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Slope stability acceptance criteria for opencast mine design

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ABSTRACT

The Factor of Safety (FoS) and Probability of Failure (PoF) are commonly used to find a compromise between the risk of opencast mine slope failure and economic return. Acceptable FoS and PoF criteria are typically selected by the geotechnical designer without explicit consideration of uncertainties, and with only a broad consideration of consequences. Some organisations may have defined acceptance criteria as part of their mine slope design guidelines, but more often the selected values will be based on some combination of the designer’s experience, project or site precedence, perceptions of uncertainty and likely consequences of failure, and pressure from mine management, consenting authorities or geotechnical reviewers. A new technique for selection of acceptable FoS and PoF for opencast mine slope design is presented based on the explicit consideration of uncertainties in the slope design, the consequences of slope failure, and the intended slope design life. It provides the ability to select defendable acceptance criteria for individual slopes, with easily-documented logic, and to achieve a more consistent level of risk management across all types of slopes.

Keywords: slope stability, factor of safety, probability of failure, risk, uncertainty, opencast mining

1 INTRODUCTION

Geotechnical mine slope design necessitates finding a compromise between the risks of slope failure and the cost of mining. The safety, environmental, and business risks associated with slope failure must be weighted up against mining costs for a particular slope design, and the design adjusted until an acceptable balance is reached. Unfortunately, comprehensive quantitative risk-based slope design techniques are still embryonic in their development, and while good progress has been made in recent years (Terbrugge et al., 2006; Steffen et al., 2008) the practical reality is that for the majority of mining projects we are budget-constrained to design slopes that can meet an “acceptable” level of stability or performance. Perhaps the most common design acceptance criterion used in geotechnical slope engineering is the Factor of Safety (FoS), which is often complimented by a Probability of Failure (PoF) or sensitivity analysis to address parametric uncertainty. Common methods of selecting FoS and PoF acceptance criteria for limit equilibrium method (LEM) slope design remain highly subjective; and do not support the type of risk-based decision making currently required in the mining industry.

Mine and quarry slopes can present a number of different challenges compared to slope engineering for civil works such as urban development, highways and dams. Some of the key differences are:

- Mine slopes are often much higher and the range of stresses equally impressive. Opencast pits often expose a wide range of geological materials from very soft soils to extremely strong rocks. This in turn requires a wide range of geotechnical skill sets.
- The location of proposed open pit and waste rock slopes can change rapidly at the whim of commodity economics, and this requires a broader and more versatile geotechnical model to deal with the changing slope risks.
- Geological structure is vitally important to pit slope stability, particularly below the weathering or soil horizon. Weak or deeply weathered rocks that fit neither standard rock mechanics nor soil mechanics models can present a significant challenge (Adams and Lucas, 2011).
- To the advantage of the geotechnical engineer, there is often a resource geology model and exploration drilling data set that can be used as the basis for a geotechnical model.
- Construction control in mining environments can be to a lower standard for both cut slopes and fills.
The consequences of mine slope failure can be very different, and slope risk profiles are commonly driven by short design-life scenarios and the ability to control access to the slope. In addition, there is often opportunity to actively manage slope failures that would generally be deemed unacceptable in most civil engineering contexts.

The primary objective of this paper is to set out a robust methodology for selection of acceptable FoS and PoF for opencast mine slope design. A simple FoS and PoF selection methodology is presented in an attempt to semi-quantitatively manage slope failure risks through appropriate consideration of the consequences of slope failure and uncertainties in the slope design. The design acceptance criteria selection methodology outlined in this paper is intended to raise the standard of limit-equilibrium mine slope design commonly utilised in the industry. The methodology should not be used to supplant more robust and comprehensive techniques for assessing slope stability and managing developing failures and risks. A methodology for the selection of seismic slope design criteria is intended to be the topic of a future paper.

