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Probabilistic three-dimensional kinematic analysis to improve design reliability of complex underground excavations

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Abstract

Conventional approaches to evaluate the stability of wedges in underground excavations include identification of dominant joint sets and deterministic stability checks on possible wedge geometries for a simplified excavation profile. However, these conventional approaches tend to produce extremely conservative results or require several assumptions as well as engineering judgement to filter and scale the wedges to achieve reasonable wedge sizes and shapes. Further, when the excavation geometry is complex, many different kinematic models need to be constructed to capture individual geometries.

An improved approach to assess kinematic stability in complex underground excavations has been developed using a discrete fracture network (DFN)-based method. The DFN method has a number of advantages over conventional kinematics; importantly, the fabric orientation pattern is applied fully without restriction, allowing more complex structural patterns to be evaluated including both deterministic structures as well as stochastically generated ones; and complex three-dimensional (3D) excavation and blocks shapes can be considered in a single analysis. Multiple realisations of the excavation-scale DFN can be generated to simulate block formation around the whole excavation surface, with unstable blocks being identified from each iteration. Then, the blocks are used to generate heatmaps of the probability of unstable block occurrence, volume, apex height and required support pressure to make the blocks stable along the excavation surface. Once the analysis has been conducted, a design wedge can be established for each key excavation surface which can be carried over to ground support design.

An example of the improved method is presented for an underground crusher complex which has complex excavation geometry and areas of concerns (e.g. multiple mine levels, large brows, and large spans). The example shows the significant advancement in the probabilistic assessment of 3D kinematics, including improved visualisation of kinematic stability checks, less arbitrary engineering judgement, and a single model that can capture complex geometries.

Keywords: *discrete fracture network, underground excavation, kinematics, risk assessment*

1 Introduction

As near-surface and high-grade ore deposits are diminishing, mines are pushing deeper and targeting lower-grade orebodies with high-tonnage mining methods. These deep and high-tonnage mines require an enormous network of tunnels, chambers, ore passes, and ventilation raises that are excavated in a wide range of rock mass conditions. The spans of individual chambers can be large, and complex three-dimensional (3D) geometries are inevitable as multiple mining levels and excavation profiles intersect, increasing the potential for kinematic instability. Simultaneously, advances in structural mapping technologies are enabling rapid collection of high-quality structural data for engineering design. However, the commonly applied conventional approaches for assessing kinematic stability are insufficient for challenging 3D geometries and do not maximise value from the high-quality structural data.

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Conventional approaches to evaluate the stability of wedges in underground excavations typically include the identification of dominant joint sets and deterministic stability checks on possible wedge geometries, typically for a simplified excavation profile. However, these conventional approaches tend to produce extremely conservative results or require several assumptions as well as engineering judgement to filter and scale the wedges to achieve reasonable wedge sizes and shapes. Further, when the excavation geometry is complex, many different simplified kinematic models need to be constructed.

There are several issues with this conventional approach. Firstly, our ability to characterise the rock mass structure has improved immeasurably since the advent of basic kinematic tools. With high-resolution geophysics, borehole televiewers, optical borehole cameras, high-resolution photography, laser scanning, and satellite imagery coupled with modern image processing techniques and photogrammetry, our ability to accurately describe rock mass fabric has dramatically improved (Rogers et al. 2006). These varied data acquisition tools help us derive information about the geometry of important structures and key fracture properties such as fracture lengths, orientations, and intensities. With this improved data collection, it also became more apparent that the distribution of fractures in the rock mass often shows considerable spatial variability. Thus, applying a simple fabric model to the kinematic analysis may be reasonable for a small drift section but may be quite inappropriate for a large excavation like a crusher chamber where variations in orientation pattern, intensities, and the presence of large major structures changes the local geometry considerably.

Analysis of wedge stability in underground excavation typically uses the same basic approach (Goodman & Shi 1985) with a range of primary key-block algorithms available (e.g. Einstein Gynn 1979; Carvalho et al. 1991; Warburton 1987). The basic algorithm is straightforward and found in a number of software packages, each with their own advantages and limitations. One of the limitations of some of these packages is that wedges must be formed by discrete planes, each of which is considered ubiquitous and infinitely continuous. This typically doesn't consider more complex block geometries (many approaches are limited to consideration of only three planes), variable, non-infinite fracture lengths, the influence of rock bridges, or the scatter in the actual field fracture orientations. The consequence of some of these limitations is that the analyses can become somewhat subjective as the user is forced to use engineering judgement to 'filter' out improbable structures and determine pole 'centres' for the joint sets that will form the wedges. While data reduction and conceptualisation are a routine part of any analysis, the question remains whether more field data can be used in a more objective way with fewer assumptions to better characterise and analyse the kinematic stability of our often-complex excavations? This paper describes how DFN models can be analysed and how the results processed to allow for a new way of considering complex excavation kinematics and a more data driven and probabilistic design process. An example of an underground crusher complex, which has complex excavation geometry and areas of concerns, is presented, but the approach is applicable to any underground geometry.

