SSIM 2021 - PM Dight (ed.)
© Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-1-0
doi:10.36487/ACG_repo/2135_29

Improving bench design through discrete fracture network analysis

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Abstract

Discrete fracture network (DFN) analysis methods can assist in our understanding of bench-scale slope performance in open pit mines and provide results that are more representative of structural conditions compared to conventional kinematic methods. Conventional kinematic analysis may not adequately capture the complexity of the fracture network and its impact on bench-scale stability because this method is typically limited to analysis of simple rock blocks or wedges formed by one or two fracture sets only. This simplification of block geometries, combined with the limitation of not adequately representing variations in the location and spacing of discontinuities forming blocks, can result in significant differences between theoretical and observed bench performance.

DFN methods provide an alternative approach to conventional kinematic methods to model the structural fabric. The fracture networks developed through DFN modelling incorporate variations in the location, spacing, and persistence of discontinuities. DFN-based approaches allow more detailed analysis of the probability of occurrence, probability of failure, and expected back-break when compared to conventional kinematic methods as wedge geometries are more explicitly defined from observed features.

This paper provides a comparison between conventional kinematic analysis and a DFN-based approach to bench design, with a focus on back-break metrics for two case studies: one slope governed by potential planar instability and a second where potential wedge failure is the controlling mechanism. The impact of mining processes and time-dependent rock mass degradation on observed back-break is discussed. Comparison between the results of both conventional kinematic and DFN methods to actual bench performance observed at the Bingham Canyon Mine indicates that the DFN approach can deliver results that are more structurally representative of field conditions.

Keywords: *bench design, discrete fracture network, kinematic analysis, back-break, bench performance*

1 Introduction

Bench-scale stability analysis is a key component of pit slope design, particularly where slopes are not constrained by overall slope performance. At the bench-scale, failure mechanisms tend to be structurally controlled and are typically analysed using conventional kinematic methods. These methods have not changed significantly since they were first developed. From the initial graphical solutions for assessing wedge stability (John 1968; Londe et al. 1969) to the introduction of software solutions of the same approach (Hoek et al. 1973; Kovári & Fritz 1975) and the use of probabilistic methods (Miller 1983; Miller et al. 2000; Carvalho 2002), the analyses are based on identifying all possible rock blocks or wedges (formed by one or two fracture sets only) that may form within a specified bench geometry. The simplification of block geometries involved in conventional kinematic approaches, combined with the limitation of not adequately capturing variations in the location and spacing of discontinuities forming blocks, can result in substantial differences between theoretical and observed bench performance.

To overcome many of the limitations of conventional kinematic methods, discrete fracture network (DFN)-based methods are finding increasing application to bench-scale analysis and design (Mathis & Elmouttie 2018; Rogers et al. 2018, 2020). DFN methods provide an alternative approach to model the structural fabric, which allows geological and structural properties to be more realistically represented in geotechnical assessments compared to conventional kinematic methods that typically involve considerable simplification of the rock mass fabric. DFN models account for variations in the location, spacing, and persistence of discontinuities, and therefore allow the fracture network to be defined in a manner that is more representative of the observed geometric properties. DFN-based methods allow detailed analysis of the probability of occurrence, probability of failure, and expected back-break as wedge geometries are explicitly defined from the full distribution of observed features.

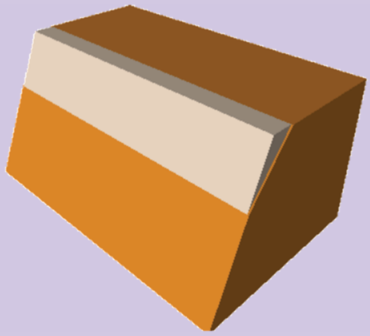
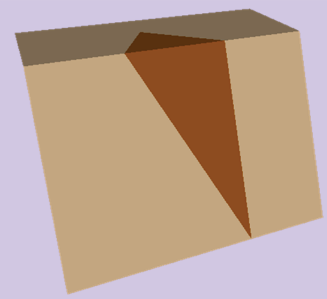
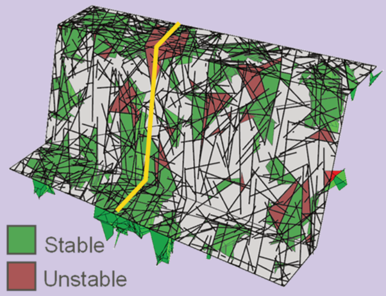
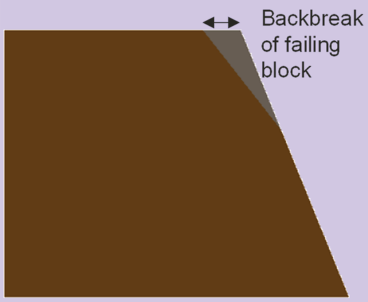
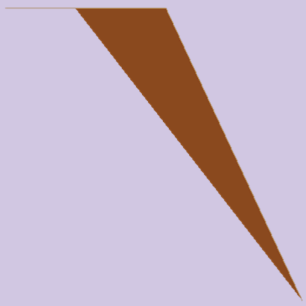
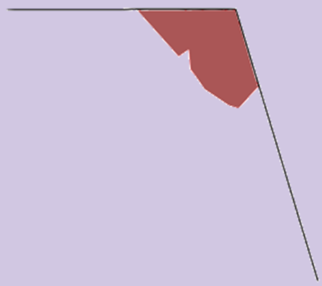
This paper expands on the DFN-based approach to bench-scale stability analysis developed by Rogers et al. (2018, 2020) to carry out a probabilistic evaluation of bench-scale stability for a range of different bench geometries. A comparison between conventional kinematic analysis and the DFN-based approach to bench design is provided, with a focus on back-break metrics. Two case studies from the Rio Tinto Kennecott Bingham Canyon mine are presented: one slope governed by potential planar instability and a second where potential wedge failure is the controlling mechanism. The results of both conventional kinematic and DFN methods are compared to actual bench performance observed at the Bingham Canyon mine. A discussion is provided on the challenges associated with reconciling theoretical to observed back-break in slopes where bench performance has been substantially impacted by processes other than kinematic controls such as blast damage and rock mass degradation over time.

2 Bench-scale analysis approach

To assess bench-scale stability, two approaches are used in parallel. The first approach (Section 2.1) consists of conducting conventional kinematic analyses using the Rocscience programs RocPlane™ (Rocscience 2021a) and SWedge™ (Rocscience 2021b). The second approach (Section 2.2) uses FracMan® (Golder Associates Inc. 2021) to develop DFN models, which are then used to identify and evaluate the stability of fully enclosed three-dimensional (3D) blocks of rock that intersect the bench face. In both approaches, the amount of bench crest loss (i.e. back-break) due to structurally controlled failure along the crest is calculated for every unstable block (Table 1), and the results of multiple simulations are aggregated to develop statistical distributions of predicted back-break for the specified bench geometry. The results of both the conventional kinematic and DFN-based approaches are then compared to actual back-break measurements collected from excavated benches (Section 2.3) to determine which approach provides back-break predictions that are most consistent with field observations.

