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Bench design optimisation in a sparsely structured rock mass

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Abstract

The quality of bench faces in the North Wall of Red Chris Mine has greatly improved since their blasting method was amended to include pre-splitting. This improvement in bench stability performance offered an opportunity to optimise bench design. Analysis of the south facing benches shows that stability is in part controlled by a sparse network of longer structures, comprising of both joints and faults. Conventional bench-scale kinematics is not suited to considering sparse networks such as this, where in reality the probability of occurrence (POBO) of problematic wedges is typically low, while conventional combinatorially modelled wedges (e.g. SWedge) result in a POBO that is unrealistically high. This results in unnecessarily conservative design recommendations.

In contrast, the generation of a discrete fracture network (DFN) model provides a more realistic definition of the structural model based upon stochastic inputs from identified structural sets. Estimates of structure size and intensity were made from local bench mapping and photogrammetry. DFN model analysis, with its realistic structural description, allows the more reliable identification of potential wedges, the classification of unstable wedges, and the estimation of back-break. The combination of POBO and probability of sliding (POS) for modelled wedges, resulted in an overall probability of failure (POF) well within the design acceptance criteria (DAC) and simulated back-break values that were consistent with field observations. Under the right conditions, DFN wedge analysis can justify steeper bench face angles (BFAs) when compared to conventional kinematic analysis.

Keywords: *discrete fracture network, optimisation, stability, structural*

1 Introduction

Red Chris is a copper-gold mine that is located approximately 80 km south of Dease Lake in northwest British Columbia, Canada. The mine is currently owned and operated by Newmont. The copper-gold deposit at Red Chris is held within a veined porphyry rock mass at the northern margin of the Skeena Mountains. Two mineralised zones, the East and Main, form overlapping hydrothermal centres dominated by low-temperature intermediate argillic assemblages at shallow depths (Rees et al. 2015). Conventional shovel and truck mining methods are being used to excavate the East and Main zones of the deposit. In 2015, the open pit mine was estimated to contain reserves of more than 301.5 million tonnes (Mt) grading at 0.359% copper and 0.274 g per tonne (g/t) of gold (Mining Technology 2015).

The Main zone of the open pit contains multiple geotechnical domains comprised of sedimentary, volcanic, and intrusive rock units (Figure 1). Much of the north wall falls within the North Domain, which has been characterised to be monzonite and monzodiorite. Pre-split blasting trials in the North Domain showed that wall performance could be significantly improved as Main zone excavation continued. With improved bench stability performance, there was an opportunity to optimise bench design. Analysis of the benches in the

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North Domain show that stability is in part controlled by a sparse network of long structures/faults. Conventional kinematics is generally not suited to considering sparse networks such as this, always resulting in conservative designs. As an alternative approach, discrete fracture network (DFN) modelling was used to define the rock mass fabric and then analyse for unstable wedges using a realistic and explicitly defined structural model. Analysis has shown that DFN wedge analysis can support higher bench face angles (BFAs) at the same probability of failure (POF) (Valerio et al. 2021).