2 Discrete fracture network methodology

2.1 Background

The discrete fracture network (DFN) approach is a modelling method that seeks to explicitly describe the rock mass fracture system through a combination of deterministic wireframed structures and stochastically generated objects by building a series of discrete fracture objects based upon field observations of fracture properties such as size, orientation, and intensity (Rogers et al. 2009). Their ability to represent the known structural system and to extrapolate to the inferred structural system provides a useful method for describing the rock mass in and around an excavation. As the structural uncertainty in mine excavations is relatively high at the design stage, the probabilistic nature of the DFN approach allows a large number of equi-probable realisations to be generated and analysed and the likelihood of a particular outcome determined. Importantly, DFN analysis and modelling provides a clear and reproducible route, from site investigation data to modelling, with more realistic fracture parameters (e.g. a full orientation description rather than mean set orientations, actual joint intensities and estimated joint radii, etc.) being maintained through the modelling process with limited approximation and judgement. The actual methodologies by which the DFN modelling inputs are obtained from site investigation are detailed elsewhere, e.g. Sewnun et al. (2022) and Byrne et al. (2023).

The rest of this section describes how a DFN model was created and analysed for a crusher complex for a large caving operation. The crusher comprises five chambers on three levels and is approximately 170 m from one end to the other. The crusher geometry is complex with several tall brows, a hanging pillar, and a sill pillar of approximately 10 m in thickness.

2.2 Model construction and parametrisation

The objective of this model build is to develop the combined deterministic and stochastic inputs for a DFN description of critical structures for the whole excavation. For this example, the stochastic DFNs were generated per Table 1. Figure 1a presents an oblique view with the location of the deterministic faults (wireframes), while Figure 1b presents a stereonet of the orientation data used.

Table 1 Discrete fracture network input properties

Input parameter	Notes
Intensity	A total fracture volumetric intensity (P_{32}) of 1 m^{-1} was considered (0.33 m^{-1} for Set 1 and 2 and 0.34 m^{-1} for Set 3). Intensity was then adjusted by size truncation.
Orientation	Three sets were defined using Fisher distributions (Figure 1b): Set 1: trend 5°, plunge 30°, K = 10 Set 2: trend 270°, plunge 40°, K = 15 Set 3: trend 120°, plunge 15°, K = 12
Size	A power law distribution with a trend of 2.0 was used for generating the DFN features. Fracture minimum and maximum were truncated to 5 and 100 m, respectively.

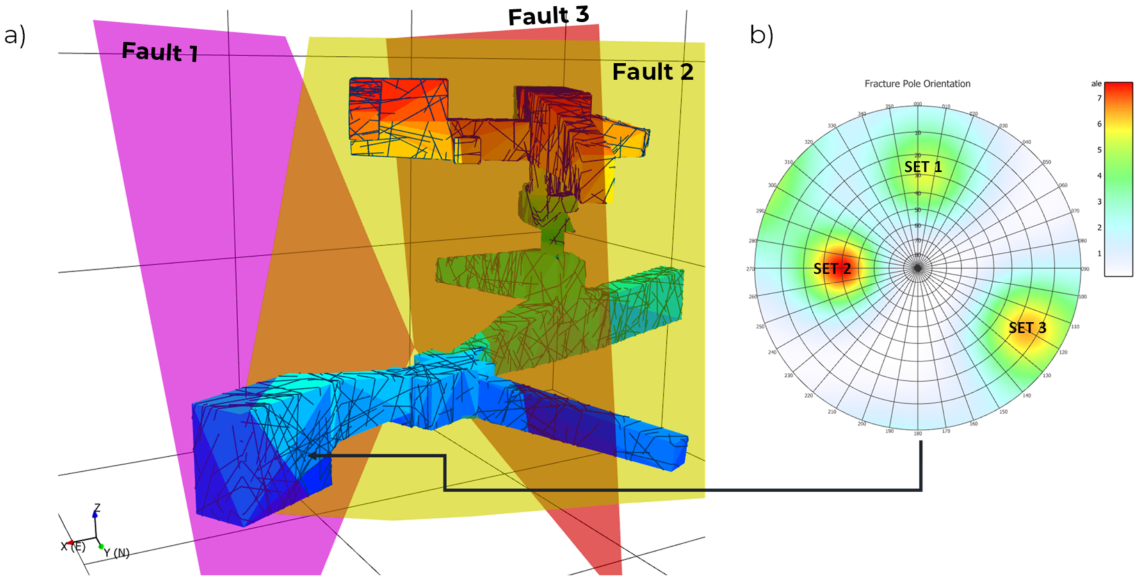

Figure 1 a) View of the crusher excavation, showing the three major deterministic faults and the traces from one realisation of the stochastic fabric generated from b) the stereonet of structures

The structural data in this example are defined by Fisher distributions of three main sets obtained from borehole data (Figure 1b). Orientation data for underground excavations are often limited and clear structural sets can be difficult to identify. If structural sets cannot be identified because the data are too dispersed, bootstrapping can be used as an input for the DFN which allows the available discrete structural measurements to be incorporated into the DFN. Bootstrapping is a statistical method based upon multiple random sampling with replacement from an original sample to create a pseudo-replicate sample of fracture orientations. A degree of 'noise' is introduced to each sample to ensure that the pseudo-sample is slightly different in order that multiple realisations will result in a similar but not unique orientation model (Rogers et al. 2006).

Once the DFN model was built, the structural fabric was searched in FracMan® (WSP 2023) to identify 3D kinematic rock blocks that formed behind the excavation surface. For the discontinuities, uniform Coulomb strength properties were considered (cohesionless and a friction angle of 30°).

2.3 Discrete fracture network kinematic approach

The first stage of the stability analysis is the identification of 3D rock blocks in the DFN models within the model volume. The algorithm triangulates the fractures within the volume, groups together polyhedron blocks, and then identifies the blocks connected to the excavation surface. The stability analysis for the DFN defined rock blocks is functionally identical to the conventional wedge analysis. The fundamental difference is that the analysis is carried out on actual defined 3D blocks for a specific realisation of the fracture geometry rather than the simple combinatorial approach of infinite fractures used in conventional kinematic analysis.

