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Towards developing a more rigorous technique for bench scale slope stability analysis in hard rock

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Abstract

The mining industry is a strong but volatile market that is focused on future growth through expanded production, increased operational efficiency and cost optimisation (Ernst and Young, 2013). As operational expenditure increases and the readily minable ore is extracted, the technical challenges facing mining are becoming more prevalent. With increased depths of open pit operations, the need to minimise the footprint of the mine and limit pre-stripping requires the optimisation of slope geometry and configurations in such a way that extraction is maximised without increasing risk to personnel, equipment or mine life. An essential component of the slope optimisation process is the rigorous geotechnical assessment of the stability of the pit walls at bench, inter-ramp and overall slope scale.

Advancements in computational power and numerical modelling have significantly progressed the analysis of overall slope and inter-ramp scale stability. However the current industry standard methods of bench scale stability analysis still heavily rely on empirical, kinematic and limit equilibrium techniques. These techniques are adequate for scoping and pre-feasibility level projects where the data availability is limited and the confidence in results restricted. In contrast, as the pit develops and progresses into feasibility to implementation stages of development, optimisation becomes a more significant component of the geotechnical assessment and more rigorous analytical methods should be employed.

This paper introduces an improved analytical method that integrates discrete fracture network (DFN) generation and kinematic analyses for bench scale slope stability analysis. Conventional kinematic analyses were conducted on a representative data set and the resulting probability of failure (POF) compared to a POF generated from a calibrated stochastic DFN model. Results showed that the conventional analysis was conservative in nature due to the inability to assess the influence of discontinuity interaction and spacing on the resultant wedge. The authors' experience of recent technical work had also flagged a dissimilarity between the conventional kinematics and real world observations. Additional numerical modelling utilising a pseudo-discontinuum modelling technique was conducted in an attempt to quantify the extent of the conservatism seen in conventional versus alternative methods of bench scale stability assessment.

The ability to incorporate a holistic DFN approach to the assessment of batter scale stability facilitates the optimisation and risk reduction process. The limitations of this alternative method are not fully established and further validation and testing is needed however, potential does exist for the inclusion of DFNs in kinematic bench scale assessments and the subsequent optimisation of slope configurations.

The authors have conducted several technical slope stability assessments for existing open pit operations in Australia. Due to confidentiality arrangements, the operations and specific details cannot be disclosed in this paper. Future work will include a detailed case study.

1 Introduction

The slope design process is well established and follows a streamlined workflow detailed by Read and Stacey (2009). Conventional kinematic analyses form an integral part of the analysis for both bench and inter-ramp scale designs and incorporate the defined structural model for each specific site. Benches within an open pit operation have one key function:

"To provide a safe environment for personnel and equipment that must work near the slope face." (Read and Stacey, 2009).

In order to satisfy this requirement stable bench faces and crest positions must be maintained as far as reasonably practicable to result in a berm width capable of mitigating rockfall hazards and allow long-term access for maintenance and monitoring (Read and Stacey, 2009). Inter-ramp designs are also critical in maintaining ramp access to the lower levels within the pit. Instability at this scale can occur from joint interactions along with large scale discontinuities such as faults and shear planes.

Conventional kinematic analysis consists of stereographical, cumulative frequency (CFA) and limit equilibrium (LE) analyses. These methods account for orientation and dip, characteristics and dynamics of discontinuities and the resultant wedge volumes. These methods of analysis are outlined in many publications (Carvalho, 2002; Read and Stacey, 2009; Wyllie and Mah, 2004). It has long been accepted that the standard methods used for stability analysis have potential to be conservative due to uncertainties in the input data (Whitman, 1984; Christian et al., 1993, Duncan, 2000; Christian, 2004). From a risk perspective this can be favourable as uncertainties in input variables can be problematic when interpreting results and applying pre-defined acceptability criteria. However, from an operations perspective, an overly conservative slope design results in unnecessary costs, reduced access to ore and consequently lost revenue. Subsequently, a trade-off between safety, acceptable slope performance and mine productivity is needed and optimisation of the slope geometry is essential. The optimisation of slope geometry is dependent on data confidence. Advanced structural analysis is also required at the bench to inter-ramp scale.