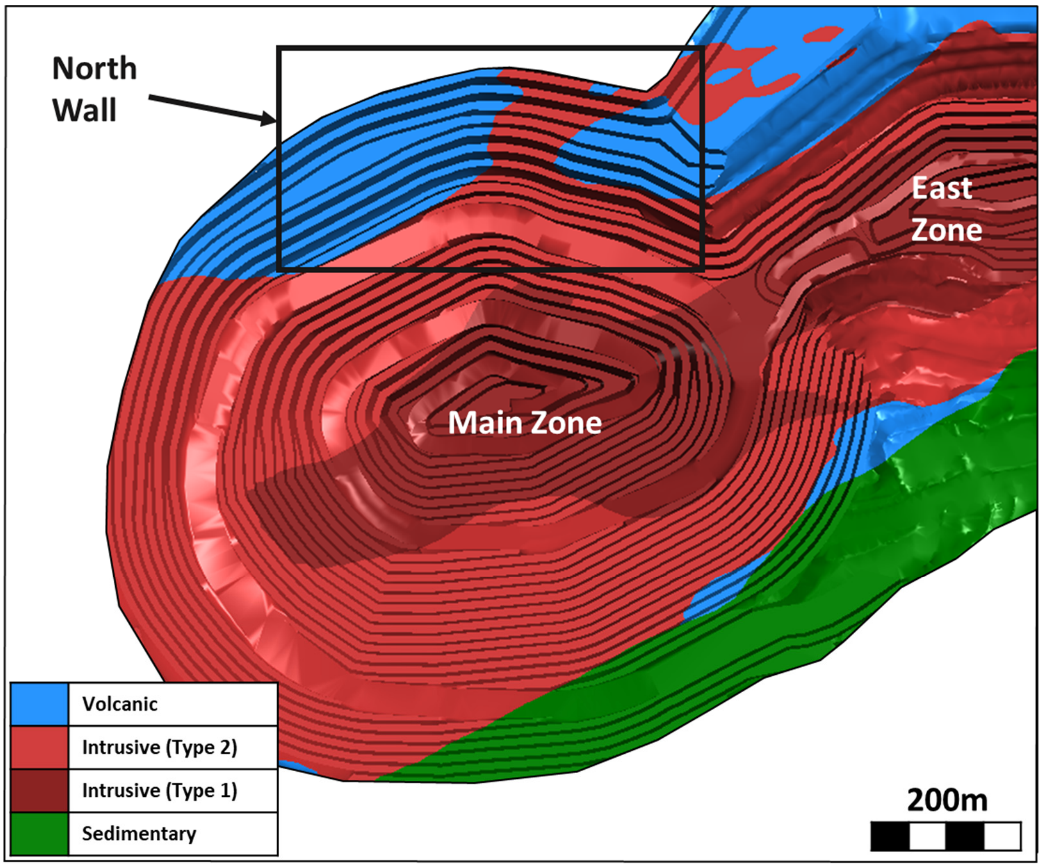

Figure 1 Lithological units in the Main Zone of Red Chris

2 Discrete fracture network model development

The workflow for running kinematic analysis using a DFN model is outlined in Figure 2. The objective of using a DFN model is to explicitly represent relevant fabric in three-dimensional (3D) space, whether that be joints, faults, bedding, or foliation. Geological and geotechnical data that has been collected locally and regionally are used to estimate quantitative parameters that describe the fracture network and its variability. Conventional combinatorial kinematic simplified methods (e.g. SWedge [Rocscience 2023]) generate wedges from fabric orientation, without consideration of the likelihood of wedge formation. In contrast, the DFN approach, based upon a modelled network – and therefore a more realistic fabric description – can replace the inherent conservatism of simplified approaches with actual realism.

Model inputs for this analysis were derived in general from photogrammetry mapping of the North wall (Figure 2 – Step 1). Photogrammetry mapping captures the fracture orientation (from plane mapping) and fracture length (from trace and plane mapping), both of which are key inputs for a DFN model. Recent photogrammetry campaigns that have been undertaken at Red Chris mine produce high-resolution imagery of large areas. Unlike bench or cell mapping, photogrammetry from drone flights enables interpretation of structures that span multiple benches, without having personnel exposed to an active mining environment. The majority of mapping for this analysis was on fracture planes (i.e. features with a visible face), however trace mapping was undertaken when the plane was not visible, but a length could be estimated. These longer lengths are considered representative of structures that would impact bench-scale stability. Fracture lengths collected from both plane mapping and trace mapping were used to develop the size distribution for the analysis. The length distribution of structures was observed to follow a power law trend. Power law analysis reflects the common observation that many geological structures show scale invariant properties over large-scale ranges (Barton 1995; Bonnet et al. 2001). Data measured over several orders of magnitude can be plotted together and, where appropriate, a single common power law trend identified for the size of structures spanning a wide range of length-scales (Rogers et al. 2016).

The information recorded on fracture planes (i.e. fractures with a face orientation visible) was used to develop inputs for the orientation distribution. Orientations from mapping were compared to previous mapping campaigns and mine-scale structural modelling (Figure 2 – Step 1b). During the comparison it was observed that part of the population had not been observed in the analysis. Orientation from photogrammetry mapping tends to preferentially capture structures that strike subparallel to the slope and dip moderately, while it underrepresents structures that strike at high angles to the slope direction, particularly those with steep dips. The importance of a robust dataset is highlighted during this kind of analysis, where photogrammetry is collected along a single wall orientation and cannot be relied upon to capture the entire orientation population. Comprehensive mapping of the North Wall has indicated the presence of two steeply dipping structural sets, the intersection of which would be critical in the simulation of wedge formation. The combined mapping sources along with the new photogrammetry were used in order to ensure that the entire structural population was being represented.