The stability analysis identifies whether the blocks are:

1. locked in (i.e. unconditionally stable)
2. conditionally stable/unstable
3. free falling.

The Factor of Safety (FoS) is calculated based on limit equilibrium assumptions, with stability being defined by either a Coulomb or Barton–Bandis model. A view of four equi-probable realisations of the identified unstable blocks formed around the excavation is shown in Figure 2.

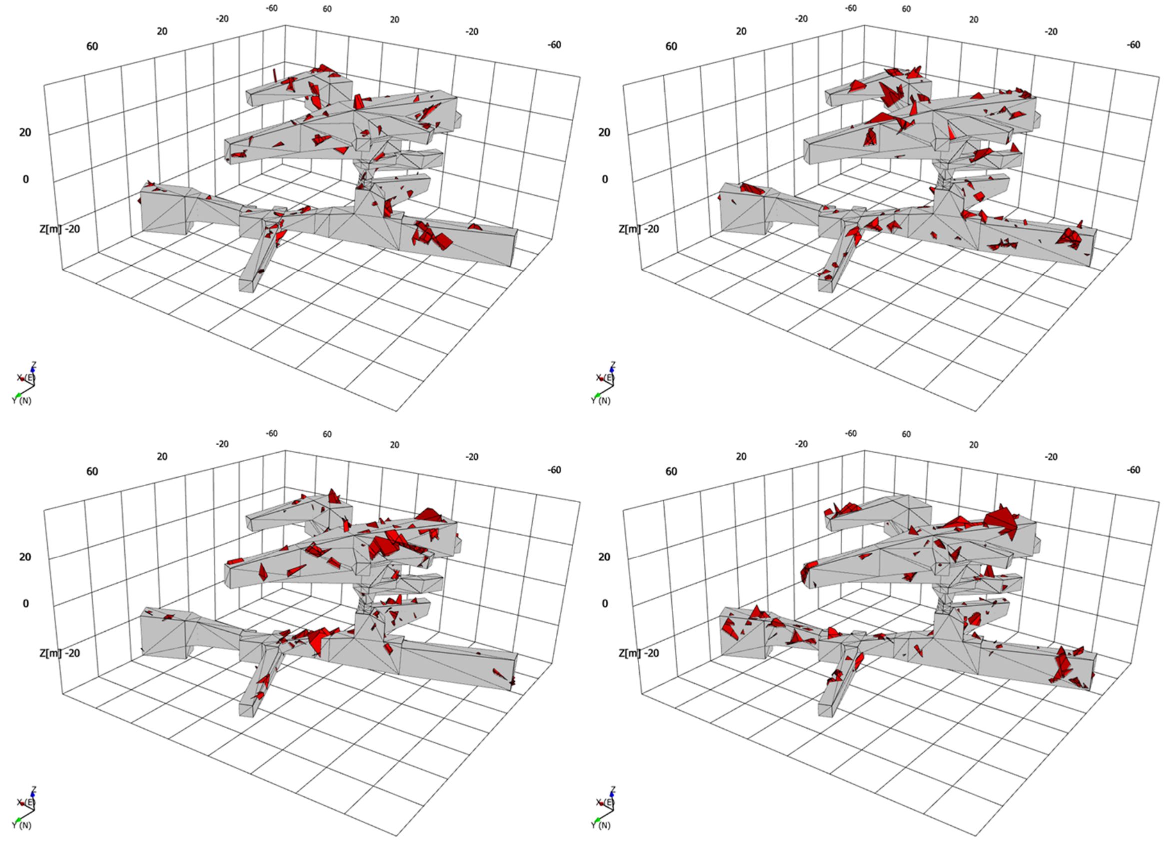

Figure 2 Oblique views from the northwest presenting unstable blocks only from four equi-probable realisations

2.4 Mapping multi-realisation results

When running multiple realisations of a kinematic search of a stochastic model on a complex geometry, presenting the result of large number of realisations is challenging. To get around this, a technique has been developed to map the results of a large number of realisations into a grid around the excavation (Figure 3), allowing the visualisation of consolidated results from all of the realisations. This allows the following spatially defined questions to be asked about the development of blocks around the excavation:

- Where are blocks forming and where are instabilities most likely to occur around the excavation surface?
- What is the local Probability of Failure (PoF), in this case referred to as block failure percentage (BF%)?
- Locally, what is a representative block apex height, volume, and required support pressure to make the blocks stable? These parameters can be used to define support requirements, including tensile strength, spacing, and length.

To answer those questions, a number of grid calculations are made based upon the kinematic excavation-scale model:

- Block probability of occurrence (POBO) is used to assess the likelihood of all fully formed blocks occurring at a certain location on the simulated excavation (calculated in a grid with cells of 1 m per side intersecting the excavation surface; Figure 3). This can indicate zones of increased block formation across the excavation that, combined with unfavorable geotechnical, structural, or pore pressure conditions, may lead to instabilities.

The definition of POBO per cell is:

$$POBO = \frac{Number\ of\ realizations\ that\ form\ blocks\ intersecting\ the\ grid\ cell}{N} \times 100\% \tag{1}$$

where N is the number of realisations (N=100 for this example).

- A proxy measure for PoF or BF% is used to identify areas of the excavation with a high propensity for unstable block formation. BF% represents the number of blocks that fail (i.e. the number of blocks with FoS <1.0) divided by the total number of blocks within a defined cell.