2 REVIEW OF CONCEPTS

2.1 Factor of Safety

The Factor of Safety (FoS) is the ratio of capacity (of the slope to resist failure) to demand (placed on the slope by driving forces such as gravity and seismic accelerations). A FoS of unity implies the slope is in a state of limiting equilibrium. Any miniscule increase in load or decrease in resistance will result in an unstable slope (FoS < 1). Conversely a FoS > 1, implies some margin of safety (MoS = FoS – 1) against failure. While the FoS is a direct output from LEM analyses, a broadly equivalent safety reduction factor (SRF) can be computed from finite element method (FEM) and other numerical analyses using the shear strength reduction method (e.g. Hammah et al., 2007).

A key problem with the factor of safety is in its name. While there is no denying a broad positive correlation between the FoS of a slope and safety, there are a multitude of other factors that need to be considered, including the characteristics of the failure, the elements at risk, and the uncertainty in the modelling process. An extreme example of FoS misuse is shown in Table 1 from Sowers (1979), which effectively asserts a direct correlation between FoS and safety. This is not the case. For example, a one metre high slope in dry sand with a friction angle of 32° and a slope angle of 32° may have a FOS of 1.0, yet in unlikely to be considered unsafe. Likewise a massive deep-seated creeping paleo-landslide may also possess a FoS close to 1.0, yet the safety risk may be negligible. On the other hand, a 10 m$^3$ rock wedge with a FoS of 1.0 and on the verge of falling onto a major highway would, without doubt, be considered a critical safety risk.

<table>
<thead>
<tr>
<th>Factor of Safety</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 1.0</td>
<td>Unsafe</td>
</tr>
<tr>
<td>1.0 - 1.2</td>
<td>Questionable safety</td>
</tr>
<tr>
<td>1.3 - 1.4</td>
<td>Satisfactory for cuts, fills; questionable for dams</td>
</tr>
<tr>
<td>1.5 - 1.75</td>
<td>Safe for dams</td>
</tr>
</tbody>
</table>

Table 1: An example of an overly generic interpretation of FoS (from Sowers, 1979)

2.2 Slope Failure

Failure of a slope is an ambiguous concept with no common universally accepted definition. Failure has meanings of malfunction, collapse, disappointment, and disaster; as well as being the opposite of success. However, as Duncan (2000) rightly notes, not all slope “failures” are catastrophic. Some are better described as unsatisfactory performance or a minor irritation. Bench-scale slope failures, for example, are generally expected and can be accepted when adequately managed by catch berms. Other terms such as “instability” or “movement” may imply less of a disaster, yet are still equally ambiguous; while terms such as “creep” or “collapse” can sometimes be used to describe the slope “failure” in a slightly more specific or intuitive fashion.

A FoS of 1.0 describes the point at which the total demand on the slope exceeds the total capacity of the slope to resist failure through all materials on the defined failure path. A slope failure is, however, much more complex than it is modelled by the LEM. In practice, failure does not occur simultaneously
along a single discrete basal surface, but rather localised material failure progressively develops into a larger slope failure. With the exception of purely structurally-controlled slope failure in a brittle rock mass, the internal deformation process also plays a large part in the development of slope failure.

Pit slope failures generally pass through several stages of movement, as shown in Figure 1. These stages are (Sullivan, 2007):
1. Viscoelastic response
2. Primary Creep, which may eventually stabilise, or progress to
3. Secondary Creep
4. Tertiary Creep (cracking and dislocation)
5. Collapse
6. Post collapse deformation

The first two stages or “initial response” include elastic rebound, relaxation and/or dilation of the rock mass (Zavodni, 2001). Secondary creep and pre-collapse deformation is associated with yielding, softening, strength loss, localised failure and slip on structures within the rock mass. The exact part of the curve in Figure 1 described by $FOS = 1.0$ is controversial, although generally accepted to be somewhere between Secondary Creep and Collapse.