An example of photogrammetry data (i.e. planes and traces) being used for intensity interpretation is shown in Figure 3. Fracture intensity measures are classified based upon the dimension of the measurement region, and the dimension of the fracture, as shown in Figure 4 (Dershowitz & Herda 1992). The fracture intensity measurements from mapping are expressed as P21 (fracture length/unit area) and then converted into a 3D intensity measurement, P32 (fracture area/unit volume).

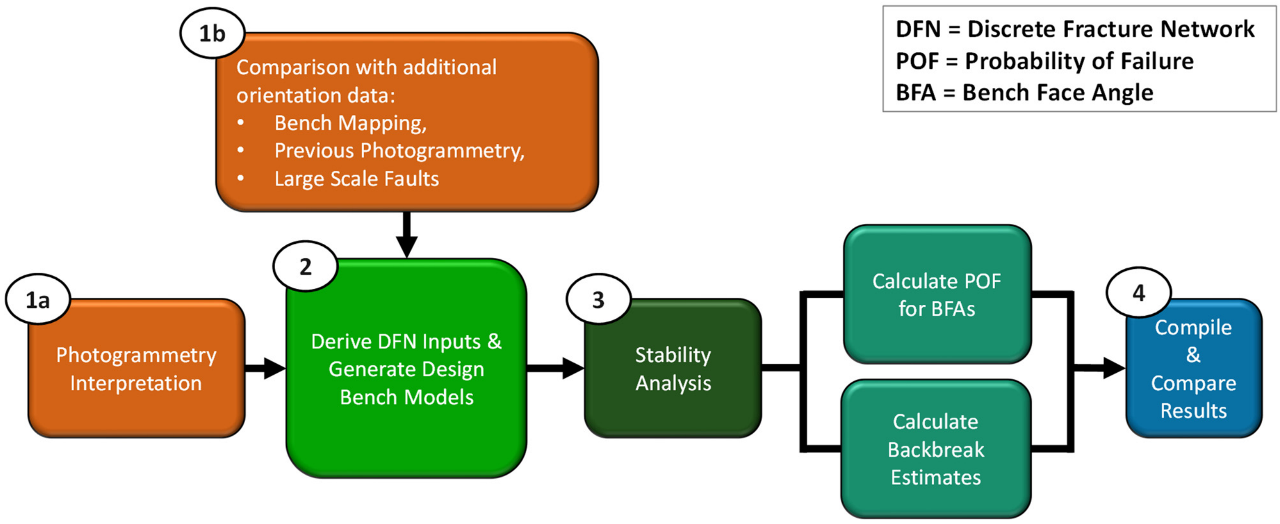

Figure 2 Workflow for bench-scale discrete fracture network analysis

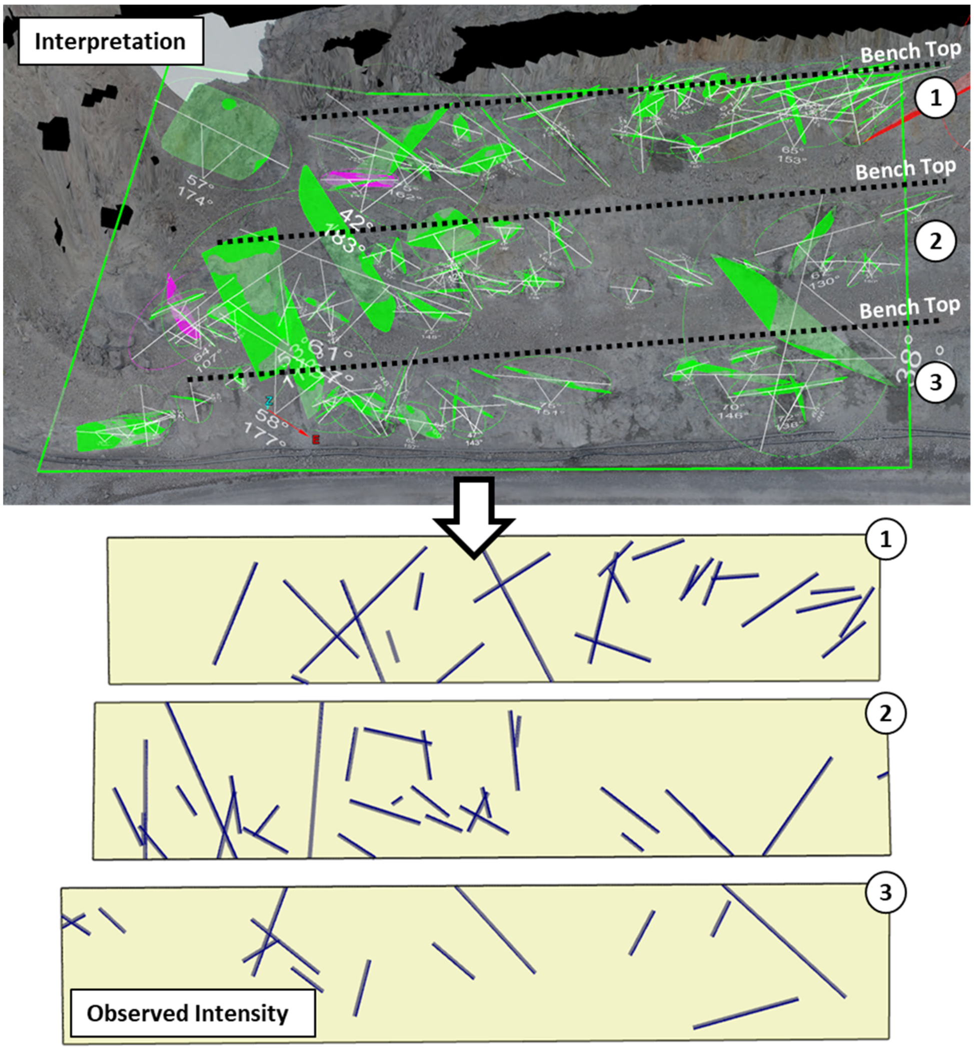

Figure 3 Photogrammetry interpretation window and observed intensity

Dimension of Sample \ Dimension of Measurement	0	1	2	3
1	**P10** No of fractures per unit length	**P11** Length of fracture per unit length		
2	**P20** No of fractures per unit area	**P21** Length of fracture per unit area	**P22** Area of fracture per unit area	
3	**P30** No of fracture per unit volume		**P32** Area of fractures per unit volume	**P33** Volume of fractures per unit volume
	Density		Intensity	Porosity

Figure 4 Intensity measurements from mapping are expressed as P21 (fracture length/unit area) and converted into a three-dimensional intensity measurement, P32 (fracture area/unit volume), adapted from Dershowitz & Herda (1992)

To convert the intensity of mapped photogrammetry traces (P21) to volumetric intensity (P32), a correlation factor was determined. This was carried out by generating multiple realisations of DFN models with known P32 intensities (e.g. 0.1–0.5). The known P32 is generated in a volume and then sampled on the trace plane surfaces, as shown in Figure 5. The relationship between the known P32 and sampled P21 can then be used to estimate a correlation factor, a schematic of which is shown in the graph in Figure 5. This correlation factor is used to convert the observed P21 (from photogrammetry) into a volumetric intensity that can be used in simulations (i.e. P32).