It became apparent through several projects in established open pit mines that conventional kinematic and limit equilibrium techniques were not producing expected results when compared to known wall performance and observations. Typically this was exhibited by analyses producing lower Factor of Safety (FS) and higher POF values than the rock mass exhibited and also variability in the amounts of crest loss associated with structurally controlled failure (i.e. not blast induced loss or loss attributed to scaling). The use of photogrammetric data collection techniques combined with conventional mapping and drill core data collection, plus in-pit laser scans enabled accurate bench performance assessments to be undertaken. The results from actual performance compared to the predicted performance did not correlate.

The use of advanced numerical modelling tools is becoming more common in slope stability analysis. Traditionally discontinuum codes have been used for the most accurate assessment of structurally controlled instability, however these codes often requires significant computational power. The recently developed pseudo-discontinuum method is considered to be an alternative to the discontinuum code but with the benefit of reduced computational power. This method combines continuum code and representative DFNs to assess failed wedge volumes defined by displacement criterion. The DFNs are modelled as weakness planes within the continua. One of the key advantages of incorporating DFNs is the inclusion of fracture intensity/density. This enables additional control on the spatial characteristics of the discontinuities and consequently the generation of a more accurate, in situ model of the test case.

A trial case example data (example case) was derived from representative structural models and utilised a common slope configuration to undertake conventional and alternative method analyses. The alternative tools have shown great potential to be used as more a rigorous analytical technique for the assessment of discontinuity controlled instabilities. This paper introduces this alternative approach to bench scale stability assessment through preliminary trials, however additional works and tests are required to fully develop this new process.

2 Conventional methods of analysis

Conventional methods of bench scale slope stability assessments typically consist of:

- Stereographical Assessment.

- Cumulative Frequency Assessment.
- Limit Equilibrium Assessment.

Stereographic methods rely solely on a detailed analysis of the structural interactions with slope geometry that may contribute to block instability (wedge, planar or toppling failure). Cumulative frequency techniques follow on from basic stereographic assessments and consider the apparent plunge of wedge intersections for a given bench face orientation. This allows for an initial POF to be determined.

Limit Equilibrium techniques take the analysis further by comparing resisting forces/ moment mobilised and the disturbing forces/moments mobilised (Eberhardt, 2003) for a defined wedge therefore allowing FS to be determined. However, limit equilibrium methods have limitations that are extensively published, but their application to stability assessments is often pushed beyond the initial intended use (Krahn, 2003). Further developments have led to the introduction of 3D limit equilibrium techniques such as SWEDGE (Rocscience, 2005); however, although they are useful for analyses, they do not consider internal fracturing and deformation in their analysis (Stead et al., 2006). Nevertheless a probabilistic-type analysis can be generated by the repeated analysis of failure and the modification of input variables.

The nature of the predicted failure type (Figure 1) dictates how the stability of the bench can most representatively be modelled. This prediction is therefore inherently limited by the understanding of the in situ structural model and data availability. The conventional methods of stability assessment detailed above are often suitable for simple translation failure types (Figure 1), however as the failure type becomes more advanced and involves the interaction of a discontinuity network and brittle fracture damage (step−path failure) (Stage II and Stage III), more advanced analysis techniques should be sought.

Intact rock deformation is accounted for in Stage II where complex geometries, material anisotropy, non−linear behaviour, in situ stress and coupled processes (pore pressures, seismic loading, etc.) can be incorporated (Stead et al., 2006). For standard kinematic and limit equilibrium techniques (Stage I) this is not incorporated.

When reviewing the conventional kinematic analysis techniques, Fenton and Griffiths (2008) comment that although the importance of spatial correlation and local averaging of geotechnical discontinuities is recognised (Mostyn and Soo, 1992), it is often omitted from probabilistic bench scale slope stability analyses. The introduction of measurable controls on the spatial distribution of discontinuities within DFNs allows the above factors to be incorporated within the bench scale assessment.

In the development of a more rigorous slope stability assessment technique for bench and inter-ramp scale failures, the impact of the limitations of conventional slope stability assessments must be quantified. A modified technique that accounts for or minimises these limitations, can then be developed based on the sensitivity of the analysis to a particular limitation.