As illustrated in Table 1, there are substantial differences in the geometry of blocks generated by RocPlane and SWedge compared to FracMan. In RocPlane and SWedge, single blocks are generated from one or two fracture sets on a pseudo-3D slope bench, which results in considerable simplification of the block geometries. FracMan generates 3D blocks along a physical bench length, which allows variations in the location, size, and geometry of the blocks to be represented based on field data.

Table 1 Illustration of simulated wedges and back-break using conventional kinematic methods compared to discrete fracture network (DFN) based approaches. Section line shown on DFN model, with cross-section figure showing only unstable wedges

View	RocPlane	SWedge	DFN – FracMan
3D			
Cross-section			

2.1 Conventional kinematic analysis

At the bench-scale, kinematic analysis combined with probabilistic methods is one of the most common approaches used to evaluate the potential for structurally controlled failures (e.g. plane, wedge, and toppling mechanisms) to occur. This approach involves assessing the stability of all the wedges that are expected to daylight for a specified bench geometry. However, these analyses are not truly probabilistic because variations in the location and spacing of the discontinuities forming the wedges are typically not adequately captured in the models. The underlying assumption is that the largest possible wedge for a defined set of input parameters (bench geometry, discontinuity orientation, discontinuity persistence, etc.) will always form and have the potential to fail, provided the wedge is kinematically admissible. This simplification of the rock mass fabric and wedge geometries may not always provide an adequate representation of the structural setting, which can lead to discrepancies between theoretical bench stability results predicted by conventional kinematic analyses and actual bench performance observed in the field.

The conventional kinematic analyses presented in this paper are conducted using the Rocscience programs RocPlane and SWedge, which allow statistical distributions of back-break distance to be developed for a specified set of input properties and bench geometries (Langford et al. 2014). These programs allow discontinuity orientation and persistence inputs to be defined by probability distributions developed from available field data. However, variations in the location and spacing of discontinuities cannot be represented in the models. The latest versions of RocPlane and SWedge provide two options for defining discontinuity spacing, both of which involve significant simplification of the actual rock mass fabric:

- **Small spacing** assumes ubiquitous discontinuities (i.e. discontinuities are numerous and may occur at any location). This option represents an upper bound solution for probability of failure and back-break because a wedge is generated in every simulation (provided the geometry of the bench and discontinuities generates a kinematically admissible wedge), independent of the spatial location of the discontinuities on the bench face (Langford et al. 2014).

- **Large spacing** assumes there is only one trace of each joint set on the bench face. The daylighting point of the failure plane (in the case of RocPlane) or the point of intersection of the two joint planes on the bench face (in the case of SWedge) is randomly located somewhere between the toe and crest of the bench, resulting in a uniform distribution of wedge height (Langford et al. 2014). This option represents a lower bound solution for probability of failure and back-break because the spacing and persistence assumptions limit wedge formation.

In the conventional kinematic analyses presented in this paper, both small spacing and large spacing assumptions are evaluated for comparison. For each scenario, probability distributions of back-break for the specified bench geometry are developed based on 10,000 simulations that consider variations in discontinuity orientation and persistence.

2.2 Discrete fracture network analysis

The basic application of DFN analysis and modelling to bench design is well documented (Rogers & Moffitt 2006; Ortiz & Silva 2009; Mathis & Elmouttie 2018; Rogers et al. 2018). Whilst conventional methods attempt to form blocks directly through imposed structures, DFN approaches build fabrics of structure constrained by intensity, orientation, and persistence and then analyse these networks to identify 3D blocks and evaluate their stability. Therefore, whilst conventional methods are evaluating the possibility of adverse block (or wedge) formation, DFN methods evaluate the probability.

The workflow for DFN analysis is relatively straightforward. Available structural data are acquired and processed to allow the derivation of inputs for joint orientation, intensity (spacing), and persistence. Experience has shown that utilising photogrammetry data has increased the accuracy of inputs to DFN models, especially when the image interpretation has included accurate structural trace length mapping as well as the measurement of feature orientations. Advantage should be taken of these modern mapping techniques that allow the characterisation of both individual features as well as the connected network of structures (Figure 1).

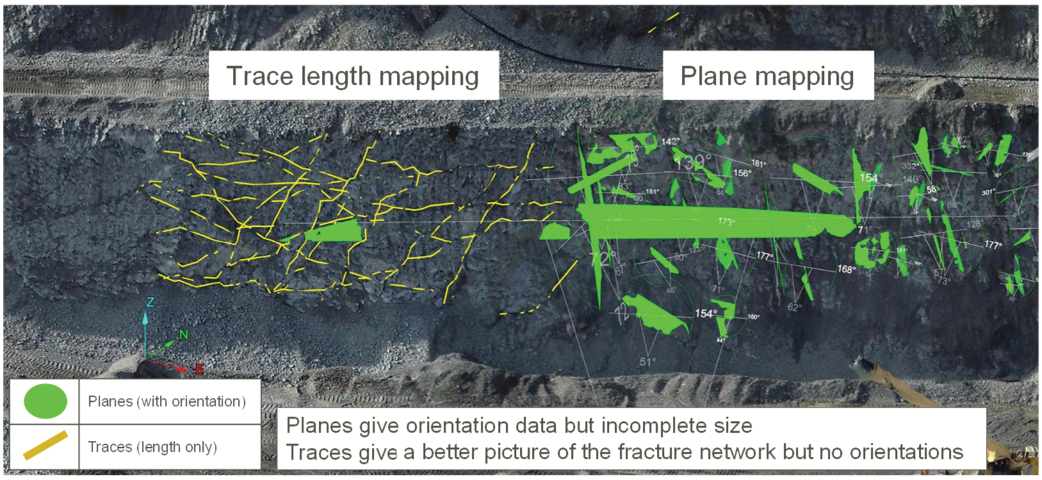


Figure 1 Comparison of the interpretation of photogrammetry image with an emphasis on trace mapping (left of image) or plane mapping (right of image) that shows how trace mapping provides a more accurate description of the overall joint network topology in this example

Conceptually, the calculation of back-break differs between conventional and DFN-based kinematic methods. With conventional methods, which analyse a single wedge or block per realisation, back-break is simply determined from the distribution of lengths from the bench front to the apex of the wedge. However, as DFN methods generate many probabilistic wedges along the bench, back-break estimates can be determined that focus more on overall bench performance along the length of a bench than on a single maximum apex measurement. Current approaches for extracting back-break results from DFN analysis include: (i) calculating the distribution for back-break using a slicing method to capture bench performance (yellow points in

Figure 2), and (ii) calculating the distribution of apex measurements for single blocks (blue points in Figure 2). While the latter approach is comparable to the conventional method, the 'slicing' approach is more aligned with how back-break metrics are derived in pit wall bench conformance studies.