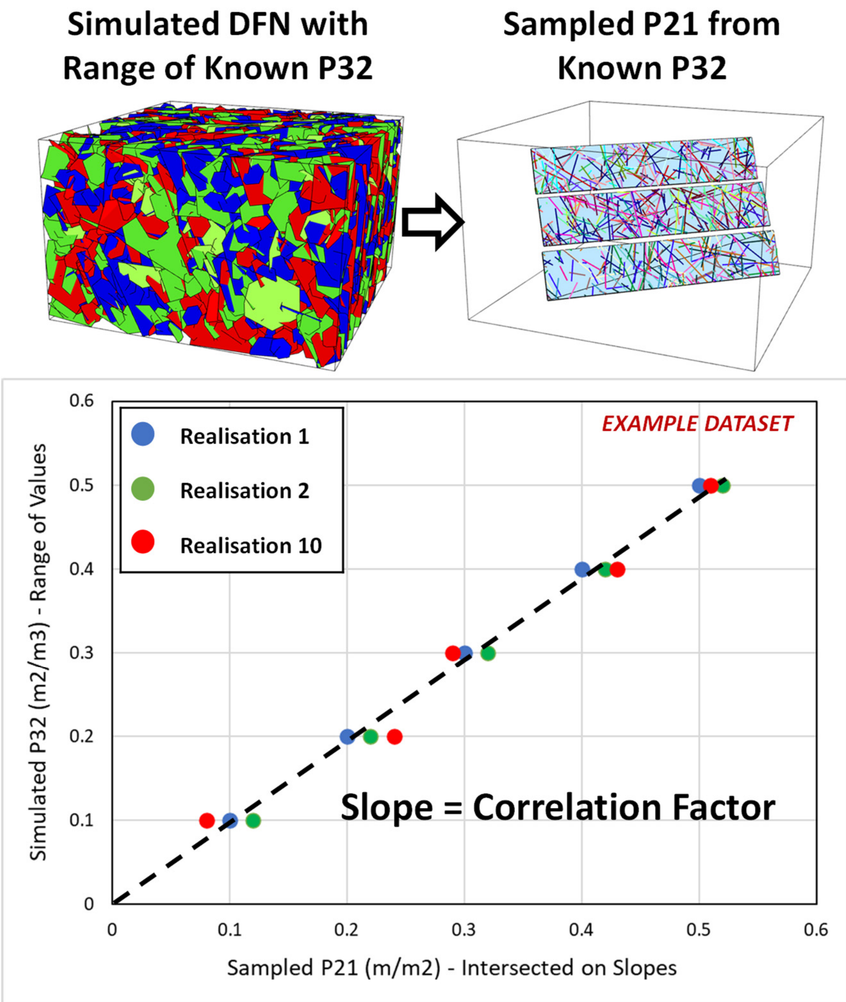

Figure 5 Intensity correlation factor is established by generating a range of discrete fracture network (DFN) models with known P32 (m^2/m^3) and sampling their P21 (m/m^2) on a slope face

3 Stability assessment

The stability analysis was carried out using the DFN model and an array of design bench slopes. The slope was rotated through 5 azimuths and the BFA of each slope was incrementally increased, from 65° until vertical (i.e. 90°). FracMan® (WSP 2023) was used to identify fracture-bounded wedges behind the slope. Simulated wedges for a range of BFAs (at a single slope azimuth) are shown in Figure 6. Both unstable and stable blocks (red and green, respectively) are shown in the examples. What can be seen from Figure 6 is that the frequency of wedge formation is very low, with typically one small and slender unstable wedge forming along the modelled 140 m bench length. Note also that the frequency of stable wedges formed is not significantly higher, at 2–3 wedges/140 m bench length.

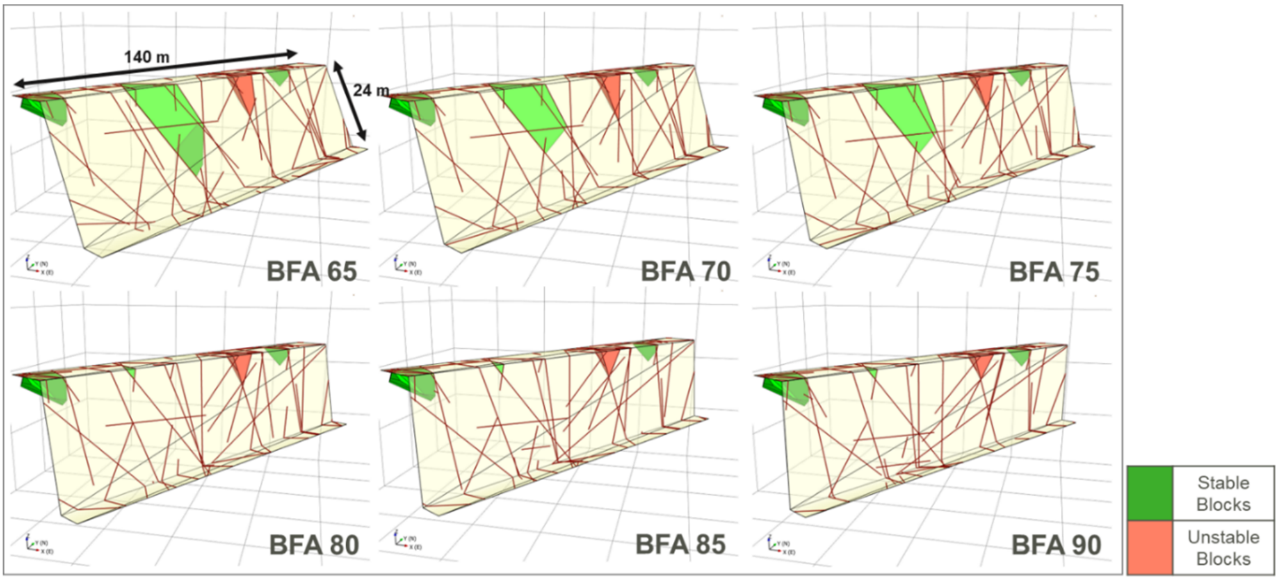

Figure 6 Array of design bench slopes; with incrementally increasing bench face angle (BFA)

