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Probabilistic versus deterministic wedge formation methods

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Abstract

The stability assessment of rock blocks/wedges in the underground environment is a critical design process in the prevention of uncontrolled failures. Traditionally a deterministic 'worst-case scenario' wedge analysis method is adopted which results in overly conservative ground support designs.

Advances in data collection, computational hardware and software design tools allow probabilistic analytical methods, which capture the natural variability of the structural environment, to be routinely used in ground support design workflows that are undertaken on site. This shift allows for the potential to optimise ground support designs, with improved safety, cost and efficiency outcomes.

To highlight the benefits of a probabilistic approach, this paper presents a comparative study of the 2 methodologies, utilising a commercially available wedge analysis tool and the mXrap Discrete Fracture Network (DFN) generator and DFN Block Analyser. Using the same input parameters, the study compared wedge size, weight and orientation and Factor of Safety (FoS). Additionally, the study evaluated the difference in ground support requirements between the methods required to achieve a predetermined FoS.

The work highlights the advantages of probabilistic approaches in producing designs that balance safety and economy, while reducing the reliance on 'worst-case' assumptions. This comparison addresses a critical gap in the practical adoption of probabilistic methods in underground kinematic wedge analysis, offering a pathway to more reliable and economically sustainable ground support strategies.

Keywords: *kinematics, probabilities, case study*

1 Introduction

Rock wedge formation remains a primary stability concern for underground excavations such as drives, chambers and crusher caverns. In practice, designers have long relied on kinematic/limit equilibrium block theory and standard wedge equations to identify unstable blocks and assess support demands, an approach that underpins widely used software implementations (Goodman & Shi 1985; Rocscience 2026).

Deterministic workflows typically evaluate a small set of joint combinations against an idealised excavation geometry, with discontinuities treated as planar and persistent, and the default computation of maximum-size wedges unless the user applies scaling controls (e.g. persistence and spacing). These assumptions are transparent and efficient but tend to bias designs toward a conservative 'worst-case' block geometry which works for early stage design (Rocscience 2026).

So-called probabilistic extensions in conventional wedge tools mainly address parameter uncertainty, by assigning statistical distributions to wedge forming geometric inputs (dip and dip direction, persistence and spacing) and to resisting forces (shear strength and induced stress) and obtaining a distribution of Factor of Safety (FoS) for the selected wedges. However, the methods generally do not quantify the probability of

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occurrence of different block geometries along real excavations because discontinuity persistence, spatial clustering and trace lengths are not represented explicitly in the rock mass description .

Addressing the variabilities in block geometries has been the focus of discrete fracture network (DFN)-based workflows that generate wedges stochastically from site-calibrated fracture networks and then track their size, orientation, and frequency along excavation surfaces. Early mining applications demonstrated reinforcement design using discontinuity network models and 3D joint networks, and subsequent work formalised DFN-based reinforcement design and conditional DFN modelling for kinematic stability (Grenon & Hadjigeorgiou 2003a, 2003b; Grenon et al. 2017; Hadjigeorgiou & Grenon 2017; Rogers et al. 2017).

Despite these advances, routine practice in underground design still commonly relies on deterministic or limited scenario-based analyses of structurally controlled wedges or key blocks, often using 'worst-case' geometries as design drivers (Goodman & Shi 1985; Hoek & Bray 1974; Rocscience 2026). Probabilistic methods can provide an improved framework for quantifying geomechanical risk when involving the inherent variability of rock masses and their associated input parameters (Einstein 1995; Baecher & Christian 2003; Hadjigeorgiou 2019).

This paper presents a 'side-by-side' comparison of a commercially available wedge analysis tool and the mXrap Discrete Fracture Network (DFN) and DRN Block Analyser workflow using case study data from BHP's Carrapateena mine site. The assessment compares wedge size, weight, orientation and unsupported FoS under consistent inputs, and it also quantifies the difference in ground support required to achieve a specified design FoS. The emphasis is on application and comparative results, and background DFN mechanics are discussed in Goulet et al. (2026).