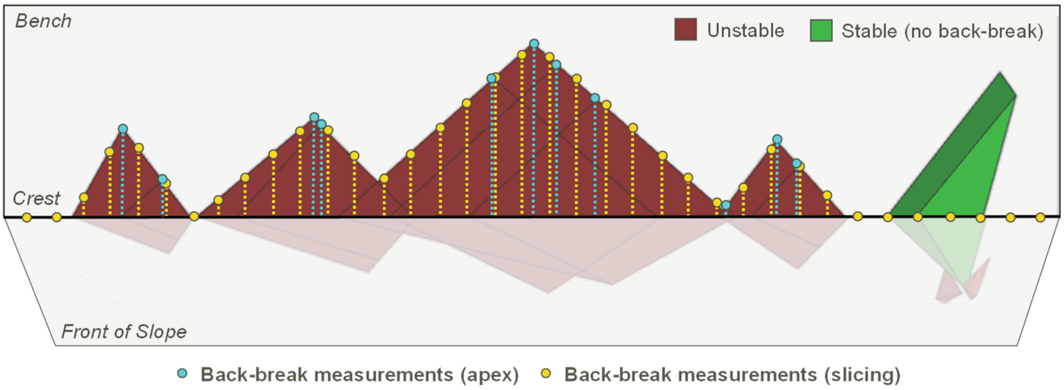


Figure 2 Illustration of different back-break measurements derived using the slices method

The slices method provides a distribution of back-break based upon the discretisation of the geometry of failing wedges. This can also include lengths of bench with no failing wedges to provide a back-break estimate that reflects the overall length of bench loss as well as depth of back-break.

The DFN-based method used to evaluate bench-scale block stability has been validated by conducting benchmarking tests between the FracMan DFN software and conventional kinematic analysis programs, RocPlane and SWedge. The benchmarking tests between FracMan and SWedge were carried out by Rogers et al. (2020). The results of the benchmarking tests between FracMan and RocPlane are presented in the Appendix of this paper.

2.3 Back-break measurement

Bench back-break is measured from 3D scans of as-built pit slopes by calculating the difference between the design crest lines and the corresponding as-built crest lines (Figure 3). Areas selected for back-break measurement target significant bench exposures where the resolution of the pit wall scan is high enough to allow accurate measurements and where there is evidence of structurally controlled bench-scale instability. The back-break measurements are then used to develop statistical distributions of observed back-break for comparison to the results of the predictive analyses. The method used for measuring the as-built back-break is similar to the method used in the DFN back-break assessment, where the distance between the bench crest and boundary of crest loss is measured along multiple cross-sections along the bench ('slicing' approach described in Section 2.2).

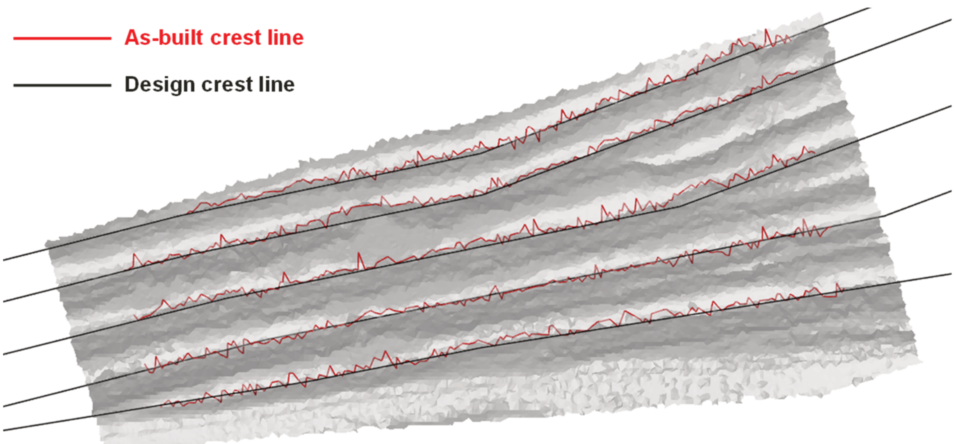


Figure 3 Oblique view of pit wall scan illustrating as-built back-break measurement approach. Back-break is measured as the distance between the design crest line (black) and the as-built crest line (red)

3 Case study: Bingham Canyon Mine

The approaches described in Section 2 were used to conduct bench stability and back-break analysis for a pre-feasibility level study for a pit wall pushback design at the Rio Tinto Kennecott Bingham Canyon Mine. The dominant rock types exposed in the Bingham Canyon pit slopes consist of intrusive units (predominantly monzonite) and sedimentary units (predominantly quartzite and a sequence of limestone beds). The structural geology is very complex and involves multiple folding and faulting cycles, highly variable bedding orientations, and several crosscutting structural sets.

The following sections describe the bench-scale analyses carried out for two geotechnical domains in which potential for structurally controlled failure mechanisms to develop at the bench-scale were identified based on review of the available structural mapping and borehole data (Figure 4). Section 3.1 describes the assessment conducted for an intrusive domain where simple kinematic analysis indicates the governing bench-scale failure mechanism consists of planar sliding along a dominant southeast-dipping joint set (Figure 4a). Section 3.2 describes the assessment conducted for a sediment domain where, based on simple kinematics, the governing failure mechanism is expected to consist of bench-scale wedges formed by the intersection between east-dipping and southwest-dipping joints and faults (Figure 4b).

Input parameters for the analyses described in Sections 3.1 and 3.2 were developed from available geological and geotechnical field data, including bench face mapping, photogrammetry mapping, geotechnical core logging, televiewer surveys, and laboratory testing data.