  The definition of BF% per cell is:

$$BF\% = \frac{Number\ of\ blocks\ with\ FOS{<}1\ intersecting\ the\ grid\ cell}{Total\ number\ of\ blocks\ intersecting\ the\ grid\ cell} \times 100\% \tag{2}$$

- Block volume, apex height, and required support pressure to make the blocks stable were calculated per cell as the maximum block value that intersects a particular grid cell per realisation. The statistical distribution of these values can be used to design support, including the required minimum bolt capacity, maximum bolt spacing, and bolt length.

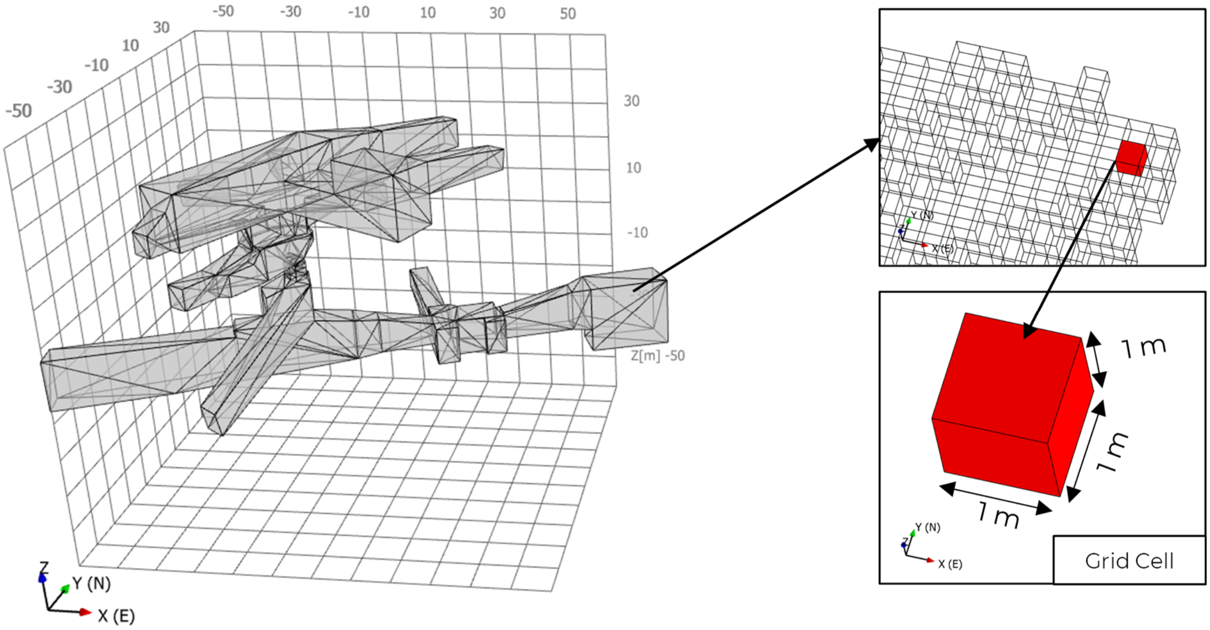

Figure 3 Discretisation of the excavation surface in 1 m per side cells

Once these metrics (POBO, BF%, or block geometries) have been calculated in the grid, they can be mapped onto the excavation surface and visualised as heat maps, providing a valuable map of the spatial variation of these critical properties. Examples of the heat maps are shown in Figures 4, 5, 6, and 7.

Figure 4 presents a heat map of the POBO results. The role of the three major faults in encouraging block formation at their intersection with the excavation is clearly shown. The heat map of BF% is shown in Figure 5. This model shows elevated BF% on the back and west wall of the excavation, as well as on the overhanging brows where tunnels intersect larger chambers and on excavation corners.

Figure 6 presents the 95th percentile (P95) of apex length, while Figure 7 presents the P95 of block volume for unstable blocks. These results can be used to directly define minimum support length requirements. Note that since the apex length represents the maximum perpendicular distance from the excavation surface to the wedge free face, this is the length that should be considered when defining the length of bolts. This length is different to the actual apex height of a wedge that describes the maximum length from the excavation to the furthest point of the wedge.

Figures 8 and 9 present the maximum and P95 support pressure required to make the unstable blocks stable. The required support pressure is calculated per block and corresponds to the pressure applied to the excavation surface that is necessary to achieve a design acceptable criteria (DAC) FoS. For the purpose of this exercise, an FoS of 1.0 was used as DAC, however, the required support pressure can be calculated to achieve different DACs. Based on the tensile strength of the support elements and the tributary area, this information can be used as a staring point to define bolt or cable spacing. Note that this methodology does not take into consideration the effective support capacity due to the actual portion of the support element anchored behind the rock block. It is recommended that the final support design is validated using models that explicitly include the bolts.

Since all the information is stored in a grid, it is easy to generate reports including cumulative frequency charts for different areas of interest or parts of the excavation, providing information to help engineers make informed decisions on support requirements.

