table for assessing likely ‘future’ stability, and delineating path forward options for closure, the various columns in Table 3 can help in defining conditions that would differentiate those slopes that might require engineering intervention, or other remediation, or be put off limits from a public access perspective, from those deemed

acceptable for direct closure planning. Specifically, the right-hand columns can also provide benchmarking guidance for suggested controls including complexity needed for post-closure monitoring.

Although a single ranking based on exposed current conditions will provide good appreciation of key issues of concern, to be of most value for closure planning it is recommended that such screening be undertaken in a phased approach as suggested in Figure 12, where the initial ‘as found’ condition rating is first determined (Step I), and then the influence of improved model confidence is rated (Step II). Taken together these initial two screening stages then provide the base case for subsequent evaluation in Step III with respect to potential PMLU options and assessment of need or otherwise for potential remediation or enhanced set-back measures. Executing Step III of the phased evaluation sequence directly then provides guidance on the TSR (to be used for stability design purposes), and finally helps in predicting sector-specific TSRs that might conceivably be achieved once any required mitigation or controls (e.g. design and management plans) are implemented (Step IV, Figure 12).



**Figure 12 Suggested staged screening and options analysis sequence for defining residual target stability reliability (TSR) ratings**

In this paper only the initial screening results per the table on the right-hand side of Figure 9 have been plotted in a full 3D diagram showing the relative rankings of the various sectors around the hypothetical pit conceptualised in Figure 8. Each of the ranking steps across Figure 12 could also be plotted as spheres within similar consequence-confidence-condition 3D block diagrams allowing tracking of potential improvements due to increased knowledge and confidence or reduced consequence resulting from improved slope condition. In the diagram included on the left of Figure 9 each sphere has been sized and coloured in accordance with their respective initial RSG scores reflecting the perceived current (existing, end of mine operations stage) residual closure concern level for each of the sectors around the hypothetical pit shell shown in Figure 8. The RSG estimates utilised for plotting the 3D diagram are unweighted scores based on simple multiplication scaling, viz  $RSG = Cf * Cq * Cl$  where  $Cf$  is the confidence rating, between 1 and 5 as per the colour shaded scale in the top right of the three matrices in Figure 9;  $Cq$  indicates the consequence rating, again on a scale of 1 to 5 per the second block in the matrix, with  $Cl$  being the slope class or PMLU rating, per the pit wall classes described on a 7-point scale (A-G), as outlined in Table 3.

In concept, the first two ranking scales,  $Cf$  and  $Cq$ , mirror the classic confidence-consequence assessment approach outlined in Macciotta et al. (2020), with the relative consequence scaled based on the notes shown around the perimeter of the hypothetical pit plan in Figure 8. Including the third dimension of the wall condition per Table 3 allows ready assessment of sectors requiring attention, as summarised in Table 4.

**Table 4 Suggested actions, dependent on RSG score**

RSG score	RSG level	Appropriate action
RSG>100	Extreme	Comprehensive and extremely rigorous analysis required, based likely on additional data acquisition so that deep understanding of failure mechanisms and behaviour can be gained to allow extremely robust controls to be implemented. Very high design reliability required. <b>FoS &gt;&gt; 2 needed unless quantitative risk analysis (QRA) undertaken</b>
50≤RSG≤100	High	Rigorous analysis necessary, so that thorough understanding of mechanisms is gained, so robust controls can be implemented High design reliability required. <b>FoS &gt; 2</b>
20≤RSG≤50	Moderate	Standard analysis sufficient, good understanding needed of scenario so that appropriate controls can be implemented Good design reliability required. <b>FoS &gt; 1.5</b>
RSG<20	Low	Apply good practice, guidance and hierarchy of controls Fair design reliability required <b>FoS &gt; 1.2</b>

Given that uncertainty in understanding is a major contributor to lack of design confidence, which in turn will dramatically affect the derived RSG score, it is worthwhile always to consider what benefit can be gained by simply attempting to increase overall stability understanding through additional investigation and/or monitoring and additional design rigour through operations such that at closure sensible measures can be implemented to help reduce the extent of engineering works needed for achieving acceptable closure.