![Figure 1. Stages of Slope Failure (after Sullivan, 2007)](image)

2.3 Modelling Limitations and Advantages of Limit Equilibrium Methods

Limit equilibrium methods (LEM) have been used for slope stability analysis since the dawn of geotechnical engineering. Increased computing power over the last few decades has enabled a move from simplistic geometries to powerful slip-surface search and optimisation routines. Key limitations of the method include the inability to model progressive failure, internal deformation of the sliding mass, or post failure displacement of the slope. It assumes that shear displacement occurs along a unique sliding surface, and for this reason slope failure mechanisms such as active-passive wedge failures and flexural toppling that are clearly governed by internal shear displacement should only be modelled by LEM with extreme caution, and preferably only where calibrated by back analysis.

Despite these limitations, the LEM provides a valuable and cost-effective tool for assessing pre-failure stability, the sensitivity of the slope to changes in slope geometry, shear strength parameters, groundwater conditions and loading; and stabilisation options such as buttressing, ground anchors and slope depressurisation. For this reason the LEM continues to be widely used within the mining geotechnical community.

2.4 Accounting for Uncertainty

The FoS is a deterministic concept and does not describe real-world uncertainty in the stability of the slope. Fortunately there are tools available that can at least partially assist in this area:

- **Sensitivity analysis** is an extremely powerful yet simple technique to assess the influence that each input parameter (such as the friction angle, cohesion or piezometric pressure) has on the resulting
FoS of the slope. It enables the designer to define the most important controls on slope stability. The process has been automated in common LEM software to assess uncertainty associated with material parameters, groundwater pressures and applied loads, yet it is still a painstaking task to assess subsurface spatial and geometrical uncertainties such as the location and orientation of weak discontinuities or weathering horizons.

- **Probabilistic modelling** is a technique used to carry uncertainty associated with input parameters through the analysis to produce a statistically distributed FoS rather than a single deterministic value. The resulting probability of failure (PoF) has become a commonly-used design acceptance criterion. Recent advances include the use of numerical analyses for probabilistic modelling (Hammah et al., 2009; Chiwaye and Stacey, 2010; Gibson, 2011).

### 2.5 Probability of Failure

The Probability of Failure (PoF) has been used and abused as a criterion for mine slope design over the last 40 years. The basic premise of the PoF concept is that a statistical distribution (probability density function) can be defined for each of the input parameters to a slope stability analysis. Using a process of stochastic simulation, it is possible to define a statistical distribution around the FoS. The PoF is defined as the percentage of results with FoS < 1. While the PoF is a nice concept, the author has become aware of some problematic issues with the way it is commonly applied in mine slope design practice. The key issues are:

- **Stochastic distribution uncertainty**: The PoF is greatly influenced by the choice of probability distribution selected for the input parameters (e.g. UCS or friction angle). In practice there is often inadequate data and understanding to base the selection on. A normal distribution often lumps data centrally and results in unjustifiably low tail risk. In the many cases it may be more reasonable to assume a broader triangular or even a uniform distribution between the estimated upper and lower-bound values. While being statistically unlikely, these distributions are useful to describe a high uncertainty or lack of knowledge in our understanding of stochastic input variability.

- **Multiplication of uncertainties**: The output distribution and PoF is strongly influenced by the number of materials in the model and the number of statistical distributions assumed for each. Multiplication of uncertainties leads to unjustifiably smaller PoFs, as more materials and random variables are added to the model.

- **Parameter correlation uncertainty**: The PoF is strongly influenced by the correlation (or lack thereof) assumed between random variables. For example, there is often a correlation between density and strength, or friction and cohesion and our lack of knowledge as to the form of this correlation introduces yet another epistemic uncertainty.

- **Highest PoF failure surface vs lowest FoS failure surface**: The failure surface with the minimum factor of safety does not necessarily have to be the failure surface with the maximum probability of failure (Oka and Wu, 1990). Therefore it is necessary to consider all failure surfaces in a probabilistic computation, not just that minimum FoS surface. This takes significantly more computing time, yet the resulting PoF can be considerably different.