Work conducted by Stacey (2006) using 2D and 3D models investigating failure mechanisms in rock slopes concluded that failure is commonly a combination of two or three modes, therefore making the failure process a complex phenomenon (Franz et al., 2007; Simmonds and Simpson, 2006). Simplifying models to one particular failure mode is often not representative as many stability problems involve complexities relating to geometry, material anisotropy, non-linear material behaviour, in situ stresses and the presence of coupled processes such as pore pressure interactions and seismic loading (Chiwaye, 2010).

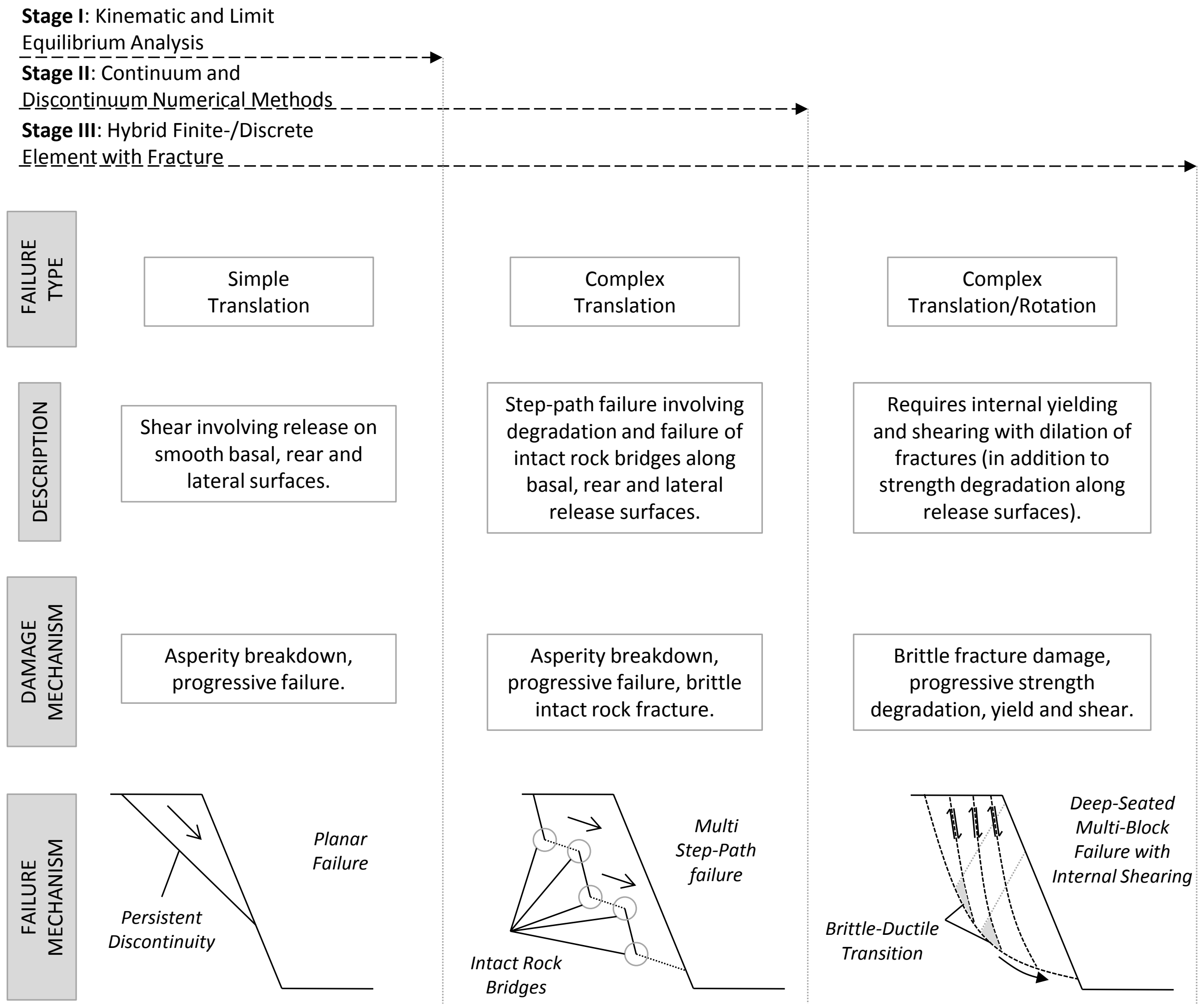


Figure 1 Application of slope stability analysis techniques to varying complexities of slope failure (modified from Stead et al., 2006)