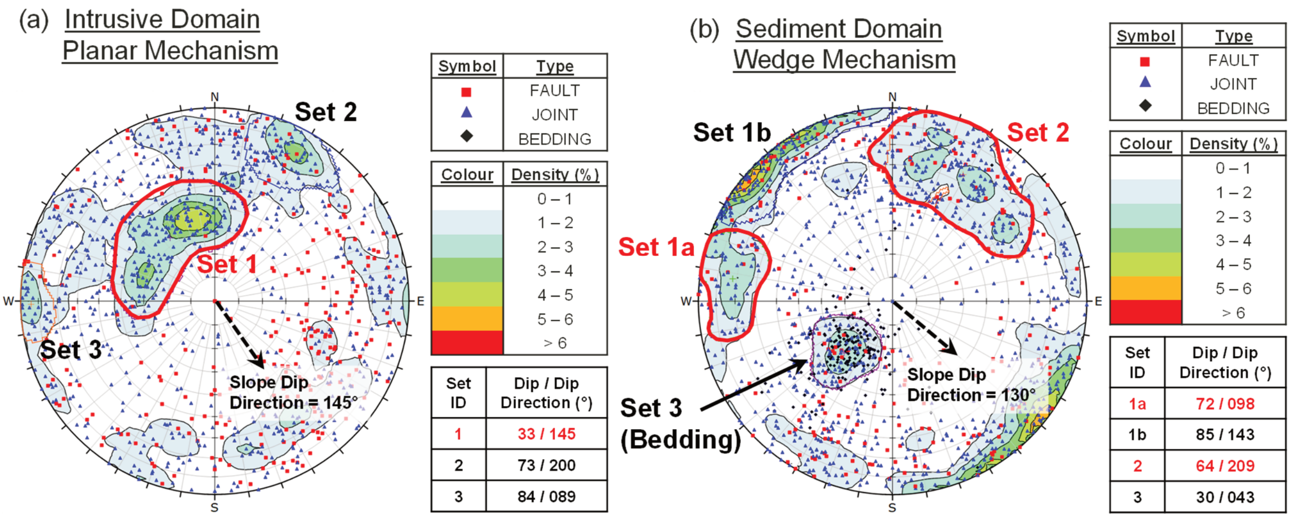


Figure 4 Stereographic projections showing available structural data and critical sets (labelled in red). (a) Potential planar sliding in intrusive domain; (b) Potential wedge failure in sediment domain

3.1 Bench-scale planar analysis in intrusive domain

In the intrusive domain, available bench performance data indicate that sub-vertical jointing is an important fabric in defining bench-scale instability, and that the failure geometries resulting in bench crest loss can be highly irregular (Figure 5). Back-break measurements of the exposed slopes indicate an average bench crest loss of less than 3 m with a maximum of approximately 6 m (Figure 5b). The slopes in the intrusive domain have been mined recently and therefore, there has been minimal back-break due to time-dependent rock mass degradation.

Predictive analyses of bench stability and back-break were carried out using conventional kinematic and DFN methods, and the results were then compared to available bench performance data. A comparison between the key model assumptions and input parameters of the two approaches is provided in Table 2.

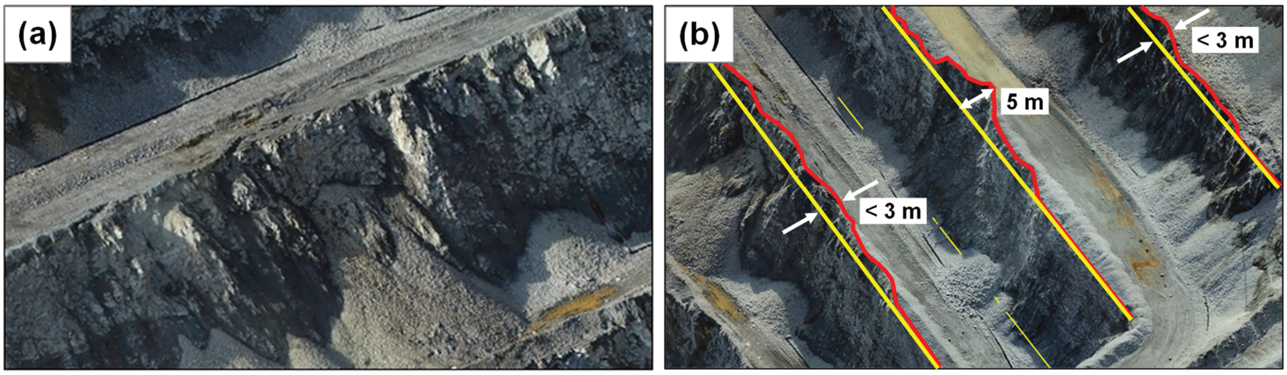


Figure 5 Examples of structurally controlled bench-scale failures in the intrusive domain. (a) Role of sub-vertical jointing; (b) Irregular failure geometries with back-break typically less than 3 m

Table 2 Summary of key assumptions and input properties for bench-scale conventional kinematic analyses and discrete fracture network analyses conducted for intrusive domain

Assumptions/properties	Conventional kinematic analysis	Discrete fracture network analysis
Bench length	Infinite length along strike	180 m explicit length
Bench configuration	Bench face dip direction = 145° Bench height = 15 m Catch bench width = 13 m Bench face angle = 68°	
Discontinuity strength	Friction angle = 28° Cohesionless(1)	
Groundwater	Dry conditions	
Failure mechanism	Planar sliding along dominant southeast-dipping joint set	Discrete fracture network model evaluates the kinematic stability of the modelled fracture network geometry without a specified mechanism
Fracture orientation	One joint set with apparent dip defined by normal distribution(2): Mean = 37° Standard deviation = 7° Minimum = 19° Maximum = 52°	Fracture orientations directly bootstrapped from mapped joints, using dispersion k = 80 around individual data points
Fracture intensity	Small spacing (ubiquitous) and large spacing scenarios considered	Defined with reference to mapped P21(3) intensity of structures, P32(3) = 0.35 m^{-1}
Fracture size(4)	One joint set with ***persistence*** defined by lognormal distribution: • Mean = 14 m • Standard deviation = 8 m	All fractures have lognormal distribution of ***equivalent radii***: • Mean = 7 m • Standard deviation = 4 m

(1) Cohesionless strengths are assumed in bench-scale analysis to simulate reduction of strength near surface due to blasting.
(2) Only discontinuities with a dip direction within 20° of the slope dip direction are included in the conventional kinematic analysis.
(3) Measurements of fracture intensity: P21 = length of fracture traces/area of exposure; P32 = total surface area of a fracture/volume of rock.
(4) RocPlane and SWedge both allow the use of joint persistence (defined as the maximum joint length as measured in any direction on a sliding plane) to describe fracture size, whereas DFN methods typically define the distribution of fracture radii. To provide a reasonably common measurement between the two approaches, the DFN radii distribution was converted to a diameter distribution, which was then used in the conventional kinematic analysis as a persistence input.

