SSIM 2025 - JJ Potter & J Wesseloo (eds)

doi:10.36487/ACG_repo/2535_07

Considerations for optimal assessment of bench–berm stability and design in competent, fractured rock masses

Victor Spirin [a,*], Ian de Bruyn [a], Jaya Mylvaganam [a], Donovan Lium [b]

[a] *SRK Consulting, Australia*

[b] *Consolidated Minerals, Australia*

Abstract

In competent rock masses, a focus on bench stability during slope design is crucial, as the achievable overall slope angle is often constrained by appropriate bench–berm geometry rather than overall rock mass strength. However, optimising bench–berm configurations is a complex process that requires considering multiple discontinuity-related input parameters and identifying the most significant ones that control design in each domain. The wide range of available tools and methods for assessment can lead to varying outcomes, and design decisions often rely on experience and engineering judgement – both in selecting appropriate analysis methods and in interpreting their results. Consequently, identifying key factors and streamlining the design analysis process are essential for improving efficiency and optimising bench–berm configurations.

Stereographic analyses are useful for quick and straightforward assessments. Simple block-based analyses are necessary for optimisation of bench and berm design. In some cases, more advanced techniques may be beneficial; stochastic joint network analysis allows for the analysis of complex, irregularly shaped failure mechanisms. The results of simple block-based and stochastic joint network analyses are typically expressed in terms of Factor of Safety and probability of bench failure, as well as crest loss, failure volume and spill width, which reflect berm retention capacity. These outcomes are highly sensitive to input parameters such as discontinuity orientation, spacing, persistence, and shear strength, making calibration and sensitivity analysis essential.

Using case studies, this paper compares several methods for assessing Probability of Failure and spill width, and highlights their influence on bench face angle and berm width justification. The results demonstrate consistent outcomes when key controlling factors are properly considered; however, when failure mechanisms involve contributions from multiple joint sets, advanced methods are required.

Keywords: *bench–berm design, Probability of Failure, berm retention capacity, crest loss, spill width*

1 Introduction

A comprehensive assessment of bench stability requires careful selection of analysis methods based on potential failure mechanisms. Structural geology plays a critical role, with emphasis on identifying main structural sets such as bedding/foliation and persistent joints, which govern the formation of potential failure blocks. Three main analysis types/methods are described in this paper including stereographic analysis, simple block-based analysis, and stochastic joint network analysis. Each offers unique insights into Probability of Failure (PoF), block geometry, and failure volume, and their combined application enhances confidence in slope design decisions.

A case study is included, which presents an example of a bench design study for open pit mines located within the Woodie Woodie mining corridor, with a focus on dolomite rock units. The objective of this study was to optimise bench–berm geometry to enhance inter-ramp angles (IRAs) and, consequently, overall slope angles, with adjustments tailored to the geological and structural conditions of each pit sector. The study

* Corresponding author. Email address: vspirin@srk.com.au

demonstrates the evaluation of bench stability using a combination of the methods described in the paper and considers various design criteria such as PoF, Factor of Safety (FoS), and berm retention capacity – in line with industry guidelines (Read & Stacey 2009).

2 Overview and application of methods

Choosing appropriate assessment methods requires an understanding of the potential failure mechanisms. Common bench-scale failure modes include planar, wedge, toppling, and circular failures (Figure 1). In bedded deposits, planar (a) and toppling (d) failures are the most prevalent. In fractured rock masses, planar (a), wedge (b), and toppling (d) failures are frequently encountered, whereas circular failure (c) is less common at the bench scale. This is because bench stability in competent rock masses is typically controlled by structural features, and the likelihood of circular failure increases as rock mass strength decreases (due to small block sizes and/or easy breakage through intact rock).