2 Methodology

Parallel workflows were implemented under consistent inputs. The deterministic workflow stream used a commercially available wedge analysis tool to compute maximum-size wedges and FoS for selected joint set combinations, subject to the method's key assumptions and persistence scaling options. The probabilistic stream used mXrap's Discrete Fracture Network (DFN) and DFN Block Analyser workflow to stochastically generate wedges around the excavation volume and compute distributions of block size/weight, orientation, and FoS across many iterations. The difference in ground support to achieve a design FoS was established by adjusting reinforcing element density and pattern (Rocscience 2026; Harris et al. 2024).

3 Case study input data

During this comparative assessment, 2 data sets' sources were utilised as input parameters for DFN generation. The 2 data sets' sources reflect what would be a common situation in underground mining, with one being a subsample of 100 m for structural data logged from a diamond drilled borehole proximal to the assessment area. One of the dataset was sourced from a domain-based summary and as such was a statistical average of multiple input sources (drillcore logging data and scanline mapping) distributed across the geotechnical domain. Both data sources are appropriate inputs; however, it is important to understand the individual limitations of each approach in regard to representation of the in situ open joint conditions of the area of interest and act accordingly through any design and execution process. Tables 1 and 2 and Figures 1 and 2 provide a summary of the local and domain-based datasets utilised in the case study comparisons which are outlined in Section 4.

Table 1 Granite domain summary discrete fracture network input dataset

Set no.	Dip (º)	Dip direction (º)	Fisher K	P32	Min diameter (m)	Mean diameter (m)	Max diameter (m)
1	78	209	27.3	0.109	0	2.4	10
2	78	105	15.3	0.156	0	2.3	11
3	81	28	29.4	0.082	0	2.3	6
4	80	280	11	0.103	0	2.6	10
5	49	272	19.2	0.139	0	2.8	10
6	42	61	39.3	0.989	0	2.8	6

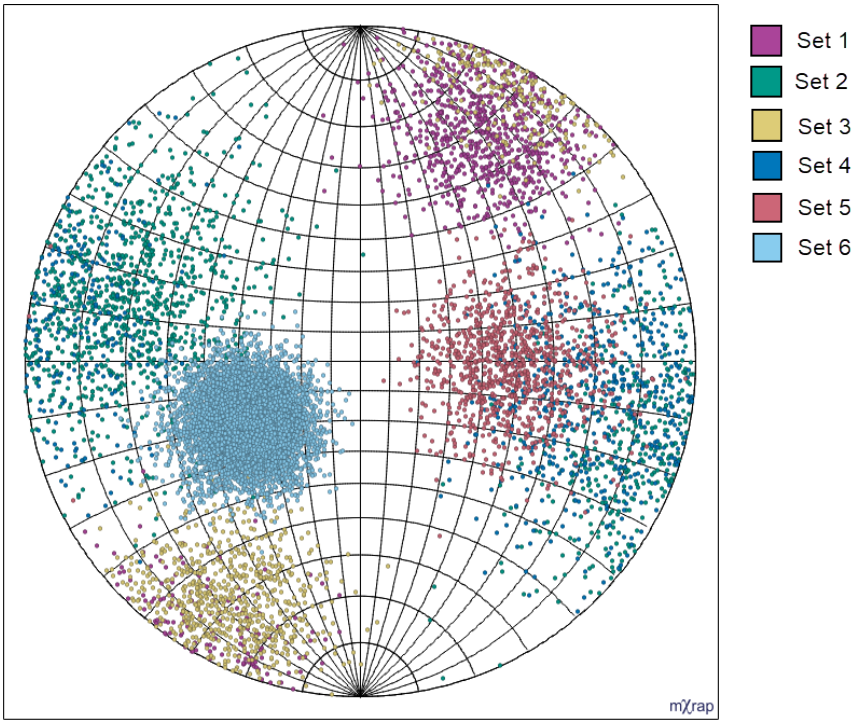


Figure 1 Stereonet of granite domain summary discrete fracture network input dataset

Table 2 100 m of proximal borehole sourced discrete fracture network input dataset (diameters are user inputs)

Set no.	Dip (°)	Dip direction (°)	Fisher K	P32	Min diameter (m)	Mean diameter (m)	Max diameter (m)
1	72	149	108.2	0.328	0	4	10
2	87	215	69.7	0.168	0	5	10
3	45	139	83.3	0.160	0	5	10
4	85	004	80.5	0.064	0	4	10
5	85	169	181	0.066	0	5	10