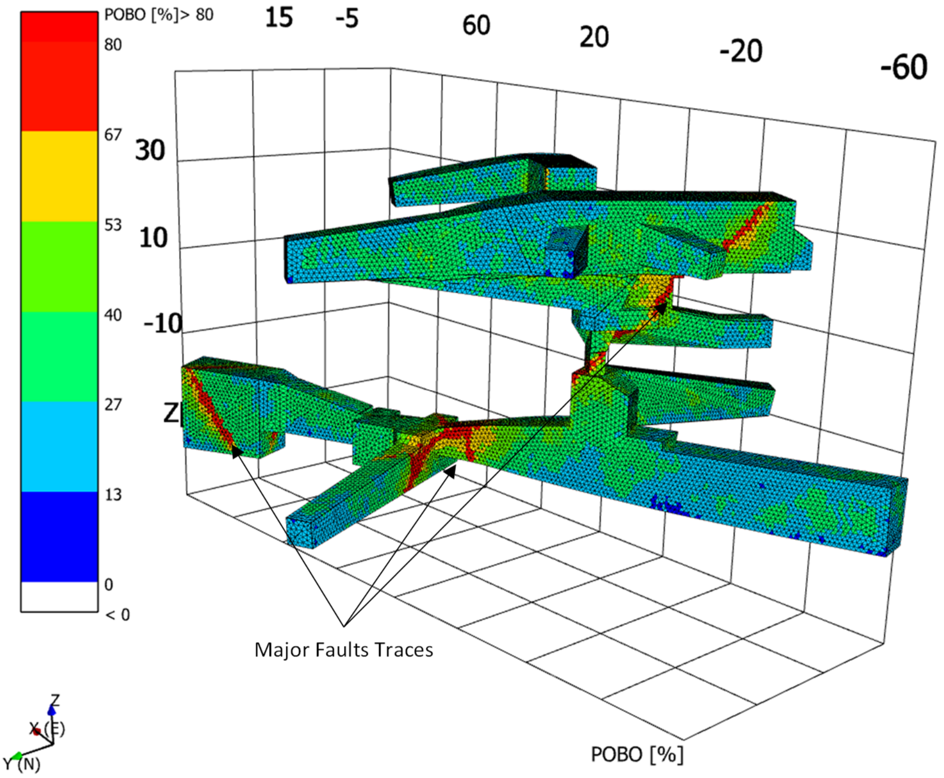

Figure 4 Oblique view from the northwest presenting the block probability of occurrence (POBO)

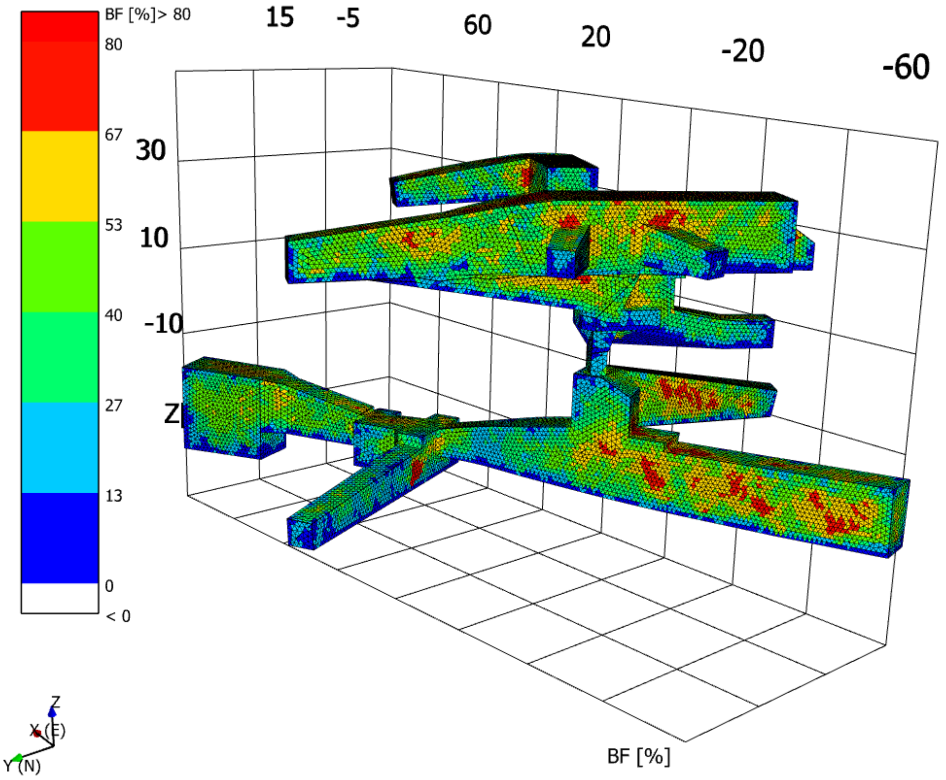

Figure 5 Oblique view from the northwest presenting the block failure percentage (BF%)