While the end of mining RSG ratings shown in the 3D block diagram and tabulation included in Figure 9 reflect the ‘as found’ conditions, they also allow identification of residual differences that might exist with respect to required closure slope class conditions based on the perceived consequence rankings (reflecting potential impact if a specific sector were to fail). These rankings can thus be directly assessed from the viewpoint of desired PMLU slope performance requirements, as outlined in Table 4, where degrees of suggested reliability improvements needed for achieving long-term closure design goals are defined per typical RSG score ranges.

This table utilises the total RSG scores built up from the individual components ranked in the table on the right side of Figures 8 and 9, with consequence/impact assessed on the basis of the notes included around the perimeter of the conceptual pit in Figure 8. These notes suggest that the consequence of pit wall failure and back-break would be much more significant on the south and southeast sides of the pit due to greater population proximity (township and infrastructure) and the sensitive heritage site, as compared with the north wall, particularly the NW section. The consequence rankings of 5 for Domains A, B and F compared with 1 for Domain D reflect this difference in presumed consequence/impact. Similarly, since slope failures have occurred in Domain E this drives the selection of a very low design confidence rating for this sector, resulting in ultimately the second highest overall RSG score ( $5 \times 3 \times 7 = 105$ ) albeit with only moderate consequence assigned due to the lower likelihood of population impact for progression of slope failure in this sector. Domain F by contrast, has the highest RSG score, largely due to its proximity to the sensitive heritage site ( $4 \times 5 \times 6 = 120$ ). These high rankings show up clearly in the 3D block diagram as large red spheres.

DESIGN CONFIDENCE STATUS		(II) IMPLICATIONS OF ASSUMED IMPROVEMENT ONLY IN DESIGN CONFIDENCE					
DESIGN	Improvements in Understanding	Confidence Rankings		Likely Remnant	Updated	See Table 4 wrt RSG implications	
LAYOUT or EXISTING PIT WALLS	(through additional mapping; subsurface drilling/logging; lab testing; back-analysis; improved monitoring etc...) Needed to raise Design Confidence Level	itemizing Sectors with Improved Design Understanding Needs (Original & Revised)		Deficit w/poss. Improvement in Design Conf. Understanding	REVISED RSG SCORE	TARGET Requisite MINIMUM Wall-Class	IMPACT: ... Needs for Increased Set Back Ext'n, or Slope Works Improvements
SECTOR	Current Status & Suggested Scope				S1-Rank		
Domain A	Nothing Major Necessary (Cf < 2)	1	1	Ext'g Rank OK	30	D, β>1.2	Minor: > 2-classes
Domain B	Limited Extra Evaluation Useful (Cf = 2)	2	2	Ext'g Rank OK	60	F, β>2.5	Major: > 4-classes
Domain C	Limited Extra Evaluation Useful (Cf = 2)	2	2	Ext'g Rank OK	16	Ext'g OK	None Required
Domain D	Additional Understanding Essential (Cf > 3)	4	3	Minor :1 class	12	Ext'g OK	None Required
Domain E	Major Improvement to Understanding CRITICAL (Cf > 4)	5	3	Signif't : 2 class	63	F, β>2.5	Major: > 5-classes
Domain F	Additional Understanding Essential (Cf > 3)	4	3	Minor : 1 class	90	G, β>3.0	Major: > 5-classes

Figure 10 Modified confidence (Cf) improvement implications on RSG score

Figure 10 illustrates the impact that improved understanding can exert on overall RSG scores. It is assumed for this example that the lowest confidence assessments could be improved by additional investigation or analysis or monitoring so that failure mechanisms and slope behaviour could be better linked as basis for improving design confidence. In Figure 10, example rankings are given to illustrate Stage II improvements that would be worthwhile undertaking for Domains E and F. The left-hand columns in this table summarise the results of an initial screening per sector regarding how much confidence improvement would be needed to warrant supplemental model confidence investigations. With a target of something in the 20–50 range as being viable for mitigation, the Step II screening results indicate that understanding improvement alone might allow Domain E at least to be more definitively characterised so that stabilisation measures or exclusion zones could be more reliably established (Rating drops from 105 to 63). For Domain F, the ratings drop to only 90 from 120, so would suggest that much more significant other measures are required.