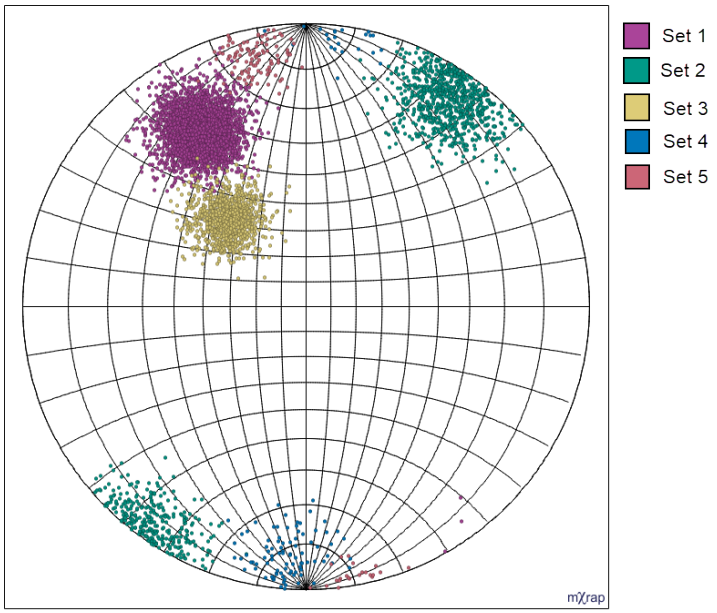


Figure 2 Stereonet of proximal borehole sourced discrete fracture network input dataset

The data used in the case studies were collected from the Carrapateena mine by the onsite geotechnical and core logging team. From them borehole fracture frequency with azimuth and dip were collected from both downhole acoustic televiewer logging (ATV) and fractures observed in drillcore.

4 Case study comparisons

Two mine geometries common to underground tunnelling were used in a side-by-side comparison for the 2 approaches. The following sections outline the outcomes of the 2 methodologies and the difference in ground support requirements.

4.1 Large 4-way intersection

To conduct a robust and defendable comparison of the 2 approaches, several iterations of the same case study input parameters were conducted. Table 3 provides a summary of the assessment scenario variables.

Table 3 Case study 1 scenario assessment summary

Scenario ID	Geometry	Source data	Analytical approach	Comments
CS01_A	Four-way intersection: 5.8 (W) × 7.0 (H) × 30 m (L)	Summary domain-based inputs	Probabilistic	Plus 1 random joint set. No ground support
CS01_B			Deterministic	
CS01_C		Localised borehole-based input	Probabilistic	No random joint set. No ground support
CS01_D			Deterministic	No random joint set. No ground support
CS01_E		Summary domain-based inputs	Probabilistic	Infinite joint diameter. No ground support

The 4-way intersection (Figure 3) represents a common excavation geometry that would require assessment to determine ground support requirements based to meet the mine ground control management plan requirements. Joint set input data, summarised in both Tables 1 and 2, was applied to both deterministic and

probabilistic approaches. For this assessment, ground support was not included in the comparative assessment due to the limitations of the deterministic assessment tool.