When comparing the LE and numerical modelling approach to slope stability assessment, Cundall (2002) concluded that numerical models have six key advantages:

1. No pre-defined slip surface is required for failure to initiate.
2. The slip surface can be any shape.
3. Multiple failure surfaces can exist simultaneously.
4. No statistical assumptions are needed.
5. Structures and/or structural elements and interfaces can be included without concern over compatibility.
6. Kinematics are satisfied.

3 Proposed alternative method

It was the aim of the authors to investigate alternative method that allow for a more rigorous assessment of bench scale slope stability that would link field observations, performance assessments and rock property testing to replicate and predict rock mass interaction and stability for varying slope aspects and geometries. The alternative method investigated was a pseudo-discontinuum method which was calibrated using a conventional discontinuum model.

The POF produced from an LE analysis does not include information on deformation within the slope as it only identifies the onset of failure. Numerical solutions can, however, account for the effect of stress redistribution within the slope and the weakening effect that it has on the slope material. The POF value from numerical modelling reflects this (Itasca, 2012) and is consequently more realistic. A numerical model can also account for the complex failure scenarios detailed previously (e.g. multiple failure mechanisms or change in failure mechanism as progressive failure occurs) (Hoek et al., 2000). Numerical models also allow for the evolution of the failure surface within the slope over time (Wyllie and Mah, 2004).

There are, however, limitations and drawbacks to numerical models. A significant limitation (depending on project length and budget) is the amount of time it takes to compute a numerical solution to slope stability compared to an LE analysis. Valdivia and Lorig (2000) make the point that an LE analysis can compute thousands of calculations within a few seconds; however, for a numerical model to produce one iteration, significantly more time is required. Hoek et al. (2000) also comment on the ease of use of numerical modelling software. 'Using these codes correctly is not a trivial process and mines embarking on a numerical modelling program should anticipate a learning process of one to two years, even with expert help from consultants'.

The selection of modelling technique is governed partially by scale but primarily the anticipated control on failure. If the slope is primarily composed of soil, massive or intact rock, or heavily jointed rock masses, continuum modelling is most representative (Itasca, 2012). However slopes controlled by discontinuity behaviour and interaction are best suited to discontinuum modelling. This study is focused on bench to multi-bench scale failure where discontinuity control on stability is the primary control on failure.

Discontinuum codes represent the most accurate analytical tool currently available for numerical stability assessments of structurally controlled environments. They account for block interactions and physics in a way that most closely represent real world interaction. Discontinuum codes however, require a significant amount of computation time and power and this is commonly the reason that they are not used as standard practice. Consequently, the authors have investigated an alternative modelling technique, defined as a pseudo-discontinuum method. It combines a continuum code with implicitly encoded weakness planes indicative of discontinuities, DFNs in this case. In this model, localised weakening of finite difference mesh zones mimic the discontinuity occurrence and orientation. This method can be implemented in commercially available continuum codes and is inherently more time efficient.

When generating a stochastic DFN, it is possible to directly import the position of discontinuities from photogrammetry, along with slope geometry in order for a deterministic model to be constructed. A statistical analysis of the interpreted structural data enables persistence to be derived.

In order to describe the intensity of discontinuities within the rock mass, the P_{32} value can be used. This value represents a volumetric measure of a two dimensional surface. P_{32} is defined as the total area of fractures per unit volume (Dershowitz, 1984) (Equation 1) and is the preferred measure of intensity as it is invariant with respect to the distribution of fracture size (Golder Associates, 2011).