- **Computed vs total PoF**: Probabilistic modelling routines within commonly used software Slide (Rocscience) and Slope/W (GEO-SLOPE) allow the user to estimate the PoF associated only with material properties, groundwater pressures and external loads. The computed PoF does not account for other significant sources of uncertainty, and as a result may be much smaller than the total PoF of the slope. Unaccounted-for uncertainties in the computed PoF include spatial variability of material properties, unknowns in the structural geology model, temporal probabilities associated with rainfall and seismic hazard, computational model simplifications and implementation variation to design.

- **Lack of time dependency**: In the absence of time-dependent input variables, the computed PoF does not have a timescale. In order to calculate the annual PoF, the reference time is often assumed to be related to the design life of the slope. In reality, the PoF of a slope is likely to be related to the rate of stress redistribution, the rate of material strength degradation (e.g. via weathering and rock mass relaxation), and the temporal probabilities of triggering events such as rainfall or earthquakes.

The preceding discussion suggests that major issues exist with the value of the computed PoF as an input to quantitative risk assessment. Some of these have been overcome via the quantitative event-
tree slope design procedures of Terbrugge (2006) and Steffen (2008). In a qualitative sense, the PoF remains a useful technique to rank the importance of various uncertainties, and to determine (for example) when a tighter input distribution (requiring more spend on drilling and lab testing) would justify a lower FoS and steeper slope, thus saving significant earthworks dollars.

3 CURRENT PRACTICE FOR SELECTION OF DESIGN ACCEPTANCE CRITERIA

The choice of an acceptable FoS for slope stability evaluation is said to require sound engineering judgement due to the multitude of factors that must be considered (Barnes, 1995). However, it is the author’s observation that acceptable FoS and PoF criteria are typically selected by the geotechnical designer without explicit consideration of uncertainties, and with only a broad consideration of consequences. Some organisations may have defined acceptance criteria as part of their mine slope design guidelines, but more often the selected values will be based on some combination of the designer’s experience, project or site precedence, perceptions of uncertainty and likely consequences of failure, and pressure from mine management, consenting authorities or geotechnical reviewers.

Commonly referred to recommendations of acceptable minimum values of FoS and PoF for the mining industry (e.g. DME, 1999; Wesseloo and Read, 2009; Safe Work Australia, 2011), tend to be based on a small number of published suggestions dating back to the likes of Hoek and Bray (1981), Kirsten (1983), Priest & Brown (1983), McMahon (1985), Pine (1992), and Sullivan (2006). The general theme which has become industry standard is to present acceptable values that depend on the size of the slope and generic consequences (e.g. Table 2). However, this approach takes little account of specific consequences, and does not necessarily present a consistent level of risk management.

Table 2: Typical design acceptance criteria for open pit slopes (based on Wesseloo & Read, 2009)

<table>
<thead>
<tr>
<th>Slope scale</th>
<th>Consequences of failure</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Bench</td>
<td>FoS ≥ 1.1</td>
<td>PoF ≤ 25-50%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-ramp</td>
<td>FoS ≥ 1.15-1.2</td>
<td>FoS ≥ 1.2</td>
<td>FoS ≥ 1.2-1.3</td>
</tr>
<tr>
<td></td>
<td>PoF ≤ 25%</td>
<td>PoF ≤ 20%</td>
<td>PoF ≤ 10%</td>
</tr>
<tr>
<td>Overall</td>
<td>FoS ≥ 1.2-1.3</td>
<td>FoS ≥ 1.3</td>
<td>FoS ≥ 1.3-1.5</td>
</tr>
<tr>
<td></td>
<td>PoF ≤ 15-20%</td>
<td>PoF ≤ 5-10%</td>
<td>PoF ≤ 5%</td>
</tr>
</tbody>
</table>