Figure 6a shows cumulative frequency curves of the conventional kinematic back-break predictions for both small and large spacing scenarios, compared to as-built back-break measurements. The small spacing scenario significantly overpredicts back-break compared to the bench performance data, with a difference in maximum back-break of over 6 m between as-built measurement and prediction. The large spacing scenario predicts smaller back-break compared to the small spacing scenario, as expected. However, even with this less conservative spacing assumption, the conventional kinematic results still predict a much greater percentage of large back-break distances (in the 6 m to full bench width range) compared to actual measurements, which indicate a maximum back-break of about 6 m.

In comparison, the DFN results show substantially better alignment with measured back-break, with the distribution of predicted back-break plotting within 1 m of the as-built back-break distribution (Figure 6b).

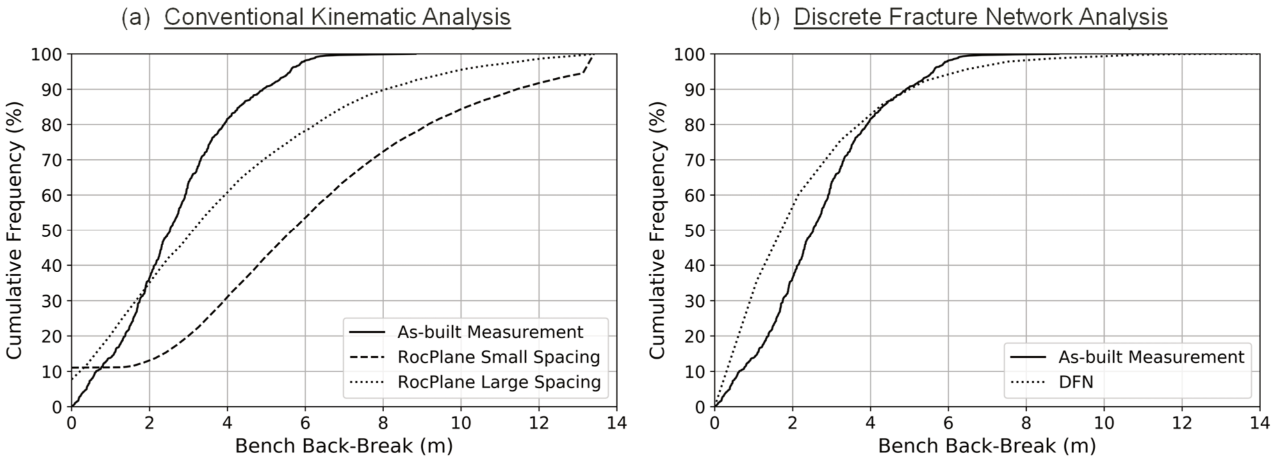


Figure 6 Results of predictive back-break analyses for the intrusive domain. (a) Comparison between conventional kinematic results (based on 10,000 simulations) and measured back-break; (b) Comparison between discrete fracture network (DFN) results (based on 50 simulations) and measured back-break. The solid black line is the same in both graphs, representing as-built back-break measurements

The results of this case study show significant differences between the DFN-based approach and the conventional kinematic analysis. The conventional method produces overly conservative results because it assumes that the joints in the critical set (dipping out of the slope at moderate angles) will always produce the maximum possible block size for the specified bench geometry, and that side release planes are ubiquitous and continuous over the full bench height in every simulation. Although simple kinematic analysis of the structural orientation data suggests that the critical failure mechanism in this domain is planar sliding, planar blocks extending over the full bench width and height are not actually observed in the physical benches.

The DFN-based approach provides an effective tool to overcome these inherent limitations in the conventional kinematic method by allowing variations in the location, size, and geometry of the blocks to be represented in the analysis based on field data. In particular, the explicit representation of side release planes results in a reduction of the probability of a sliding block being formed. The wider range of block sizes and geometries generated by the DFN model provides better alignment with the size and geometry of blocks observed in the physical benches within this domain, which in turn produces back-break results that are more consistent with bench performance observations.

3.2 Bench-scale wedge analysis in sediment domain

In the sediment domain, available slope performance data indicate that bench back-break is largely controlled by wedge failure mechanisms, including bench-scale wedge columns that are susceptible to destabilisation (Figure 7a). Review of the available pit wall scans indicates several areas where bench performance has been impacted by mining operations (Figure 7b). In contrast to the recently mined slopes in the intrusive domain, the slopes in the sediment domain have been exposed for several years, which has resulted in deterioration of the benches in some areas due to time-related rock mass degradation and weathering (Figure 7c).

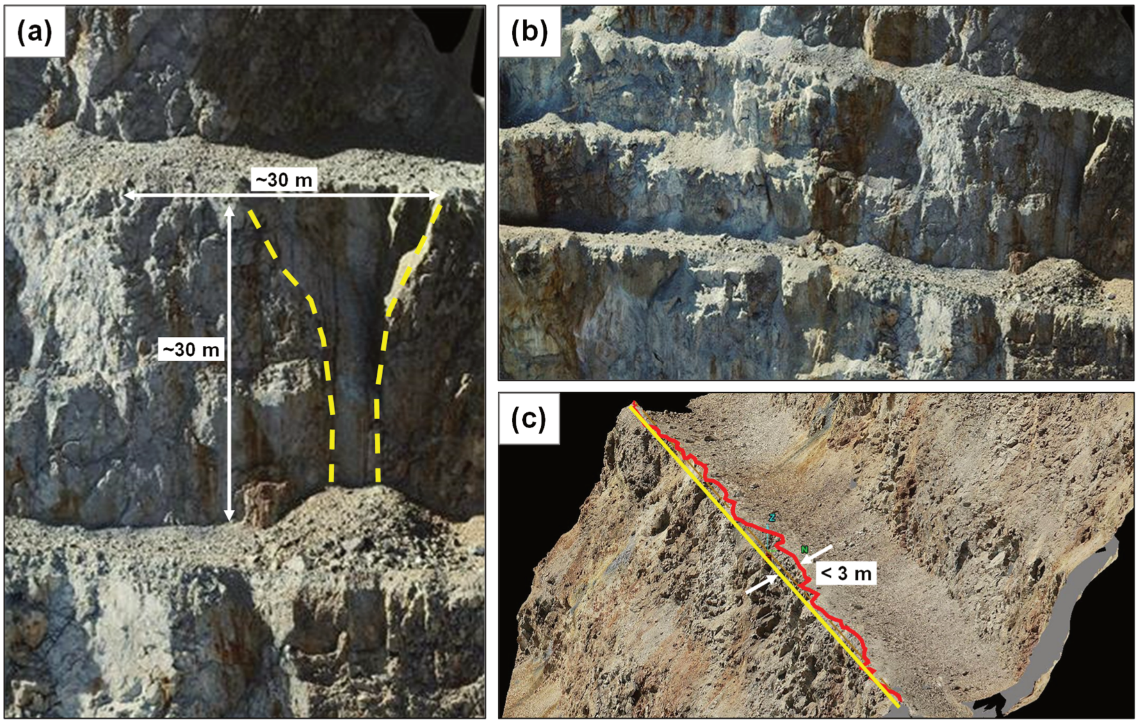


Figure 7 Examples of bench performance in sediment domain. (a) Rock wedge columns susceptible to destabilisation; (b) Impact of mining processes on bench performance; (c) Time-related rock mass degradation and weathering