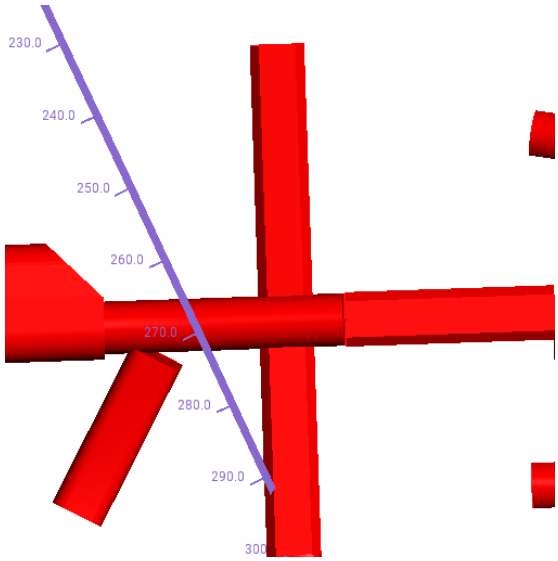
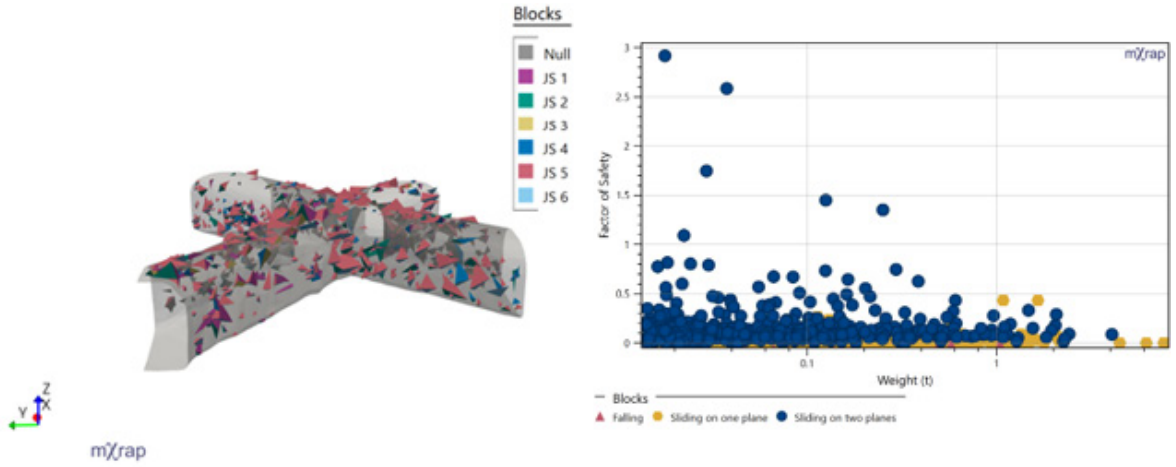


Figure 3 Illustration of assessment area and geotechnical investigation diamond drillhole

4.1.1 CS01_A and CS02_B scenario assessment results

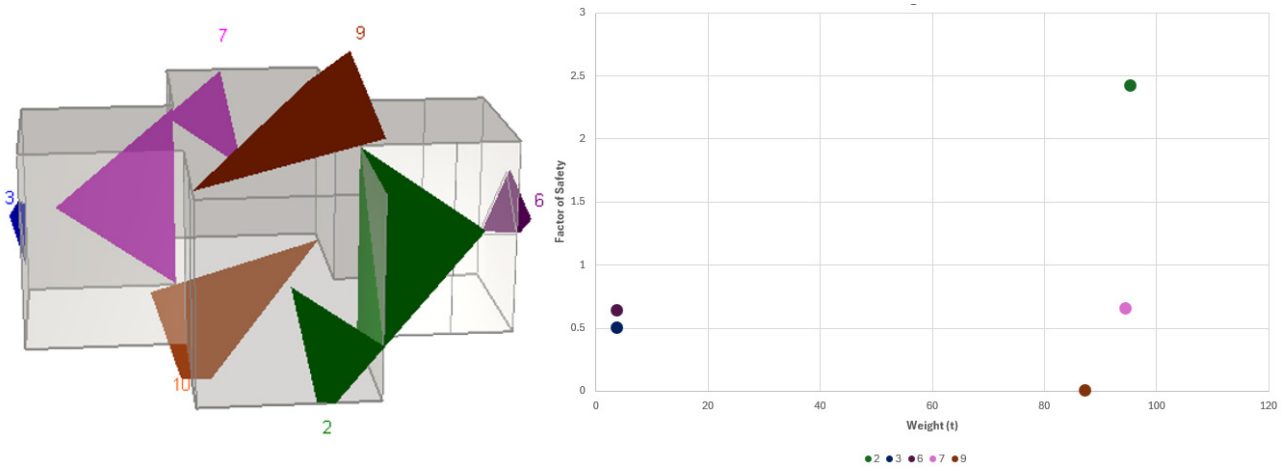
The results of the probabilistic assessment, based on 200 model iterations, and the deterministic assessment, both utilising the domain-based summary joint set data, are presented in Figures 4 and 5, respectively. From a maximum wedge volume and corresponding wedge weight perspective, the following results were generated by the 2 approaches:

- Probabilistic (mXrap):
  - Maximum wedge volume generated = 2.2 m^3
  - Maximum weight 6.2 t.
- Deterministic:
  - Maximum wedge volume generated = 23.8 m^3
  - Maximum weight 95.4 t.