4 PROPOSED METHODOLOGY FOR SELECTION OF DESIGN ACCEPTANCE CRITERIA

A simple technique to select appropriate acceptance criteria for slope design involves development of a FoS-PoF Selection Matrix. The method is intended to ensure slope stability risks and uncertainties are considered in a logical and robust way. It can be broken down into five basic steps:

Step 1. Establish the context: The stability-performance requirement for any particular mine slope depends on the slope characteristics, design life, consequences of failure, and the feasibility of slope stabilisation or other contingency plans. Safety and environmental performance requirements may be dictated by regulatory conditions and legislation, and/or may be driven by various stakeholders including mine employees, management, neighbouring landowners or lobby groups, etc. Financial performance requirements should be driven by a well-articulated business risk strategy. The role of the geotechnical engineer is to define the hazard and the model uncertainties, yet the performance requirements are best defined in consultation with those affected.

Step 2. Identify and rank the uncertainties: Common sources of uncertainty in the slope design process are categorised and listed in Table 3. A semi-quantitative judgement must be made on the relative level of design confidence. This is made by attributing a confidence ranking (High, Med, Low) to the relevant uncertainty types listed in Table 3. The basis of selected confidence levels should be recorded to develop consistency. Future improvements to the methodology could involve a weighting technique to arrive at a single ranking for “residual level of slope design uncertainty”.

Step 3. Describe the feasible slope failure scenarios: The range of potential slope failure mechanisms and characteristics can only be understood with a robust geotechnical model, and/or precedent behaviour of slopes in similar geological and tectonic environments. Slope failures are typically
classified into rockfall, block toppling, flexural toppling, slumping, slides and flows (e.g. Varnes, 1978), but other important categories include planar slide, rotational slump, wedge, active-passive wedge (e.g. Hegan and Read, 1988). Each mechanism can occur on a variety of scales and slope angles, and these things define the triggers, likely velocity, back-break distance, volume, and runout zone; which are central to characterising the potential consequences. The back-break and runout define the areas at risk. The slide velocity determines the ability of people to escape the hazard. The volume will influence the cost of remediation and management.

**Step 4. Identify and rank the consequences:** In a mining environment, consequences are typically classified into at least three impact categories: [1] Health and safety, considering primarily harm, injury or fatality; [2] Environmental impacts, considering the severity, extent and duration of impacts; and [3] Business impacts, including direct financial costs associated with clean-up and remedial earthworks, damage to equipment and mine infrastructure, lost production due to delay or shutdown, and any less tangible impacts such as reputation loss. Slope failure consequences should be estimated based on the assessment in Step 3, and ranked into qualitative levels that align with a defined consequence table (e.g. Table 4). It is recommended to base the consequence table on a relevant risk matrix (see AS/NZS, 2004) such as one that has been developed specific to the mine site or organisation. Consequence tables should preferably be expanded with slope failure examples for clarity and consistency (see Table 4).

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Consequence Level</th>
<th>Insignificant</th>
<th>Minor</th>
<th>Moderate</th>
<th>Major</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health &amp; Safety</td>
<td>First aid injury</td>
<td>Medical aid injury</td>
<td>Lost Time Injury (LTI)</td>
<td>Permanent impairment</td>
<td>Fatality (e.g. any rapid failure with people exposed)</td>
<td></td>
</tr>
<tr>
<td>Environment</td>
<td>Contained (e.g. wedge failure contained on bench, minimal sediment to water)</td>
<td>Localised impact (e.g. sediment slug from failure contained by site water controls)</td>
<td>Impact within mine only (e.g. highwall failure contained within pit)</td>
<td>Off-site impact can be remediated (e.g. waste-rock slide runout)</td>
<td>Severe off-site impact (e.g. toxic tailings release to external waterway)</td>
<td></td>
</tr>
<tr>
<td>Business</td>
<td>No delay, cost &lt; $10K (e.g. small failure outside of work area)</td>
<td>Minor delay, $10 - $100K (e.g. inter ramp slope failure requires stabilisation)</td>
<td>Total loss $100K - $5M (e.g. main access ramp destroyed causing delay and re-planning)</td>
<td>Total loss $5M - $100M (e.g. production pit closed for significant period, ore sterilised)</td>
<td>Total financial loss &gt; $100M (e.g. failure large enough to close mine)</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3:** Sources of uncertainty in pit slope design