Similar to the intrusive domain, predictive analyses of bench stability and back-break were conducted for the sediment domain using conventional kinematic and DFN methods. DFN modelling of the sediment domain requires a slightly different approach to the intrusive domain. Bedding joints do not crosscut each other and so a different modelling approach is required to the purely stochastic generation used for the intrusive domain. In this case, a growth algorithm is used (Libby et al. 2019), which increases the geological realism and reduces the probability of bedding joints crosscutting each other. Figure 8 shows a comparison between a section of photogrammetry interpreted traces of bedding and crosscutting joints and how that is preserved in a section of the DFN model. This is an advantage of the DFN approach where geological reality of the joint system is better preserved, in contrast to conventional kinematic approaches.

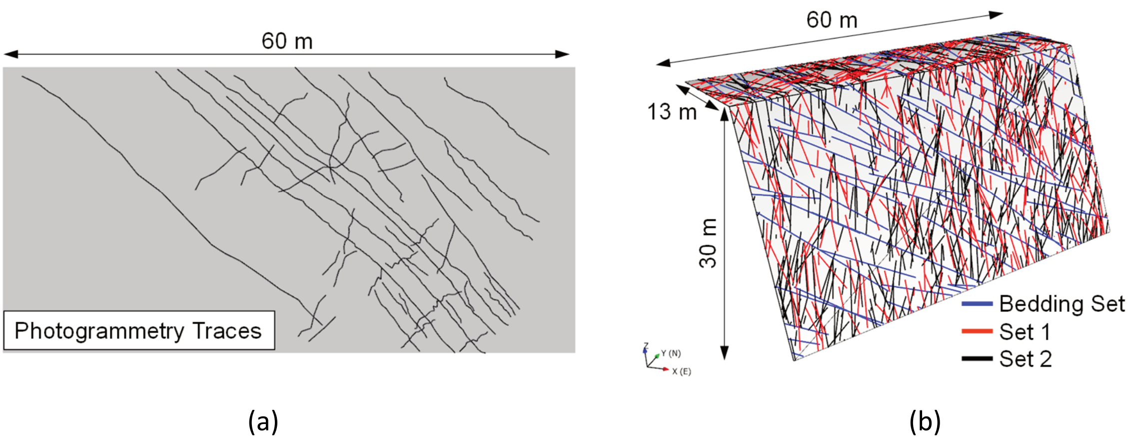


Figure 8 Section of photogrammetry showing (a) how the long bedding joint traces remain broadly parallel and (b) their implementation within the discrete fracture network model

Table 3 shows a comparison between the conventional kinematic and DFN model assumptions and key input parameters used for the sediment domain.

Table 3 Summary of key assumptions and input properties for bench-scale conventional kinematic analyses and discrete fracture network analyses conducted for sediment domain

<table>
<tr><th>Assumptions/properties</th><th>Conventional kinematic analysis</th><th>Discrete fracture network analysis</th></tr>
<tr><td>Bench length</td><td>Infinite length along strike</td><td>180 m explicit length</td></tr>
<tr><td>Bench configuration</td><td colspan="2">Bench face dip direction = 130°
Bench height = 30 m
Catch bench width = 13 m
Bench face angle = 68°</td></tr>
<tr><td>Discontinuity strength</td><td colspan="2">Friction angle = 29°
Cohesionless(1)</td></tr>
<tr><td>Groundwater</td><td colspan="2">Dry conditions</td></tr>
<tr><td>Failure mechanism</td><td>Wedge failure due to intersection between east-dipping set (Set 1) and southwest-dipping set (Set 2)</td><td>Discrete fracture network model evaluates the kinematic stability of the modelled fracture network geometry without a specified mechanism</td></tr>
<tr><td>Fracture orientation(2)</td><td>Set 1 Fisher distribution:
Mean dip = 72°
Mean dip direction = 098°
Fisher constant = 46
Set 2 Fisher distribution:
Mean dip = 64°
Mean dip direction = 209°
Fisher constant = 16</td><td>Set 1 Fisher distribution:
Mean dip = 72°
Mean dip direction = 098°
Fisher constant = 46
Set 2 Fisher distribution:
Mean dip = 64°
Mean dip direction = 209°
Fisher constant = 16
Set 3 (bedding) Fisher distribution:
Mean dip = 30°
Mean dip direction = 043°
Fisher constant = 72</td></tr>
<tr><td>Fracture intensity</td><td>Small spacing (ubiquitous) and large spacing scenarios considered</td><td>Defined with reference to mapped P21(3) intensity of structures, P32(3) = 0.25 m^{-1}</td></tr>
<tr><td>Fracture size(4)</td><td>Persistence for Set 1 and Set 2 defined by lognormal distribution:
Mean = 6 m
Standard deviation = 2 m</td><td>All fractures have lognormal distribution of equivalent radii:
Set 1 and Set 2 lognormal distribution:
Mean = 3 m
Standard deviation = 1 m
Set 3 (bedding) lognormal distribution:
Mean = 8 m
Standard deviation = 6 m</td></tr>
</table>

(1) Cohesionless strengths are assumed in bench-scale analysis to simulate reduction of strength near surface due to blasting.
(2) Only the two critical wedge forming sets for the specified bench geometry are included in the conventional kinematic analysis. In contrast, the DFN analysis can include multiple sets. In this example, a third set (bedding) is included in the DFN analysis to provide a more accurate representation of the structural conditions in the sediment domain.
(3) Measurements of fracture intensity: P21 = length of fracture traces/area of exposure; P32 = total surface area of a fracture/volume of rock.
(4) Persistence has been taken as twice the joint radii to provide a common framework for both approaches. See Table 2 for further details.

Unlike the intrusive domain example discussed in Section 3.1, the sediment domain represents benches excavated several years ago, and the available pit wall scans clearly show a range of different processes that have impacted bench performance, including kinematic instability, time-dependent rock mass degradation, and blast damage (Figure 7). Whilst it is outside the scope of a kinematic analysis to consider both the creation of new fractures and the extension of existing ones during blasting, the explicit definition of blocks within a DFN model does allow us to consider the impact of increased pore pressures (associated with blasting) on the stability of the blocks.