(a) (b)

Figure 4 (a) mXrap Discrete Fracture Network generated stacked wedges after 200 iterations (domain-based data); (b) Chart of wedge weight versus Factor of Safety with no ground support applied



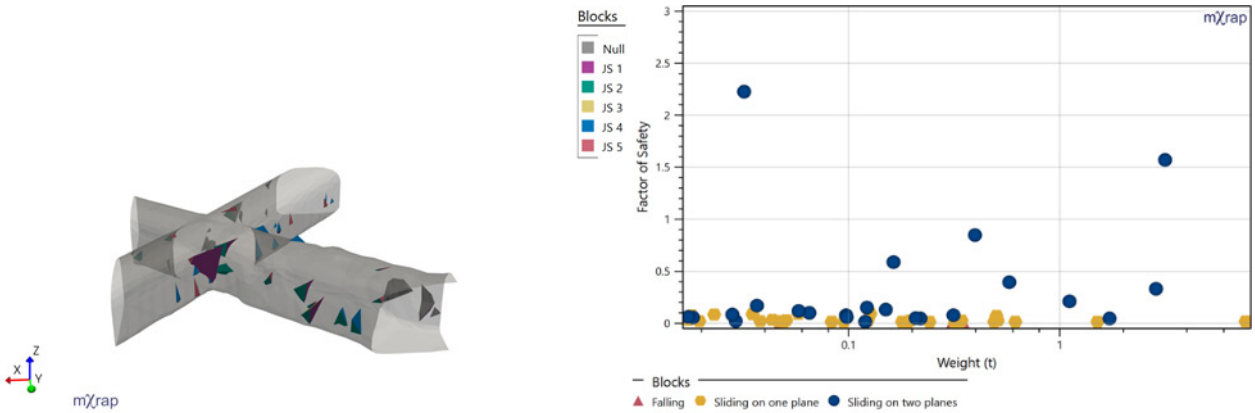
(a) (b)

Figure 5 (a) Deterministic generated wedge analysis; (b) Resultant wedge parameters and Factor of Safety

4.1.2 CS01_C and CS02_D scenario assessment results

The assessment was repeated for scenarios C and D but with a probabilistic DFN generated based on core logging data (refer Table 2) sourced from a proximal diamond drillhole. Unlike the first 2 scenarios (A and B), no random joint set was included, with the DFN generated from the drillcore logged based data with the same summary data used for the deterministic joint set inputs.

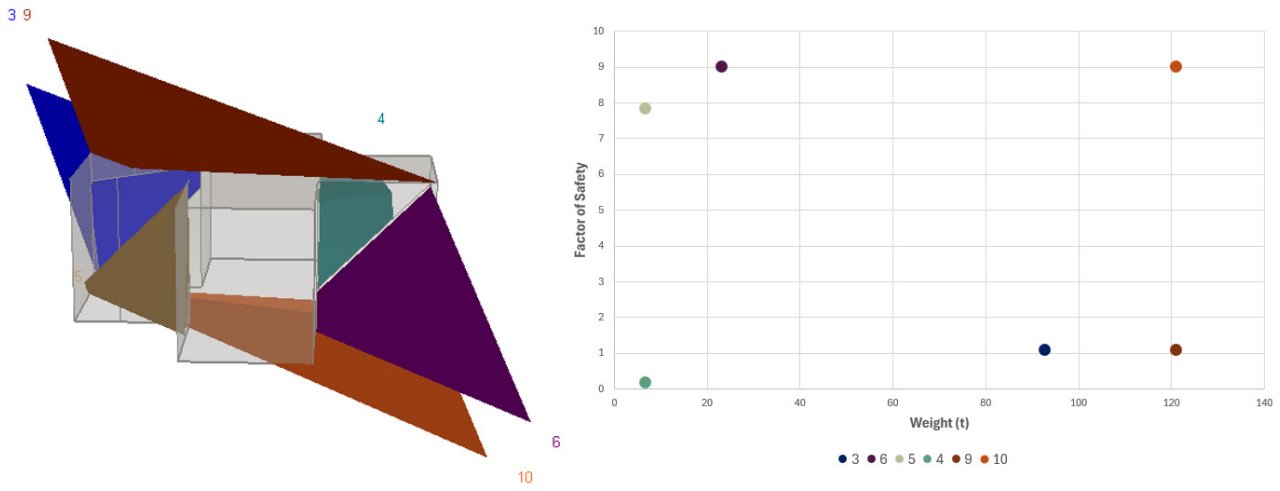
After 1,000 iterations using this method, mXrap was able to generate a block of 2.7 m^3 in volume that weighed 7.6 t (Figure 6). As joint sets 1, 3 and 5 are approximately parallel, fewer kinematically permissible blocks were created which resulted in the increased numbers of iterations.