<table>
<thead>
<tr>
<th>Uncertainty Type</th>
<th>Source of Uncertainty</th>
<th>Proposed Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Parameter</td>
<td>Stochastic variation in material properties due to limited data and inherent variability, including material strength, density and hydraulic conductivity.</td>
<td>Use sensitivity analysis or PoF criteria (with caution) to assess influence of tail risk. Parameter uncertainty can be reduced by further measurements and testing.</td>
</tr>
<tr>
<td>2 Geometrical</td>
<td>Topography, groundwater pressures, geological boundaries and discontinuities (faults, weathering horizons, etc), spatial variation in properties through the model.</td>
<td>Fundamentally different geological models to be analysed separately. Attribute confidence ranking (High, Med, Low) to remaining geometrical &amp; spatial uncertainty.</td>
</tr>
<tr>
<td>3 Temporal loading or strength reduction (triggers)</td>
<td>In-situ stress redistribution, rainfall intensity, duration and frequency, piezometric pressure variations, earthquake hazard estimates, blasting-induced stresses, other loading scenarios (trucks, waste dumps, etc), weathering or relaxation effects on material properties.</td>
<td>Each significant temporal scenario is typically analysed as a separate design case. Scenarios could be combined by event tree analysis for qualitative risk assessment, if required.</td>
</tr>
<tr>
<td>4 Slope Behaviour</td>
<td>The structural geology, material properties, groundwater conditions and loading scenario all influence the failure mechanism, volume, runout, back-break and velocity.</td>
<td>Attribute confidence ranking (High, Med, Low) based on experience and precedent slope behaviour.</td>
</tr>
<tr>
<td>5 Computational</td>
<td>Simplifications and deviation from the physical processes of slope failure, including sub-models such as the strength failure criterion, and limitations of analysis techniques such as 2-D LEM.</td>
<td>Attribute confidence ranking (High, Med, Low) depending on the confidence in the computation method to accurately model the anticipated slope failure mechanism.</td>
</tr>
<tr>
<td>6 Human factors</td>
<td>Operational deviation from design assumptions, in terms of highwall geometry, blast damage, etc; human errors at either the design or implementation phases.</td>
<td>At the preliminary, feasibility or design stage, estimate operational deviation. Eliminate errors in the design process via robust QA/QC checking and review protocols.</td>
</tr>
</tbody>
</table>

**Table 4:** Example of a consequence table, expanded to include some example slope failure scenarios.
Step 5. **Develop a FoS-PoF Selection Matrix**: An example matrix to select appropriate FoS and PoF design acceptance criteria is presented in Table 5. Key inputs include the slope design life (Step 1), the level of confidence in the slope design (Step 2), and the consequence level (Steps 3 & 4). As well as suggesting an appropriate FoS and PoF, the Selection Matrix also suggests an appropriate level of slope stability risk management to apply.

The range of FoS and PoF values in Table 5 has been selected to match the ranges that have historically been used mine slope design (ref. Section 3). Specific values in each box have been developed by a process of interpolation and comparison against typical industry-standard recommendations. The key benefit of the proposed method is in the ability to select more defendable (logical and easily documented) acceptance criteria, and achieve a more consistent level of risk management across all types of slopes, via explicit consideration of the hazard characteristics, consequences and uncertainties associated with each specific slope.

Table 5 may require modification to suit specific mining projects, risk matrix definitions, or legal jurisdictions. One could argue that the far right-hand column (Major to Catastrophic consequences and Low confidence in the design) may represent an unacceptable slope design scenario, yet that would depend on the specific definitions adopted.