Any increase in pore pressure reduces the stability of the sliding blocks. It was found that the addition of pore pressure up to ~172 kPa (25 psi) increased the failure tonnage. Above this pressure, the remaining blocks were all kinematically locked in (either daylighting 3D blocks held stable by other stable blocks, or non-daylighting wedges) and there was no further increase in failure tonnage. The back-break results have been reported for both with and without this blasting (pore pressure) sensitivity. It is recognised that this is an imperfect solution for capturing the impact of blast damage on bench performance. However, it does provide a method of allowing the simple static kinematic analysis to incorporate an element of blast damage by removing 'loose' blocks, where loose is defined as kinematically removable from the slope. This is an ongoing area of research.

Figure 9a shows cumulative frequency curves of the conventional kinematic back-break predictions for both small and large spacing scenarios compared to actual back-break measurements. The small and large spacing scenarios both produce similar results, and both underpredict back-break compared to the available bench performance data. This underprediction occurs because the discontinuities that have the potential to form simple wedges (from two fracture sets only) are steeply dipping and have limited persistence (less than half a bench height, on average). Therefore, most of the kinematically admissible wedges that form are steep and narrow and result in small back-break. Even when incorporating water pressure into the analyses to simulate the impact of blasting on wedge stability, bench crest loss is still underpredicted (i.e. the back-break distribution increases by less than 0.5 m) in comparison to the bench performance data because the additional wedges that are destabilised remain narrow and result in small back-break.

This underprediction of back-break is also observed in the DFN results for the base case scenario (Figure 9b). However, in contrast to the conventional kinematic method, the DFN analysis incorporates multiple fracture sets (three in this case) that allow multi-faceted blocks of varying sizes and geometries to form. Therefore, the DFN model generates blocks with a wider range of potential back-break distances compared to the simple narrow wedges identified by the conventional kinematic analysis. For this reason, when blasting pressures are considered in the DFN analyses (simulated using an additional pore pressure), all kinematically admissible blocks are mobilised, including larger and wider blocks that result in larger bench crest loss. As shown in Figure 9b, the DFN models considering blasting show close agreement with bench performance data in the sediment domain, with back-break predictions within 1 m of as-built back-break measurements, on average. However, it is clear from field observations that there are other mechanisms influencing bench performance in the sediment domain, notably rock mass degradation, that neither the DFN-based nor conventional methods capture.

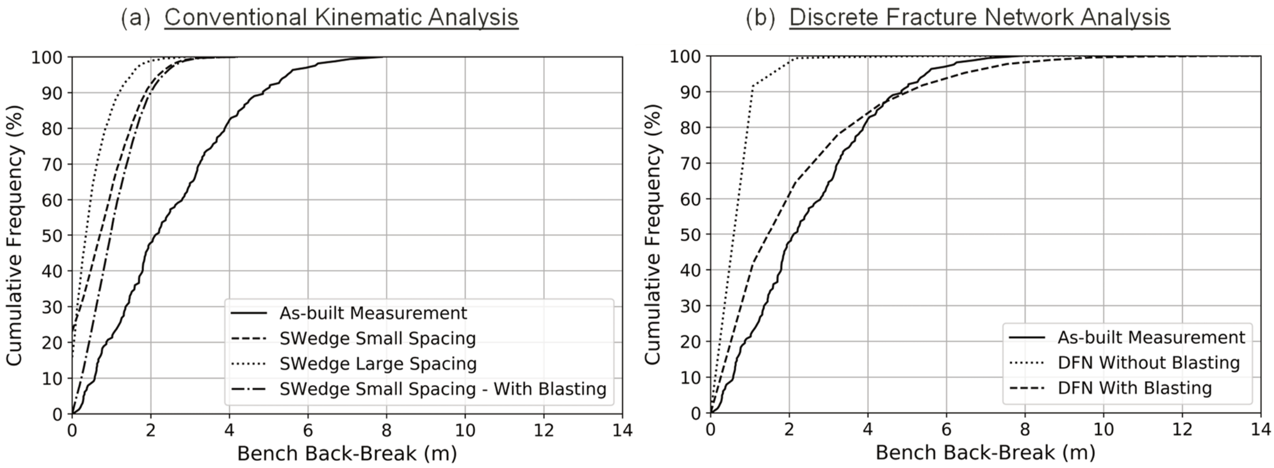


Figure 9 Results of predictive back-break analyses for sediment domain. (a) Comparison between conventional kinematic results (based on 10,000 simulations) and measured back-break; (b) Comparison between discrete fracture network (DFN) results (based on 50 simulations) and measured back-break. The solid black line is the same on both graphs, representing as-built back-break measurements

4 Limitations and ongoing research

The results of the sediment case study presented in Section 3.2 highlight some of the challenges associated with reconciling theoretical to observed back-break in slopes where bench performance has been substantially impacted by processes other than kinematic controls, such as blast damage and rock mass degradation over time. Other recognised limitations of the conventional kinematic and DFN methods presented in this paper, as well as key areas of ongoing research, are discussed below.

- The two case studies discussed assume constant discontinuity strength properties, as the primary focus of this initial project phase is to evaluate the spatial uncertainty and variability in the fracture network (i.e. variation in fracture orientation, persistence, and spacing parameters). However, discontinuity shear strength is also a key input to kinematic models, and whenever possible, the preferred approach is to develop probabilistic distributions of discontinuity strength from direct shear testing data. Both the conventional kinematic and DFN methods presented in this paper allow discontinuity strength to be represented as a probabilistic distribution.
- It is recognised that all kinematic approaches will struggle to account for rock mass processes such as weathering and degradation and their impact on slope performance, in particular back-break. It is likely that site-specific correction factors will need to be developed based upon the structural condition of the rock mass, the intact properties, and its susceptibility to time-dependent degradation.
- The approach described within this paper to account for blast damage by removing kinematically stable blocks is a pragmatic attempt to capture a complex mechanism through a simple process. It is hoped that in the future, a more robust solution can be developed that more accurately captures the impact of fracture generation and extension associated with blasting. In addition, future studies will attempt to quantify the increase in back-break resulting from blasting and other mining processes based on observations from high-resolution pit wall scans.
- The analyses described here build on the high-quality structural data that are acquired using modern photogrammetry systems, particularly the length scale of structures. Of course, if the technique were applied to a greenfield site with only borehole data and no length scale, it would be difficult to apply these approaches with confidence. However, with increasing usage and the collection and analysis of fracture size data, analogue information on fracture size will be able to

supplement borehole data to provide a reasonable assessment of bench stability, bracketing upper and lower bound cases.