		(III) TARGET POST CLOSURE RANKINGS				(IV) PREDICTED TSR (WITH CONTROLS IN PLACE)		
PMLU	Target-Class*	# of Wall Classes Improvement		Maximum Credible Conf. Cf	TARGET PMLU REQD	TARGET PLMU Longterm Conseq. Cq		PREDICTED TSR WITH CONTROLS IN PLACE (with LONG-TERM REVISION for consequence)
ADJACENT TO PIT SECTORS	A = 7 B = 6 C = 5 D = 4	NECESSARY by Sector	Existing Conseq. Cq			Very High	VH = 5 H = 4 M = 3	
Mine 1	E = 3 F = 2	Extensive >5 Major ≈ 4 Moderate ≈ 3 Minor ≈ 2	VH = 5 H = 4 M = 3 L = 2	VL = 5 L = 4 M = 3 H = 2	(with NO CHANGE in consequence)	Moderate Low Very Low		
SECTOR	G = 1	V. Minor ≈ 1	VL = 1	VH = 1				
Domain A	G	5	VH=5	1	25	VH	5	25
Domain B	F	4	VH=5	2	40	H	4	32
Domain C	F	0	H=4	2	0	M	3	0
Domain D	D	0	VL=1	3	0	M	3	0
Domain E	E	4	M=3	3	36	H	4	48
Domain F	G	5	VH=5	3	75	L	2	30

Figure 11 Modified consequence (Cq) improvement implications on RSG score

The left-hand side of Figure 11 summarises the outcomes of the Stage III step in the evaluation sequence. This step starts by assuming that the Step II confidence improvements have already been made. Step III then evaluates the various PMLU options to determine target TSR rankings to guide decisions on selecting relative stability targets consistent with the closure vision. The right-hand side of the table then provides predictions for the final TSR scores that could be achieved once all design and management plans are implemented. As is evident all sectors are now within reasonable range for achieving closure compliance. The assessment suggests however in order to achieve these targets that Domains A, B, E and F each require significant improvement in slope class due to their proximity to a population centre or heritage location, demanding stringent PMLU controls be implemented. The ranking results lead to the conclusion that unless the proposed PMLUs for these sectors can be altered (and model confidence for each sector substantially increased),

stringent closure stability improvements would be a necessity. As outlined in Table 4 the screening suggests that comprehensive and extremely rigorous analysis is now required, based likely on additional data acquisition so that deep understanding of failure mechanisms and behaviour can be gained to allow extremely robust controls to be implemented.

These Step III/IV evaluations assume that the heritage site protection adjacent to Domain F warrants Class G slope performance for long-term stability, therefore  $3 \times 5 \times 5 = \text{TSR } 75$  is required, implying that  $\text{FoS} > 2$  should be considered for initial stability analysis. Relocating heritage sites is often impractical and typically not socially acceptable, therefore other engineered remedial measures would also need to be considered (such as locally buttressing or reshaping the slope). For Domains A and B, the screening analyses suggest that sufficient buffer between the town infrastructure should be factored into slope performance requirements.

It is hoped that the application of these procedures to the hypothetical example pit shown in Figure 8 are sufficiently illustrative to show how the proposed ranking approach could be realistically implemented for real case pits to make preliminary closure screening assessments of failure risk. Plotting individual sector results in the 3D nomograph format shown in Figure 9 provides rapid visual winnowing of problem slope sectors from a closure perspective versus those for which closure planning would be straightforward.