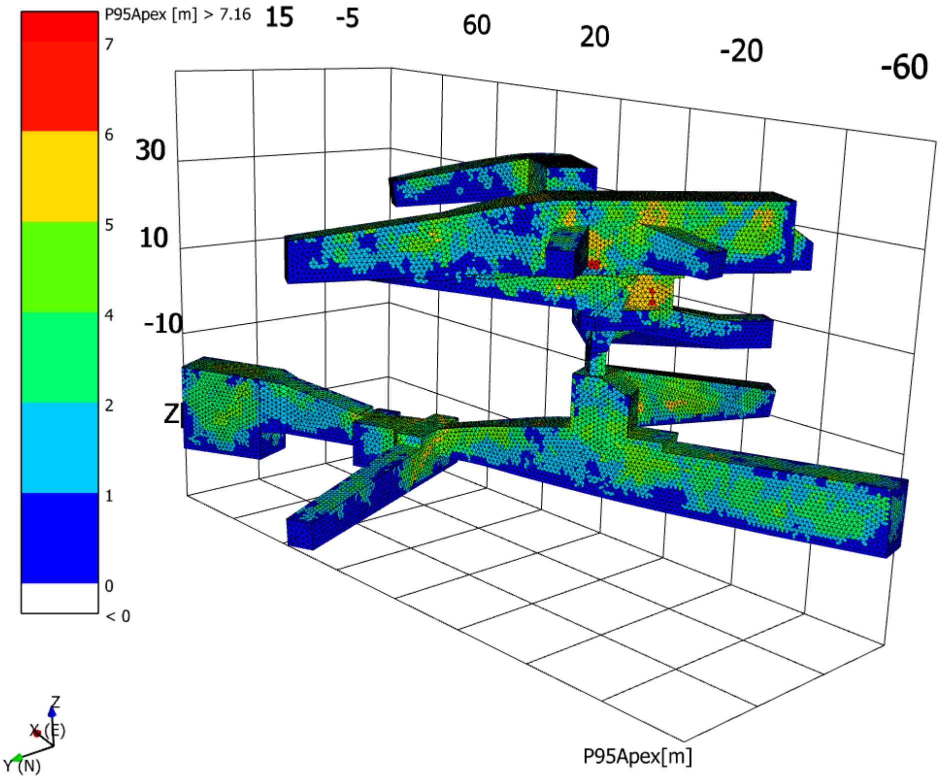

Figure 6 Oblique view from the northwest presenting the 95th percentile (P95) of apex length of unstable blocks

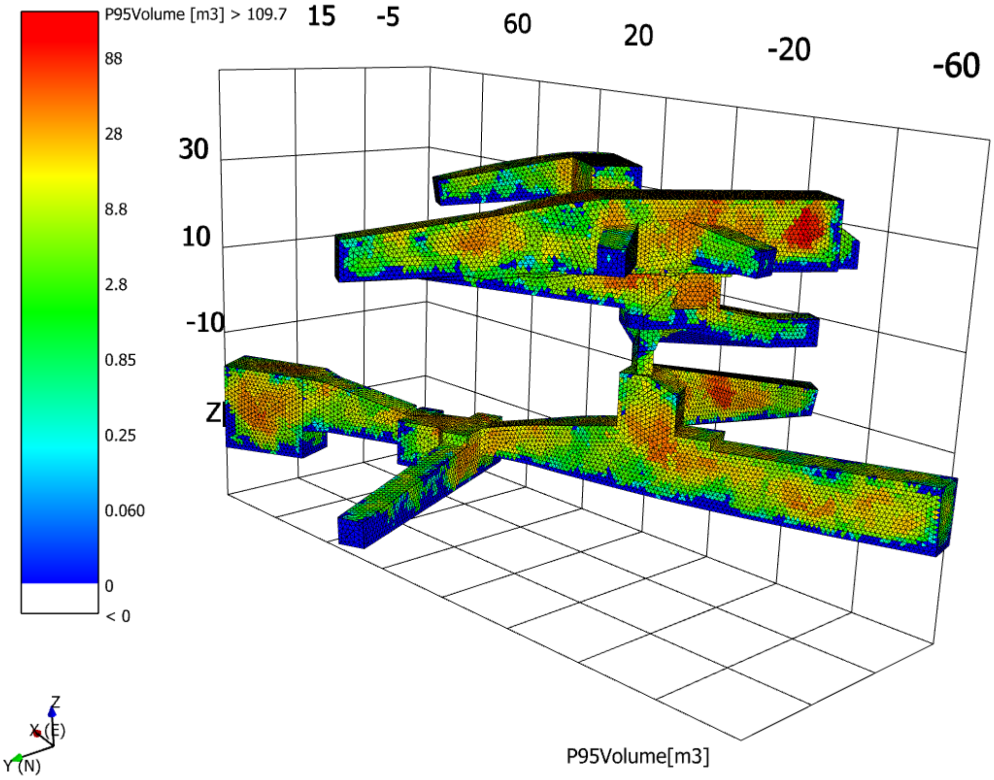

Figure 7 Oblique view from the northwest presenting the 95th percentile (P95) of unstable block volume