$$P_{32} = A_f / V_t \tag{1}$$

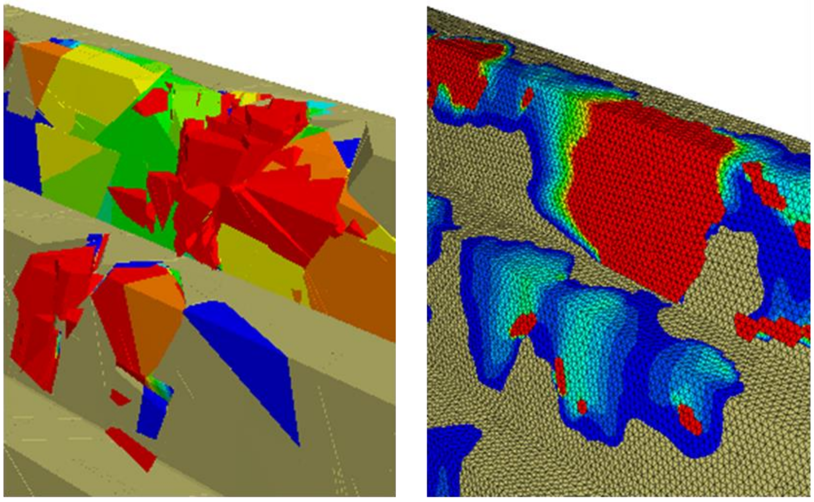
Where:

A_f = Total area of fractures

V_t = Total volume

3.1 Validation of proposed new method

Before undertaking a complete assessment using the pseudo-discontinuum approach, a validation process was run between the conventional discontinuum code and the proposed pseudo-discontinuum method. An example DFN was introduced to both models to calibrate/validate the suitability of the proposed pseudo−discontinuum method. From the discontinuum code it was established that a POF value of 4% is expected for the DFN under study. With the established failed volumes from the discontinuum code, displacement criteria were used to calibrate the pseudo-discontinuum model until the POF value was replicated. A visual inspection was also undertaken to check the failed volumes were produced in the same regions in the model (Figure 2).



(a) (b)

Figure 2 Discontinuum (a); and pseudo-discontinuum (b) model calibration

4 Case example

To choose the most appropriate modelling technique for an operation, it is important to consider four main points:

- Data available.
- Project stage.
- Failure mechanism.
- Failure driver.

Data availability and project stage are inter-related and defined in Read and Stacey (2009). This concept assumes that as the project advances from concept level through to feasibility and operations level, the data confidence also increases. They are both also defined for each operation individually. In contrast failure mechanism and drivers can vary across lithological domains and also sectors defined on average slope aspects. The authors also acknowledge that the proposed alternative method is not applicable to all situations and conventional methods may be appropriate. The example case consisted of a bench stack of three, 18 metre high benches with a berm width of 9 metres and bench face angle of 75°. The properties adopted for discontinuity 1 are detailed in Table 1. A cohesion of 5 kPa and friction angle of 35° were also applied to the discontinuities.

Table 1 Joint set characteristics used for the example case

Characteristic	Mean	Max	Min	Standard Deviation
Dip	54	69	40	7
Dip direction	127	159	96	17
P_{32}	0.2	–	–	–
Persistence (m)	3	21	0.78	2.65

The relevant parameters were incorporated into the conventional limit equilibrium wedge analysis and the pseudo-discontinuum alternative method and the results compared.

4.1 Conventional analyses

Conventional wedge analyses consider the discontinuity orientation and dip, cohesion, friction and persistence relative to a user defined slope geometry. Established calculations define the forces driving failure versus forces resisting failure and can also determine the failure mechanism and plunge of the wedge intersection. Using distributions of the input variables and multiple Monte–Carlo simulations, a distribution of FS and a POF can be established.

For the example case defined above the distribution of FS is shown in Figure 3. The analysis showed that of the 5,000 simulations run, 2,125 wedges were generated with a FS<1, with a POF of 43%. Using acceptance criteria defined by Read and Stacey (2009), this value far exceeded the accepted bench scale POF threshold of 25% and FS of 1.2.