## 7 Conclusion

For each credible failure mode identified at the start of closure planning, e.g. in early conceptual and Pre-Feasibility (PFS) stages, the design reliability and consequence ratings for closure design options need to be considered from a risk perspective. They then need to be re-assessed for each subsequent project stage until the closure plan can be finalised before the start of actual closure works implementation. The dichotomy of different perspectives at the end of operations between achieving the steepest possible short-term slope angles for economic recovery and leaving post-closure slopes with the most stable long-term slope angles needs to be managed via the Closure strategy and agreed to by the business, and all stakeholders since it involves risk-based decisions about both economic and safety risks. Such a Closure strategy might consider:

1. **Avoidance of any slopes with RSGs > 100.** Such slopes would plot in the lower centre back corner (Generally Unacceptable) region of the 3D Nomogram chart in Figure 9, where slopes viewed from a long-term closure design perspective cannot be justified except in the most extraordinary circumstances and with restrictive controls.
2. **Targeting slope geometries to achieve RSG scores of less than 20,** thus plotting far from the back-wall corner of the 3D Nomogram in Figure 9. In such cases the results of the Risk Assessment Ranking likely would suggest that no supplemental risk reduction controls would be required, i.e. any slopes plotting in this region would typically be deemed stable enough for closure.
3. **For all other intermediate slopes, with RSG scores between 20 and 100, dependent on assessed stability, either implementing mitigation measures or defining appropriate set-back/exclusion zones that are commensurate with each slope's defined residual risk.** All such slopes will lie in the central region of the 3D Nomogram. If the outcomes of risk assessment plots a slope within the lower tiers of the confidence-consequence ranges such that it falls in this central part of the 3D-chart, then either the residual risk at closure needs to be passively managed (by for example extending exclusion/set-back limits) or further design controls are required to shift the slope into the broadly acceptable region (i.e. the slope would need further assessment, and potentially also engineering works). IF RSG's are in the 30–50 range potential improvements may be practical, but at the other end of the scale sensible mitigation may not be viable. In such cases if further risk reduction is deemed impracticable, due to lack of resources or because measures would be grossly disproportionate to potential risk reduction that can be economically viable to achieve, then establishing extensive exclusion limits may be the only acceptable closure approach.

Using the proposed RSG ranking system in concert with application of sensible risk assessment approaches may well help in achieving target closure goals. In this regard, three approaches have merit for demonstrating or justifying that adequate performance has been practically achieved:

1. **Generic methods** demonstrating that good practice, industry guidelines and standards, hierarchy of controls or safety management systems have been implemented.
2. **Well-Reasoned Argument (WRA) approach**, using a qualitative, rational explanation of how all reasonably foreseeable hazards have been systematically identified and all reasonably practicable risk remediation measures have been implemented (Miller 2019). The WRA approach generally incorporates the components of the generic methods.
3. **Qualitative (risk matrix) and/or QRA methods** that have historically been used to demonstrate that risks (with or without remediation measures) are compliant with indicative suggested tolerable limits. A comprehensive QRA generally incorporates the components of a WRA.

It is considered that generic methods alone are only applicable to the simplest of scenarios and more rigorous approaches are required for more complex scenarios. The application of frameworks such as that presented in Figures 9 through 11, executed per the steps outlined in Figure 12, provide potential benchmarks for generic methods, but are only an aspect of demonstrating ALARP. In cases where the closure scenario allows for public exposure, the lower the anticipated FoS for a slope at the time of closure, the greater the likelihood of requiring engineering intervention to achieve relinquishment status. Higher levels of engineering, e.g. design evaluation, investigation validation, will be needed for any slopes that classify with RSG scores in the 20–50 range that conceivably can be mitigated sufficiently for relinquishment.

As far as can be researched, to date no standard formula exists for verifying that ALARP has been achieved in any specific situation. Furthermore, an accepted ALARP remediation option for one project may be a different solution to a similar situation on another project depending on each local stakeholder's risk tolerance and other factors. Establishing agreements on ALARP requires consensus building as ALARP cannot be defined as a notional numerical value threshold or line on a risk matrix map but needs to be negotiated and agreed with principal stakeholders.