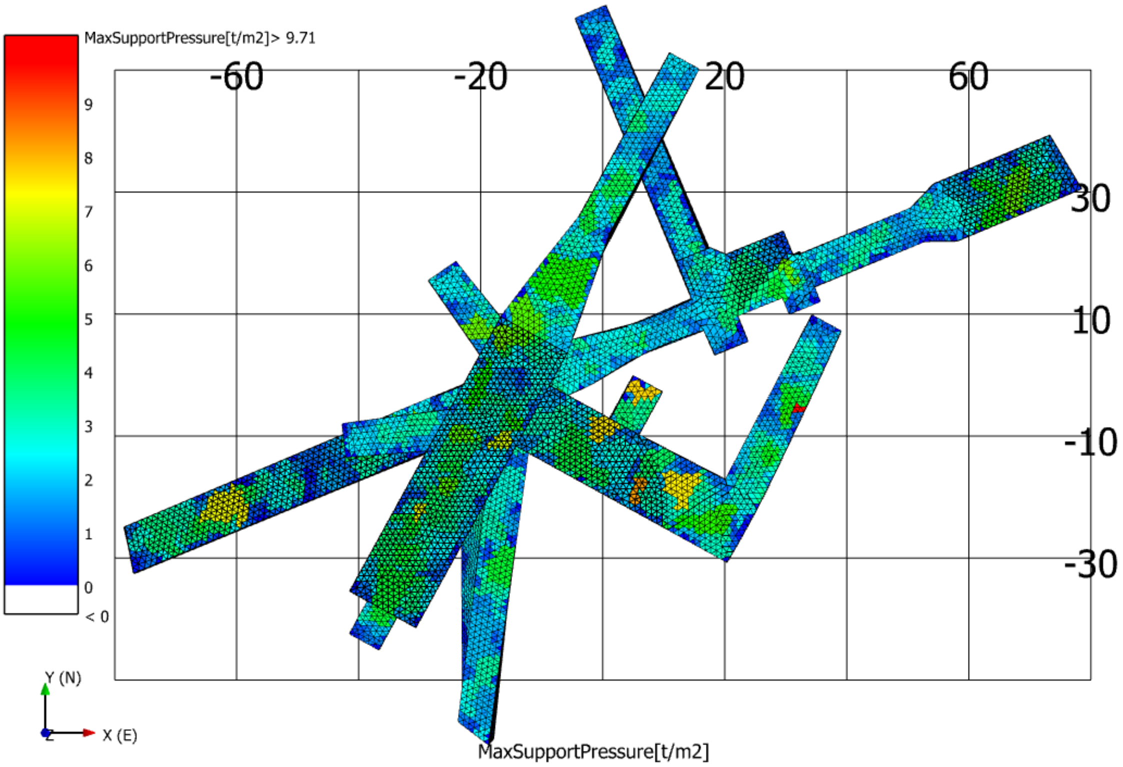

Figure 8 Plan view presenting the maximum support pressure required to stabilise the blocks

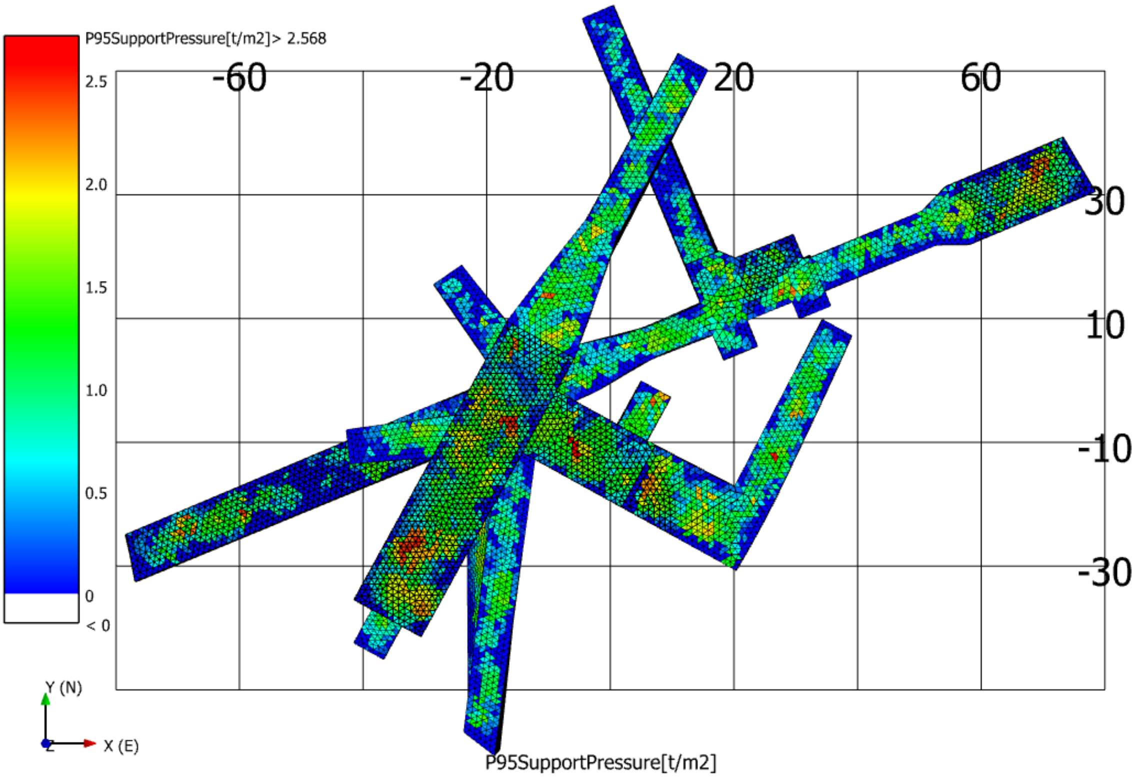

Figure 9 Plan view presenting the 95th percentile (P95) of required support pressure to stabilise the blocks intersecting a particular grid cell

3 Discussion

One of the advantages of the DFN approach over conventional methods is that it uses a more accurate representation of the 3D fracture and fault network geometry. Historically, one of the main arguments against the use of discrete fracture modelling methods was the lack of accurate data describing the fracture geometry and its physical properties. Over the last decade or more, there have been tremendous improvements in our ability to define the geometric properties of the fracture network. Much of the data required to derive the DFN inputs are now acquired as part of a standard geotechnical site investigation executed for even moderate-sized mining projects. The use of borehole televiewer systems, laser scanning systems, and advanced photogrammetry techniques are burgeoning within the mining industry. These techniques provide a rapid way for mapping drift faces and ribs and, when coupled with image processing tools, provide the necessary input to DFN modelling, namely the distribution of fracture orientation, fracture length, and fracture intensity. There is some pre-processing of the data required but in general, the approach is not significantly more difficult than the more conventional approach and any additional time and cost is easily outweighed by the benefit. When combined with standard geotechnical mapping and core logging to assess the engineering parameters (e.g. strength) of the discontinuities, the DFN approach becomes a powerful design tool.