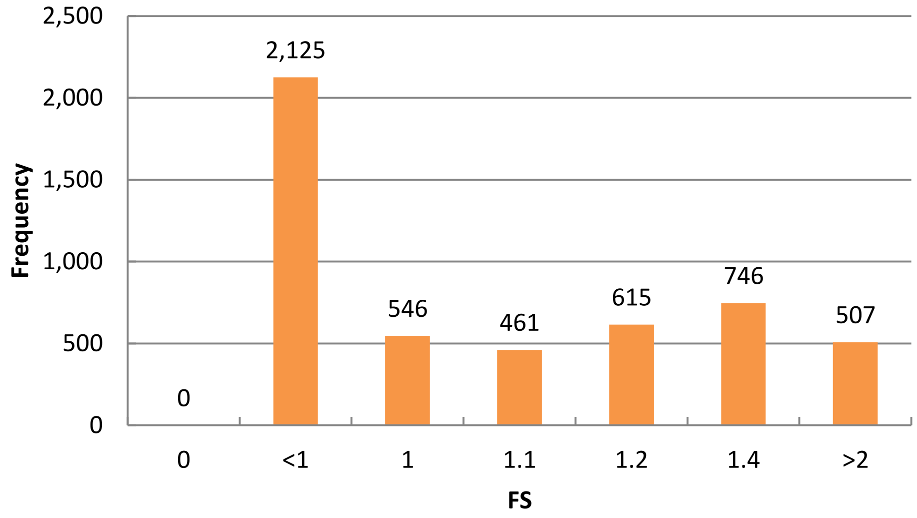


Figure 3 Distribution of FS for the example case

Whilst suitable for a first-pass analysis of the potential for failure, the conventional LE analysis generates the largest wedge possible within the defined slope geometry. When considering bench scale failure, it is acceptable to have some failure of crests, the extent of which is defined based on site specific risk profiles. If FS or POF alone is used to determine the acceptability of a design, the example case would not be accepted. However the persistence and spatial distribution of the discontinuities has a significant impact of the volume of the failed wedge. A higher probability of failure may be acceptable if the generated wedge volumes are small and sufficient catch capacity is available on the berm below to retain 80% or more of any failed material (Read and Stacey, 2009).

The addition of persistence and its statistical distribution is possible within conventional limit equilibrium programs, however, the influence of spatial distribution and the resulting interaction of discontinuities cannot be accounted for.

4.2 Proposed alternative method

A pseudo-discontinuum method has been used in this study, as previously discussed in Section 3. It combines the reduced computational requirements of continuum code with implicitly modelled discontinuities for the assessment of discontinuity driven failure at the bench scale.

Using the input parameters previously discussed (Table 1) a base model for the example case was generated and run to produce a POF of 13% (Table 2). A displacement criterion, which was previously calibrated against a discontinuum code, was used to determine failed volumes and POF within the model.

Table 2 Pseudo-discontinuum model results

Intensity (P32)	Persistence	POF	Variance
0.2	3	13.27%	± 0.3742%

The only parameter introduced into the pseudo-discontinuum model that is not controllable in the limit equilibrium model is fracture intensity (P_{32}). The inclusion of fracture intensity in this alternative method resulted in a 30% reduction in POF compared to conventional analysis.

As previously described, discontinuities are included within the pseudo-discontinuum implicitly within a continuum code. Each model is deterministic and multiple iterations, using randomly generated seed points, must be run until a specified accuracy is met.

4.3 Comparison of results

When interpreting the results of a limit equilibrium analysis the POF is determined by dividing the total number of blocks formed by the total number of blocks with a FS less than one. When analysing LE POF values either the user defines a minimum block size as a limiting factor or all blocks irrespective of volume are included in the analysis. The former requires the user to determine a volume/weight of a block that they consider to be significant which is likely to vary with each individual user. The later has the potential to skew the reported values if numerous small unstable blocks are formed that in reality would not be significant for bench scale failure as they would be caught by the berm.

In contrast, numerical modelling techniques take the total volume of failed blocks and divides by the volume of the model available for failure (Figure 4). The introduction of volume into the POF calculation produces a more realistic value that can be compared to site specific acceptability criteria. Utilising the numerical modelling approach produces a POF that is scaled using volume without a user defined minimum volume/weight therefore removing the need to define a significant block volume/weight. Numerical analysis of deterministic DFNs (based on photogrammetry or line/window mapping) also has the potential to predict areas of poor performance and increased risk in areas where clustering of discontinuities occurs.