- Current DFN and conventional kinematic methods provide a single stage of stability analysis, identifying blocks that are unstable. In practice, there are often additional blocks present behind unstable blocks, whose stability ought to be evaluated in a more recursive way as the lead blocks are removed. This approach is currently being piloted.
- The DFN block identification technology employed currently requires that fractures intersect to fully define a closed surface. In practice, small gaps between fractures may not alter the way in which a volume of rock behaves. Further development of the existing block identification algorithm is ongoing to allow identification of closed block surfaces even when there are small gaps between the fractures forming the block.

5 Conclusion

The discussion of conventional and DFN-based approaches to bench-scale stability analysis presented in this paper illustrates key differences between the methods in terms of the probability of unstable block formation and the expected back-break. DFN models permit 3D block geometries to be explicitly defined from fracture networks that are more representative of structural conditions than the combinatorial approach (limited to one to two sets) used in conventional kinematic analyses. Furthermore, advancements in computational efficiency now enable more rigorous approaches to bench design, such as the DFN-based methods, with the goal being increased reliability in design.

A comparison between the DFN-based approach, conventional kinematic analysis, and actual bench performance at the Bingham Canyon Mine was presented through two case studies: one slope governed by potential planar instability in an intrusive domain, and a second where potential wedge failure was identified as the controlling mechanism in a sediment domain. In the intrusive domain, the results of the conventional kinematic analyses significantly overpredicted back-break compared to the bench performance data, whereas the DFN-based approach produced results that were broadly consistent with measured back-break.

In the sediment domain, both the conventional kinematic and DFN-based methods underpredicted back-break compared to observed slope performance. These results illustrate some of the challenges associated with reconciling theoretical to observed back-break in slopes where bench performance is controlled by processes other than kinematic instability, such as blast damage and rock mass degradation, particularly in slopes that have been exposed for several years. A simple approach was presented to simulate the impact of mining operations on block stability and back-break. However, this is an ongoing area of research and it is recognised that a more robust solution is needed to adequately capture the impact of these complex processes on bench performance.

Whilst the advantages of DFN-based bench stability analysis are not yet fully compelling, the work presented in this paper has shown that DFN methods do show much promise, especially in their ability to capture greater reality and therefore represent a wider range of mechanisms within a single model. Future studies will consider assessing a broader range of pit slope configurations and geological settings to provide further validation of the approach, as well as the recursive evaluation of stability by removing unstable blocks and recomputing the block Factor of Safety. Future work is also intended to provide guidance on whether blasting pressures (or some other proxy) should be considered for bench design based upon size and shape of wedge formation. Comparison between the results of both conventional kinematic and DFN-based analyses to actual bench performance observed at the Bingham Canyon Mine indicates that the DFN approach can provide an improved basis for pit slope design by producing results that are more structurally representative of field conditions.

Acknowledgement

The authors acknowledge Rio Tinto, Rio Tinto Kennecott, and their employees for their support, collaboration, and permission to share the results of this work as a case study from which other practitioners in the field of rock mechanics and slope stability may learn.

Appendix: method validation

A simple benchmarking test was performed between conventional kinematic analysis using RocPlane (Rocscience 2021a) and DFN-based analysis using FracMan (Golder Associates Inc. 2021) to exhibit their equivalence for planar failure mechanisms. Rogers et al. (2020) demonstrated similar benchmark testing of FracMan and SWedge for wedge shaped failure mechanisms.

The conventional kinematic analyses consisted of sampling on 1,000 trials using the Latin Hypercube method for each 15 m vertical bench (bench face angle of 90°). The bench length and bench width were varied from infinite to finite (width from 1,200 m to 12 m, bench length from 6,000 m to 60 m) in the test. Mohr–Coulomb properties with cohesion ranging from 0–35 kPa and a constant friction angle of 28° were used. Planar features were generated from a normal distribution with a mean apparent dip of 37° and standard deviation of 7°. The orientations of all 1,000 planar blocks for each scenario were exported from RocPlane and imported into FracMan for recreation of the block geometries.

The Factor of Safety (FOS), probability of failure, and back-break metrics from the two tools were evaluated and compared, with excellent agreement (ignoring minor numerical rounding issues) for all scenarios. The FOS and back-break comparison for the infinite bench width/length scenario is exhibited in Figure A1 as an example. For planar mechanisms, the two methods of back-break calculation in the DFN analysis discussed in Section 2.2 (apex and slicing methods) produce identical cumulative distribution functions (as the slicing method for planar wedges that are aligned with the slope dip direction produces multiple measurements, equal to the single apex value measurement).

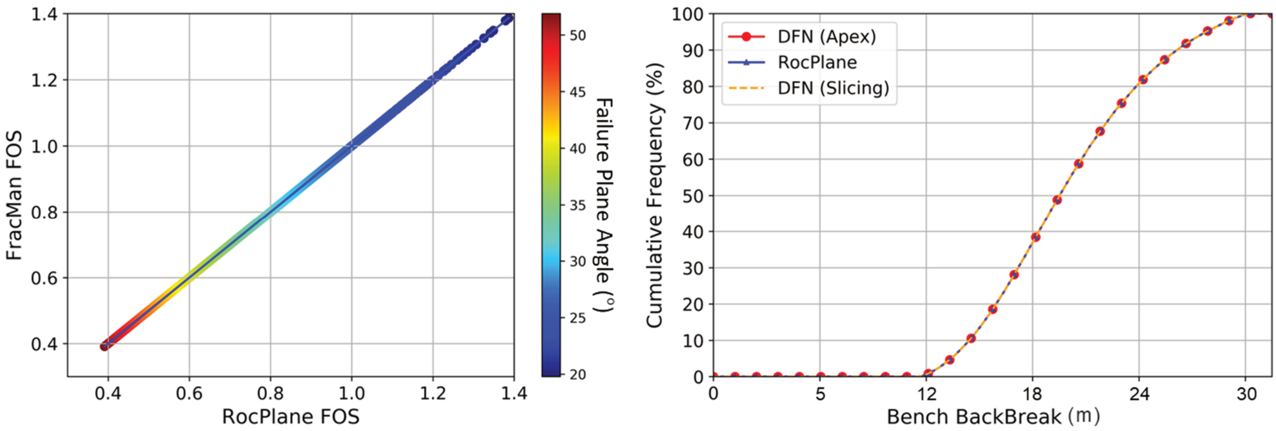


Figure A1 Comparison of results from FracMan and RocPlane for the infinite bench width and infinite bench length scenario. (a) FracMan FOS versus RocPlane FOS, coloured by failure plane dip; (b) Cumulative density function of back-break from RocPlane and FracMan (apex and slicing method measurement)

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