The principle of risk abatement to satisfy ALARP performance is embraced by the mining industry; however effective demonstration of this can be challenging. However, Figure 13 outlines a systematic pathway to demonstrate ALARP, thereby achieving such a negotiated solution for the closure objectives laid out in this paper.

The suggested workflow steps outlined on Figure 13 fall into three stages:

- **Stage 1: Outlining Objectives and Risk**, encompassing:
  - Defining closure vision with measurable completion criteria.
  - Selecting RSG for closure scenarios (based on a confidence-consequence matrix approach, see Figures 9 through 12 and Tables 3 and 4).
- **Stage 2: Conducting Stability Analyses and Options Iterations**, including:
  - Reviewing closure remediation options and relative stability outcomes (construction cost, efficacy, reliability, practicality, etc.).
- **Stage 3: ALARP Demonstration**
  - Engaging with stakeholders to align on a final plan for implementation and acceptance based on the plan for achieving ALARP.
  - Demonstrating that the cost of measures for achieving ALARP are not grossly disproportionate to the benefit.

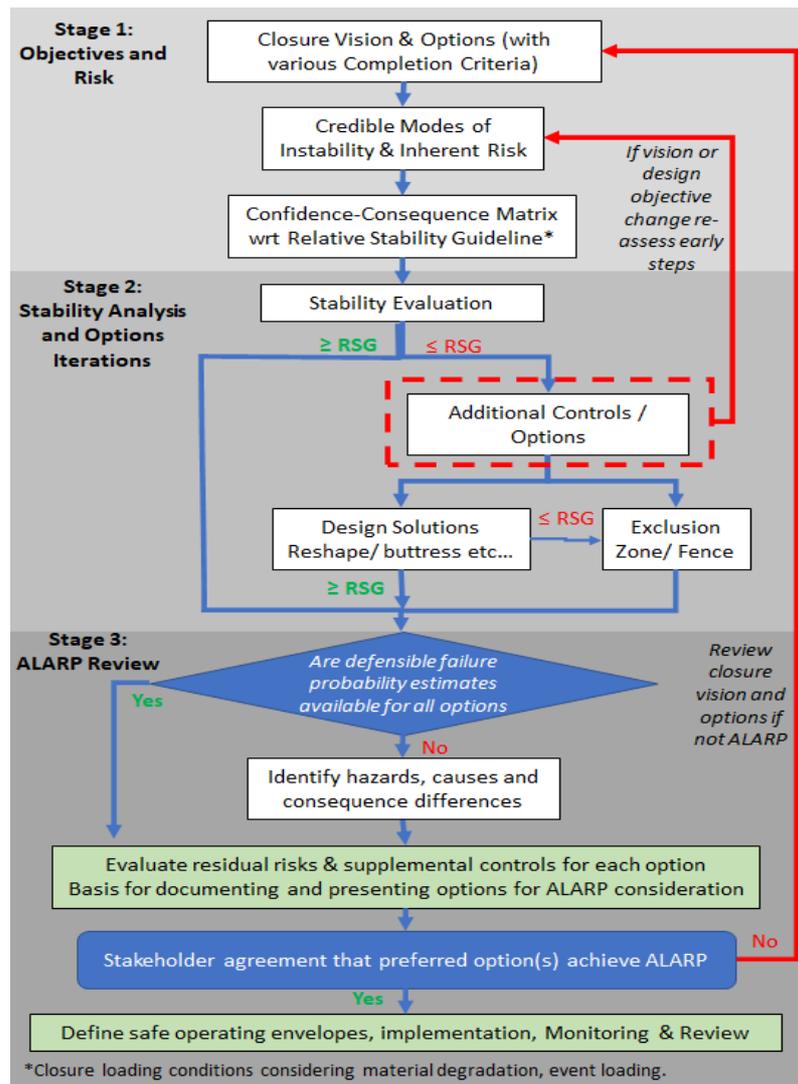


Figure 13 Suggested pathways to demonstrate ALARP for open pit mine closure

## Acknowledgement and disclaimer

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