<table>
<thead>
<tr>
<th>Consequence Level</th>
<th>Insignificant to Minor</th>
<th>Moderate</th>
<th>Major to Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level of Design Confidence</strong></td>
<td><strong>High</strong></td>
<td><strong>Med</strong></td>
<td><strong>Low</strong></td>
</tr>
<tr>
<td><strong>Permanent cut, fill or natural slope</strong> (Design Life &gt; 10 years)</td>
<td>Min FoS</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Max PoF</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Level of Risk Management</strong></td>
<td>No monitoring or access restrictions</td>
<td>No monitoring or access restrictions</td>
<td>Minimal monitoring for defined timeframe, and/or access restrictions</td>
</tr>
<tr>
<td><strong>Interim cut or fill slope</strong> (Design Life 0.5-10 years)</td>
<td>Min FoS</td>
<td>1.2</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Max PoF</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td><strong>Level of Risk Management</strong></td>
<td>Basic GCMP including periodic slope monitoring. Access dependant of safety risks</td>
<td>Comprehensive GCMP including slope monitoring and TARPs. Access dependant of safety risks</td>
<td>Comprehensive GCMP including slope monitoring and TARPs. Access dependant of safety risks</td>
</tr>
<tr>
<td><strong>Temporary cut or fill slope</strong> (Design Life &lt; 6 months)</td>
<td>Min FoS</td>
<td>1.2</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>Max PoF</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td><strong>Level of Risk Management</strong></td>
<td>Basic GCMP including periodic slope monitoring. Access dependant of safety risks</td>
<td>Comprehensive GCMP including slope monitoring and TARPs. Access dependant of safety risks</td>
<td>Comprehensive GCMP including slope monitoring and TARPs. No access to slope.</td>
</tr>
<tr>
<td><strong>Excavation for immediate backfill</strong> (Design Life &lt; several days)</td>
<td>Min FoS</td>
<td>1.05</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Max PoF</td>
<td>45%</td>
<td>40%</td>
</tr>
<tr>
<td><strong>Level of Risk Management</strong></td>
<td>Detailed risk assessment and robust operational controls, including continuous monitoring and TARPs. No access to slope</td>
<td>Detailed risk assessment and robust operational controls, including continuous monitoring and TARPs. No access to slope</td>
<td>Detailed risk assessment and robust operational controls, including continuous monitoring and TARPs. No access to slope</td>
</tr>
</tbody>
</table>

1. Consequence Level: See Step 4 and Table 4.
2. Level of Design Confidence: See Step 2 and Table 3.
3. PoF (probability of failure) is defined in this table as the “computed PoF” from SlopeW, Slide, or equivalent LEM software, not the “total PoF” (see Section 2.5).

### 5 CONCLUSIONS AND RECOMMENDATIONS

Commonly-used limit-equilibrium slope analysis methods, and associated FoS/PoF design acceptance criteria have many limitations that must be understood in order to use them effectively. Nevertheless they remain as simple and powerful tools to evaluate mine slope stability, provided all the relevant uncertainties can be accounted for. It is recommended that deterministic FoS analyses are always backed up with a comprehensive sensitivity analysis. PoF analyses should be used with caution, particularly if the computed result is intended for use in a quantitative risk analysis.
A new technique for selection of acceptable FoS and PoF for slope design has been presented based on explicit consideration of uncertainties in the slope design, the consequences of slope failure, and the intended design life. It provides the ability to select defendable acceptance criteria for individual slopes, with easily-documented logic, and to achieve a more consistent level of risk management across all types of slopes. The method described in this paper does not constitute unilateral endorsement of the FoS approach in all situations, but is rather intended to improve the current practice. Application of this methodology could be extended to civil earthworks, dams or highways, however in these environments, design criteria are often dictated more rigidly by approved codes and guidelines. Further improvements to this methodology will include tables to assist in the detailed description of slope failure scenarios, and improved descriptions and quantification of consequence and confidence levels.

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