(a) (b)

Figure 6 (a) mXrap discrete fracture network generated stacked wedges after 1,000 iterations (proximal core data); (b) Chart of wedge weight versus Factor of Safety with no ground support applied

Applying the same joint set data deterministically in the commercially available software did result in the generation of a wedge that weighed 121 t with a volume of 30.3 m^3 which can be seen in Figure 7.



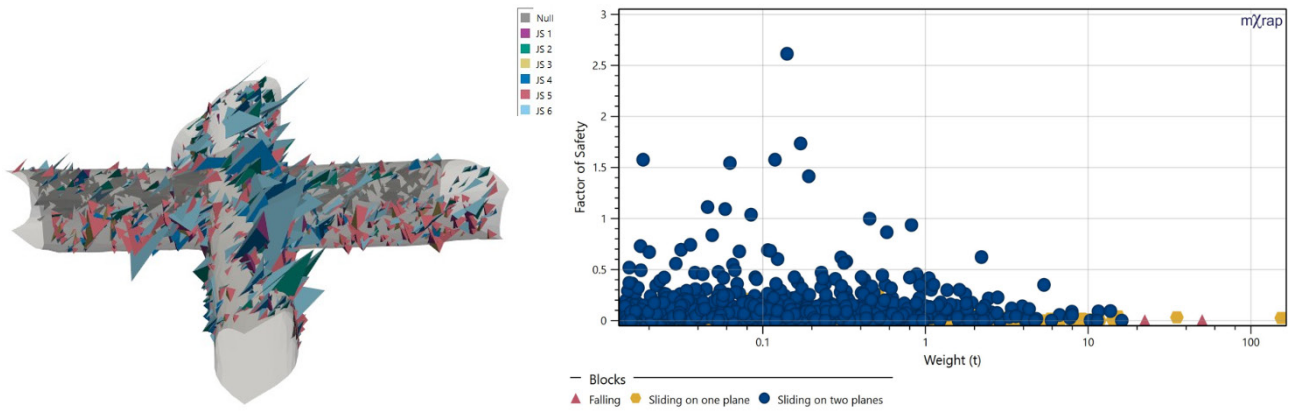
(a) (b)

Figure 7 (a) Deterministic generated wedge analysis based on proximal core data; (b) Resultant wedge parameters and Factor of Safety (FoS) (stable wedged assigned FoS = 9 for visual purposes)

During the development of the 4-way intersection no major blocks or overbreak was observed in the development. This is likely due to all of the small wedges being removed during blasting and scaling processes whilst no large wedges are able to be formed due to the joints being parallel. Based on actual observation of the intersection post-development, it was found that the DFN method in scenarios A and C was more representative of the rock mass as no major wedges presented themselves during development.

4.1.3 CS01_E scenario assessment results

Following the results of scenarios C and D – which demonstrated a significant difference in observed predicted wedge formation – a check was undertaken to determine if diameter was the primary cause of the variance between methods. This was achieved by removing the structural maximum diameter value and allowing infinite joint diameter. In theory, the resultant wedge formation should compare closely to those generated by the deterministic methodology. This analysis approach was run for 200 iterations with mXrap generating a maximum wedge of 154 t and a volume of 54.9 m^3 (see Figure 8). This validated the process and showed that it is possible to generate a wedge larger than the commercially available deterministic software. This is because with sufficient iterations the probabilistic workflow will be sampling from the end members of the input distributions.



(a) (b)

Figure 8 (a) mXrap discrete fracture network generated stacked wedges after 200 iterations (proximal core data and infinite persistence); (b) Chart of wedge weight versus Factor of Safety with no ground support applied

A summary of the maximum generated wedge volume and corresponding weights for all case study 1 (4-way intersection) scenario iterations are shown in Table 4.