To illustrate the comparison between the DFN approach and a more conventional kinematic approach, a number of combinations of critical sets, taken from the same orientation pattern, were analysed using SWedge (RocScience 2023). A summary of the POF results from both approaches is shown in Figure 7. The summary includes DFN results and SWedge results (for 2 critical set combinations) for a single slope orientation at the range of BFAs. A typical design acceptance criteria (DAC) of 40% is added as a red dashed line. The DFN results remain well below the DAC of 40%, while the SWedge results are both seen to exceed the 40% DAC at the steeper BFAs. Based upon these results and considering only kinematics, the DFN analysis can support a BFA of 90°, whereas the conventional analysis for configuration 1 can only support a BFA of ~83°.

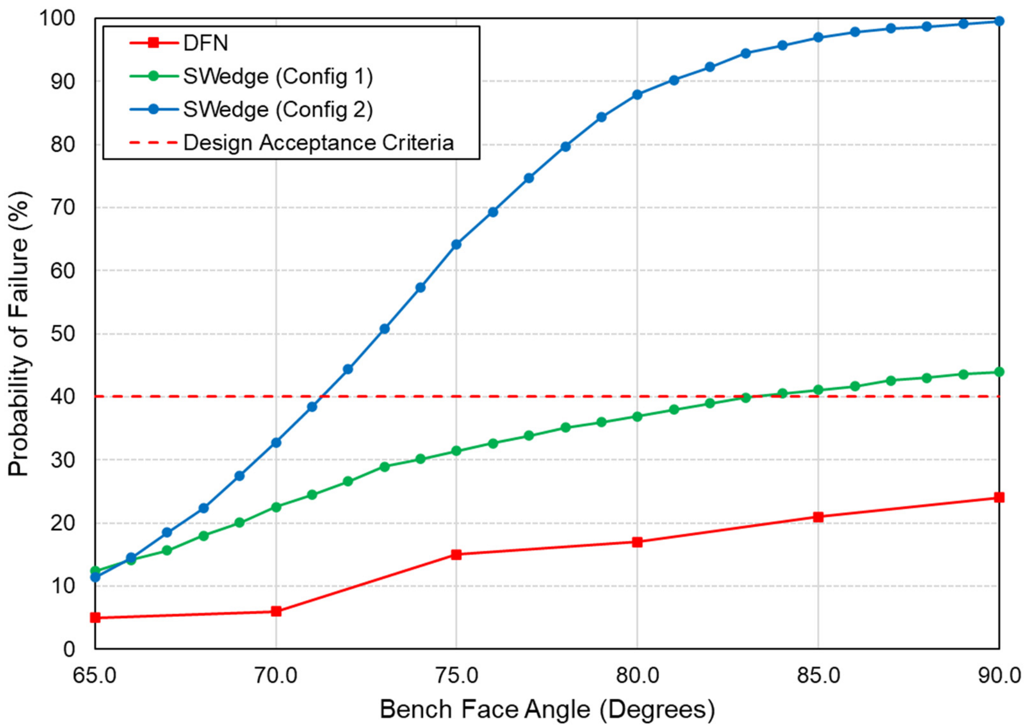

Figure 7 Array of design bench slopes; with incrementally increasing bench face angle

We can explore further the differences between the DFN and conventional approach by looking at modelled back-break. For simplicity, the 50th and 80th percentile back-break for both analyses are shown in Table 1.

Table 1 Comparison between the 50th and 80th percentile back-break from discrete fracture network and conventional kinematics

	DFN back-break	Conventional kinematics back-break
50th Percentile (m)	1.8	6.9
80th Percentile (m)	5.2	9.5

These results show that the 80th percentile back-break for the conventional analysis is almost double the DFN results, which are more aligned with pit observations. When considering both the back-break and BFA analysis results, we must appreciate the different considerations that go into each simulation. Conventional combinatorial kinematic analysis selects fracture orientations from 2 sets and forms a wedge. The wedge probability of occurrence (POBO) (the number of wedges divided by the number of realisations) is typically close to 100%. In contrast, the DFN approach models a structural fabric based upon estimated intensities/spacing, structure size, and structure orientation. The structural fabric is formed first and then blocks are searched for. As a result, it is quite possible that blocks will not always be formed, which results in a significant reduction of POBO.