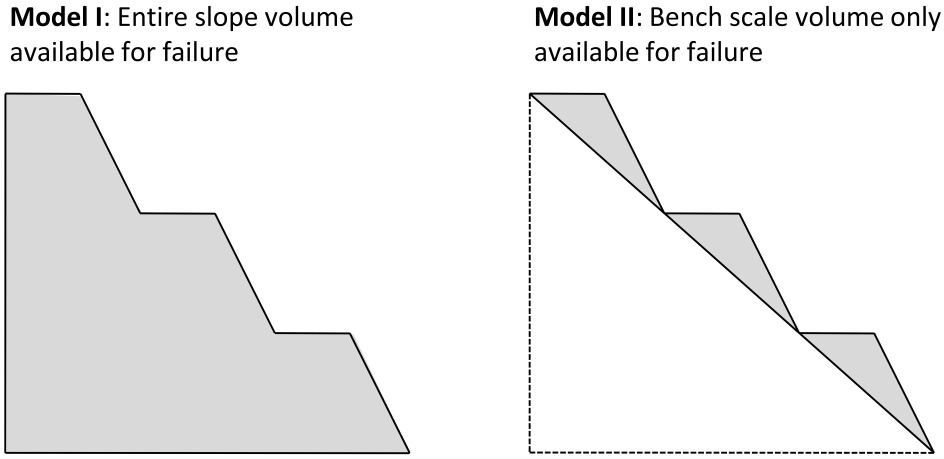


Figure 4 Failure volume available for analysis and comparison of results

A direct comparison of conventional analysis methods against the proposed alternative methods shows significant variability in the results and highlights the need to carefully consider how a bench is modelled (Table 3). Limit equilibrium analysis considered block physics and geometry and resulted in a POF of 43%. Numerical modelling using the pseudo-discontinuum method further reduced the POF to 13%.

Table 3 Comparison of slope stability analysis methods POF

	Method	POF (%)
Conventional method	LE analysis*	43
Alternative method	Pseudo-discontinuum method	13

*Only the analysis of wedges is included in this instance. Sliding on one plane was included as a valid wedge failure mechanism and is believed by the authors to best represent planar failure in pit walls.

When considering the example case, the use of a pseudo-discontinuum method of analysis of bench scale stability has enabled the improvement of the predicted POF. In a slope design context, this could facilitate optimisation of wall geometry and allow for an assessment of likely failure volumes.

5 Further work

The work conducted for this paper was the first step in developing a more rigorous technique for bench scale slope stability analysis in fresh rock. The authors have outlined five key steps that need to be undertaken to progress the development further:

1. Investigation into the relationship between persistence, spacing and fracture intensity/density.
2. Investigation of the sensitivity of pseudo-discontinuum models to density/intensity.
3. Investigate other alternative methods such as kinematic stability assessment of the generated probabilistic DFN using Fracman software (Golder Associates, 2013).
4. Application of the assessment techniques to detailed real-life case studies and assessment of suitability of the proposed pseudo-discontinuum method.
5. Integration of block volume into acceptability criteria FS and POF to assist in reducing overly conservative stability assessments.

6 Conclusion

The use of a pseudo-discontinuum method of analysis of bench scale stability has enabled a potential improvement of the predicted POF when compared to conventional analysis techniques. In a slope design context, this could facilitate optimisation of wall geometry.

A review of literature and current industry standard slope stability techniques has shown that the limitations of kinematic and limit equilibrium techniques are widely known and available in published research. However the implications of these limitations on analysis technique selection and analysis results are not always fully understood in relation to specific projects.

Conventional analysis techniques are adequate for the initial stages of slope stability assessment for open pit projects. However, as the structural database expands and if it includes high reliability data for persistence and spacing, improved assessments of wall stability become available. As the project level develops from scoping to pre-feasibility and onto feasibility level and implementation studies, the methods used for the analysis of slope stability also need to advance.

Improved methods of analyses rely on numerical models that can consider the effect of stress and displacement within the slope and on a statistically representative DFN. The choice of model (discontinuum or continuum) is dependent on the anticipated material behaviour.

Software choice is becoming less restricted due to developments in all software. At the bench scale, discontinuum and continuum-stochastic DFN codes provided comparable results and highlighted the need for detailed information concerning persistence and spacing/ fracture intensity.

Fracture intensity (P_{32}) was shown to have a greater effect on stability than persistence for the example case. Further investigation into the impact of P_{32} is needed to establish a relationship between spacing, persistence and P_{32} in any structural model.

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