Table 4 Summary of maximum generated wedge volume and corresponding weights for all case study 1 scenario iterations

Scenario ID	Source data	Analytical approach	Max wedge volume (m^3)	Max wedge weight (t)
CS01_A	Summary domain-based inputs	Probabilistic	2.2	6.2
CS01_B		Deterministic	23.8	95.4
CS01_C	Localised borehole-based input	Probabilistic	2.7	7.6
CS01_D		Deterministic	30.3	121
CS01_E	Summary domain-based inputs (infinite persistence)	Probabilistic	54.9	154

A similar assessment was then undertaken on a wide span development drive to further compare the 2 workflows. In addition, ground support standard FoSs were input to determine the potential difference in ground support requirements.

4.2 Wide span development

To compare mXrap and the commercially available software, a standard drive design was chosen and it was then placed within the granite domain as there is high confidence in the structural data within this domain. The drive geometry was then constructed in both mXrap and the commercially available wedge analysis tool. As with the 4-way intersection case study, several iterations were assessed to explore the resultant outputs of the 2 approaches and their differences in ground support density to achieve a common FoS solution. A summary of the scenario iterations can be found in Table 5.

Table 5 Case study 2 scenario assessment summary

Scenario ID	Geometry	Source data	Ground support	Analytical approach	Comments
CS02_A	Wide span drive 6.0 (W) × 5.8 (H) × 60 m (L)	Summary domain-based inputs	2.4 m resin bolt 1.1 mW Bolt spacing 1.4 mW ring spacing	Probabilistic 200 iterations	Max joint persistence +1m
CS02_B				Deterministic	
CS02_C				Probabilistic 500 Iterations	

The DFN was generated with a maximum joint diameter of +1 m. This value was chosen to constrain the mXrap workflow so that it generated wedges of similar size to the deterministic approach using the commercially available software.

For the probabilistic approach, 2 different scenarios were executed: one with 200 model iterations and the other with 500 iterations. This approach was undertaken to maximise the likelihood of large wedges being generated and allowed for easier comparison of the 2 approaches.

Due to the simple excavation geometry, it was possible to apply a generic ground support standard to both approaches. The design scheme applied is shown in Figure 9, which includes both reinforcement in the form of 2.4 m long resin bolts applied at a density of 0.65 bolts/m^2 and surface support in the form of 50 mm of fibre-reinforced shotcrete and 5.6 mm gauge mine mesh applied from shoulder-to-shoulder.

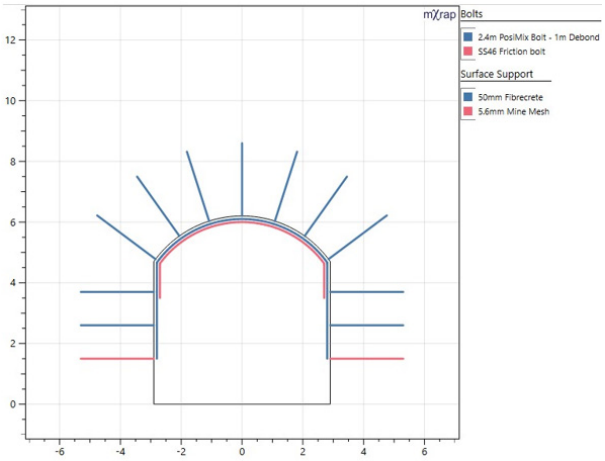


Figure 9 Ground support schema applied to probabilistic and deterministic analytical approaches. Image from mXrap ground support generator (Harris et al. 2024)

4.2.1 CS02_A, CS02_B and CS02_C scenario assessment results

Comparison of the maximum generated wedge volume and corresponding maximum wedge weight are shown in Table 6.

Table 6 Summary of wedges generated for case study 2

Software	Volume (m^3)	Weight (tonnes)	Factor of Safety
Commercially available software	21.6	58.6	9.8
Commercially available software	32.8	88.9	6.9
mXrap 200 iterations	75.3	210.9	0.04
mXrap 500 iterations	52.0	145.7	0.00

From the comparison, it was observed that mXrap can generate wedges of similar or larger sizes than the commercially available software without having to use unlimited joint diameter. However, when re-tested later (with the same input data) mXrap was unable to recreate the 210 t wedge with 200 iterations. The inference from this observation is that specific testing is required to assess the minimum number of iterations required to achieve a statistically stable block population in each structural domain and excavation geometry.