The wedge POF in the DFN analysis is expressed as the POBO multiplied by the probability of sliding (POS). Wedges are considered 'locked-in' if they require failure through rock mass, or if they are not kinematically admissible (e.g. high cohesion or low friction angle on structures). However, if wedges are fully formed in the slope and are not obstructed, they will slide out of the slope (i.e. unstable). The POS is therefore defined as the number of unstable wedges divided by the number of formed wedges.

The POBO, POS, and POF results from a DFN model at a single slope orientation and a BFA of 90° are shown in Figure 8 (a, b, and c respectively). The 'wedge apex' dimension is the depth of the block, measured from the 'apex' of a wedge perpendicular to the crest. This is traditionally referred to as 'back-break' distance for unstable blocks. The back-break distance is the depth of the block, measured from the 'apex' of a wedge perpendicular to the crest. Figure 8a is annotated with the 50th percentile and 80th percentile of wedge apex depth that was estimated from SWedge. It can be seen that the scale of blocks from conventional analysis is significantly greater than anything generated by the DFN model.

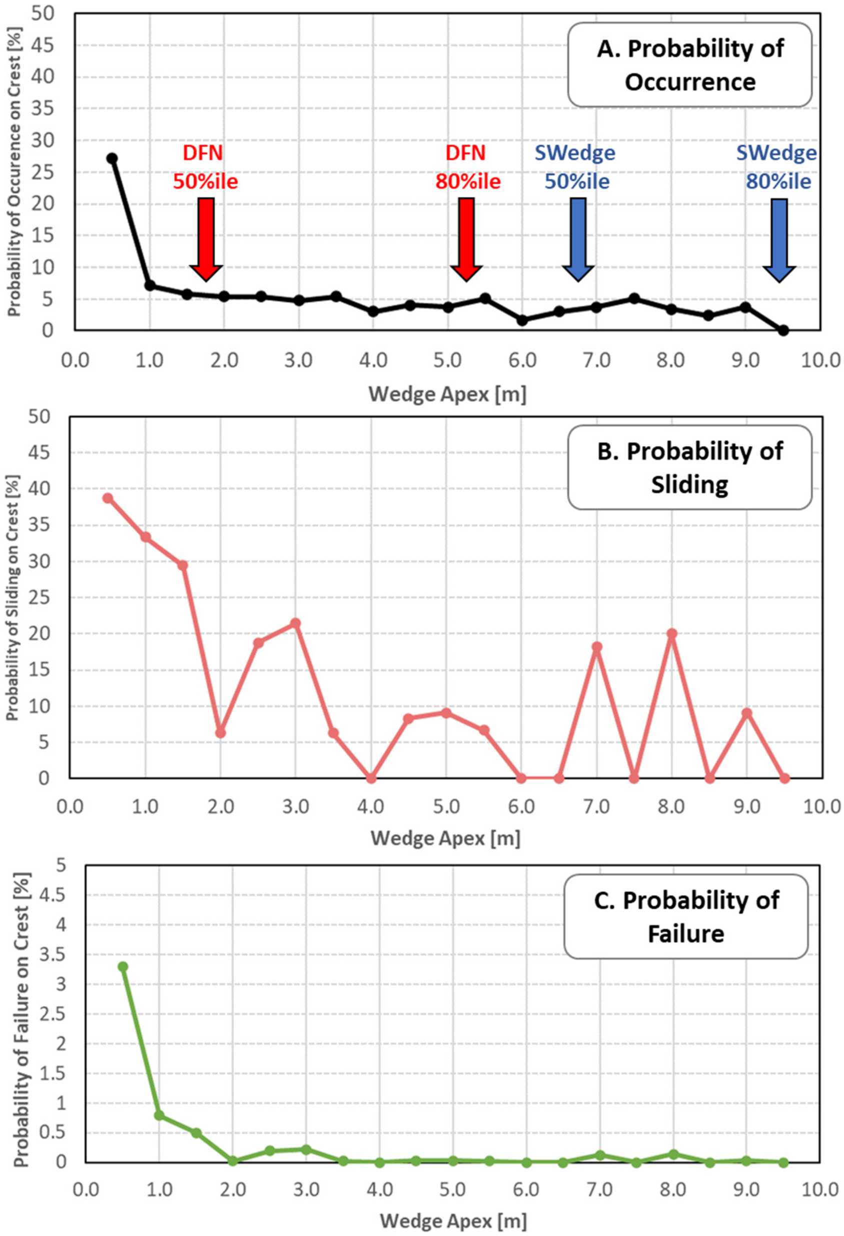

Figure 8 **(a) Probability of occurrence annotated with the 50th and 80th percentile (%ile) of wedge apex depth from the discrete fracture network (DFN) model and the SWedge model; (b) Probability of sliding; (c) Probability of failure results for a discrete fracture network model at a single slope orientation with a bench face angle of 90°**

4 Sensitivity consideration

Several sensitivities were carried out to evaluate the response of the results to a number of critical inputs such as the catch bench width, the fracture size, and the fracture intensity. Increasing the catch bench width showed minimal change, even with wider catch benches. Decreasing the fracture