Another key benefit of the DFN approach is the ability to handle the results in a more probabilistic way for use in design studies. For example, it may be overly conservative in some cases to design for the largest wedge if it represents the 99th percentile of wedge size and/or is predicted to occur only once or twice in tens of kilometres of mine development. Similarly, for preliminary design of ground support for large underground openings, support requirements may be developed for a lower threshold (e.g. 95th percentile wedge size and/or weight), not for the maximum possible wedge. This probabilistic approach using measured fracture size and orientation data effectively allows the engineer to apply an appropriate level of conservatism to the design application. The analysis also allows the engineer to optimise bolt sizes, lengths, and spacing to provide the most effective support system to meet a given design criteria.

The presence of 'rock bridges' or zones of intact rock between planes that would otherwise form a completed wedge may be considered in the DFN method. Wedges are not predicted to form if rock bridges exist along the fracture path that would otherwise define a wedge. However, a model may be run multiple times, progressively increasing the fracture lengths and creating a greater number of wedges or blocks. This allows the user to evaluate the sensitivity of the model results to variations in fracture size and associated rock bridge, designing slope angles and/or support accordingly.

Ultimately the potential of the DFN approach is its ability to more accurately characterise and model the fracture system and its impact upon the stability of even complex excavations developed within that rock mass. With the DFN approach first considering the probability of block occurrence (largely ignored by combinatorial kinematic analysis) and then evaluating the identified block's FoS, we consider tunnel designs developed using the DFN approach to be more reliable. Greater realism in modelling allows a closer agreement with actual performance. This applies to the evaluation of larger excavations and long sections of tunnels where the approach has the ability to evaluate a large number of potential blocks formed by the structural network. For the evaluation of a single potential wedge at a specific excavation location, there is less advantage as conventional and DFN kinematics are both effectively applying the same deterministic analysis, with the probability of block occurrence already established at 100%. However, for these complex, large excavations, the DFN modelling approach, coupled with the ability to handle the analysis probabilistically, provides a more intelligent way of handling risk.

4 Conclusion

This paper has described the extension of conventional wedge stability analysis techniques for underground excavations using DFN methods. The example shows the significant advancement in the probabilistic assessment of 3D kinematics, including improved visualisation of kinematic stability checks, less arbitrary engineering judgement, and a single model than can capture complex geometries. The DFN method provides the following advantages over conventional kinematic approaches (Rogers et al. 2006):

- Fractures are modelled with defined size and shape, rather than being assumed to be infinite.
- Fractures can include a combination of deterministic features identified during site characterisation and features simulated from geological and statistical inference.
- Fractures can include both planar and non-planar structures.
- Fracture persistence and rock bridge failure can be modelled explicitly.
- Multiple realisations of the DFN provide a probability distribution function for unstable wedge development for a given excavation geometry.

By more realistically modelling the geometry and properties of the structural features that control the stability of the rock mass, the DFN wedge analysis has the potential to produce safer tunnel designs and optimised support requirements for underground excavations.

Evaluating kinematic tunnel stability remains a critical task in underground operations. As the industry increasingly moves to a risk-based approach, there is a continuing need for more accurate rock mass characterisation that feeds directly into the ultimate assessment approach. Probabilistic DFN based kinematics is one such approach.

References

Byrne, C, Zorzi, L & Rogers, S 2023, ‘Structural data collection as a key input for discrete fracture network analysis’, in PM Dight (ed.), *SSIM 2023: Third International Slope Stability in Mining Conference*, Australian Centre for Geomechanics, Perth, pp. 399–408, https://doi.org/10.36487/ACG_repo/2335_24

Carvalho, J, Hoek, E & Lee, B 1991, *UnWedge: Underground Wedge Analysis*, Department of Civil Engineering, University of Toronto, Toronto.

Einstein, H & Glynn, E 1979, ‘Probability of kinematic instability in rock slopes: a numerical approach’, *Proceedings of the 20th US Symposium on Rock Mechanics*, ASCE, New York, pp. 317–325.

Goodman, R, & Shi, G 1985, *Block Theory and Its Application to Rock Engineering*, Prentice Hall, New York.

Rogers, S, Chorley, D, Pesendorfer, M, Zawadski, W & Greer, S 2009, ‘Hydrogeological characterisation & conceptual DFN flow modelling of slope pressures within the Diavik diamond mine, NWT’, in *Proceedings of the International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering*, Santiago.

Rogers, S, Moffitt, K & Kennard, D 2006, ‘Probabilistic slope and tunnel block stability analysis using realistic fracture network models’, *Golden Rocks 2006, The 41st U.S. Symposium on Rock Mechanics*, US Rock Mechanics Association, Golden.

Sewnun, D, Wesseloo, J & Heinsen Egan, M 2022, ‘A review of structural data collection methodologies for discrete fracture network generation’, in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 1047–1060.

Warburton, PM 1987, ‘Implications of keystone action for rock bolt support and block theory’, *International Journal of Rock Mechanics, Mining Science, and Geomechanics Abstracts*, vol. 24, pp. 283–290.

WSP 2023, *FracMan*, version 8.1, computer software, FracMan Technology Group, Montreal, https://www.wsp.com/en-us/services/fracman/