However, the analysis showed that it is possible to generate one 210 t wedge in 10 km of tunnels (not 3-way or 4-way excavations) within the granite domain, i.e. generating a very large wedge is possible in a standard mine drive. It is, however, a low probability outcome and it is likely to be clamped by the in situ stress.

The deterministically generated blocks were all stable due to them being generated in the floor of the drive. Meanwhile the wedges formed by mXrap were reported as unstable with low FoS. This outcome is likely caused by issues within the reinforcing element solution workflow within mXrap application, where the ground support was not being applied to the tunnel correctly, resulting in a low FoS. This is a result of the app being in beta/early stages of development when the assessments were conducted.

4.2.2 Probabilistic occurrence of worst-case wedges

Utilising the probabilistic analytical approach in mXrap, it is possible to plot the reverse cumulative distribution of block sizes. The approximately linear trend observed in the upper tail of the distribution can be interpreted as a Pareto (power law) exceedance relationship. This relationship provides a basis for

extrapolating the observed data to estimate the frequency of larger 'worst-case' wedges as created by the deterministic approach.

In the example shown in Figure 10, an exceedance rate for a 173 t wedge is 0.01 blocks per 100 m based on the input parameters for CS02_C. This probability corresponds to an average occurrence of one large block in every 10 km of development for the granite design structural domain.

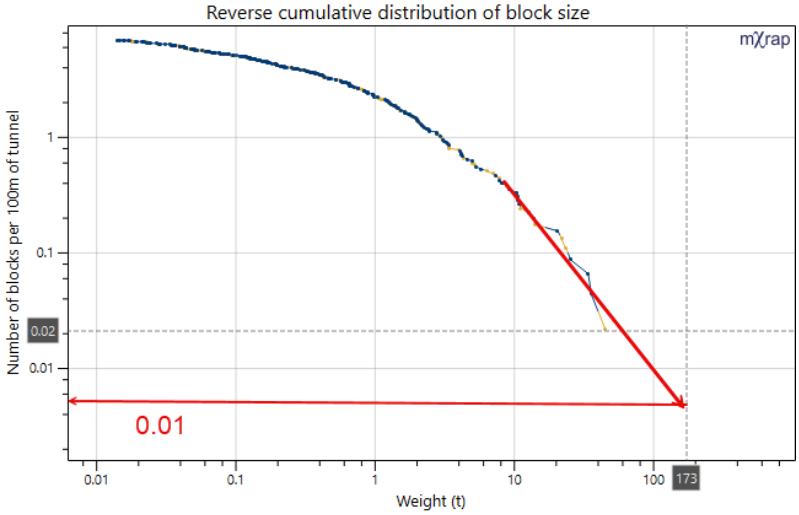


Figure 10 Reverse cumulative distribution of block size indicating the number of blocks per 100 m of the equivalent volume to the deterministic derived wedges

5 Discussion

Deterministic analyses frequently generate very large wedges (notably floor wedges in this case) due to the assumptions associated with planar, persistent joints and constant excavation cross-sections. Deterministic wedge geometry can be modified by scaling geometric inputs persistence or spacing (Rocscience 2026).

Probabilistic DFN simulations can reproduce large wedges at reduced frequencies and in some instances can generate larger wedges than those from equivalent deterministic assessments. This indicates that probabilistic methods are not inherently less conservative (than deterministic methods) and can also provide size and occurrence likelihood outcomes which are useful for communication of risk and allow for the potential ground support design optimisation (Rogers et al. 2017; Grenon et al. 2017).

To date, the DFN workflow discussed in this paper is not implemented at the Carrapateena mine site. Additional analysis and review are required to allow the workflow to pass through the site's management of change process prior to any implementation. However, observations to date indicated that that through the subapp developed within the mXrap platform it is possible to generate realistic ground support designs with the structural data sets and mine geometries at Carrapateena.

The key limitation in this alternate methodology is in the communication, and application, of the probability of exceedance philosophy to kinematic ground support design. A key future choice that is required prior to the implementation of this analysis is in the choice of the probability of exceedance design criteria.

6 Conclusion

The Carrapateena case study indicates that DFN-based probabilistic wedge analysis offers a robust framework for ground support design and potential optimisation. The workflow complements deterministic assessments by generating likelihood of occurrence outcomes. This allows definition of the known conservatism within the current industry standard workflow.

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