size did not have a significant impact on the stability results, however, it did produce a higher count of small blocks. This result emphasises the important of the size distribution and the effect that longer structures can have on bench-scale stability. The variation of fracture intensity had the most substantial impact on the stability assessment. Fracture intensity was increased to 125% and 150% of the observed intensity (base case), as shown in Figure 9. Although these results were not quantified, it was demonstrated that with an increase in the intensity of structures – from a sparely connected network to a network with abundant structures – it is likely that the results of DFN analysis and kinematic analysis would become more comparable.

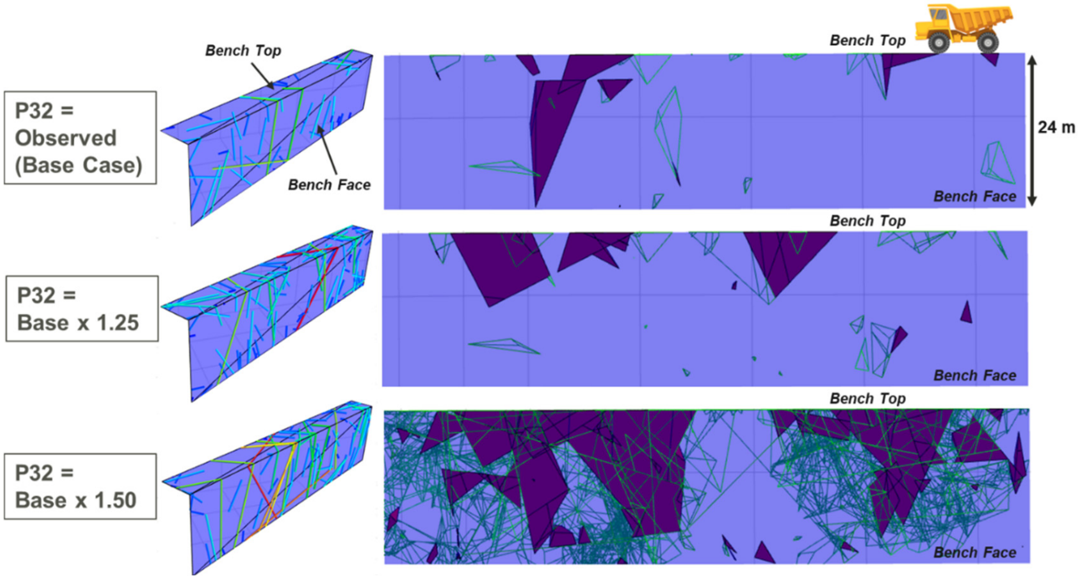

Figure 9 Discrete fracture network sensitivity with increasing intensity

5 Conclusion

The DFN approach outlined in this study combines the POBO and POS for simulated wedges in order to estimate an overall POF. The results of this analysis were well within a typical DAC of 40% and simulated back-break values that were consistent with field observations at Red Chris mine. The absence of fracture frequency or intensity as an input for conventional approaches, which define joint spacing as simply small or large, could result in a sparse network of structures being over-represented. This makes DFN wedge analysis highly useful for providing realistic probabilistic results in a geological setting where the probability of wedge occurrence is low and should be a critical consideration in the overall POF.

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Red Chris Mine operates on grounds that belong to the Tahltan Territory. I am grateful to have had the opportunity to work on these lands and meet the people that call it home. Thank you to Newmont supporting this research.

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