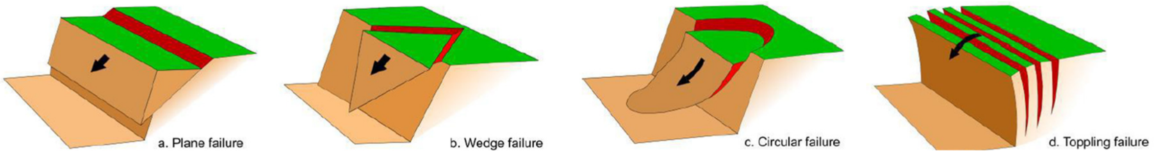


Figure 1 Common failure mechanisms in rock slopes (Hoek 2009)

Additionally, this paper considers complex failure modes involving blocks formed by multiple intersecting joints. Combined failure mechanisms – where blocks are not fully defined by joint planes and rock mass properties influence the failure – are beyond the scope of this paper but represent another category worth noting. Regardless of the method used, a thorough understanding of the structural fabric is essential. During analysis, it is critical to differentiate between key structural sets (e.g. bedding or foliation planes and persistent joints) and minor sets (e.g. weak, non-persistent joints). Key sets primarily influence failure, while minor ones can often be considered as 'noise'.

2.1 Methodological classification

Rigorous methods that rely primarily on structural data can be broadly classified into the following categories:

- Stereographic analysis: suitable for assessing planar, wedge, and toppling failures. This is a simple and reliable set of methods that identify kinematically feasible failures, which are useful for first-pass assessments. They generally assume infinite joint persistence, zero cohesion, and do not consider joint spacing.
- Simple block-based analysis: assesses the stability of simple shapes (planar or wedge) generated from the input of several joint sets (with statistical distributions for each). Joint spacing is not explicitly considered. Blocks are typically predefined, so a general understanding of the likely failure mechanism is required before performing the analysis.
- Stochastic joint network analysis: involves the effective generation of a discrete fracture network (DFN) across the slope using the statistical distribution of joint sets, followed by stability assessment of the resulting blocks. For this method, block geometry emerges from the joint fabric itself, rather than being predefined – this allows for complex and irregular block geometries to be assessed and removable blocks to be identified, based on joint connectivity and spatial variability. Importantly, it also allows for visualisation of the actual spatial variability of block size and position within the bench or bench crest. While this method is more advanced and capable of capturing complex failure modes, it also requires considerable experience and engineering judgement for both the analysis process and the interpretation of results.

Block stability is typically assessed using the limit equilibrium method (LEM) to estimate the FoS and/or the PoF, whereas stereographic analysis relies on a geometric approach to evaluate the Probability of Undercutting (PoU). Table 1 summarises the methods and their application, which are described in more detail in Section 3.

Table 1 Application of bench–berm analysis methods

Methods	Description	Software examples	Joint set inputs	Advantages	Disadvantages	Application
Stereographic analysis	Discrete-oriented data analyses rely on a geometric approach Outputs: Probability of Undercutting	Dips	Joint sets and their orientations from pole-plot statistics Joint friction	Simple and quick assessment Relatively straightforward approach	Only typical failure mechanisms are considered Limited range of joint set input parameters Block geometry and spill volumes are not assessed	Best for preliminary assessments Early stages Shallow and short-term pits Bedded deposits where bedding is the primary control
Simple block-based analysis	Stability assessment is usually based on limit equilibrium method. Predefined blocks of simple shapes (e.g. planar or wedge) are generated from the input of several joint sets Outputs: Factor of Safety, Probability of Failure, volume, crest loss, spill width (only certain software)	RocPlane Swedge MWedge	Joint sets and their orientation Persistence Joint cohesion Joint friction Statistical distributions	Reasonably simple and quick assessment Persistence is considered to define blocks of different volumes	Only typical failure mechanisms are considered Limited calibration capability	Preliminary assessments Intermediate stages Shallow and short-term pits Only typical failure mechanisms are considered Limited reliable data for advanced analyses
Stochastic joint network analysis	Stability assessment is usually based on limit equilibrium method. Joint network simulation is performed stochastically across the slope, with block geometry emerging from the joint fabric itself rather than being predefined. Removable blocks are then identified and assessed. These blocks can have complex geometries, often outlined by two or more joint sets Outputs: FoS, PoF, volume, crest loss, spill width (only certain software)	RocSlope3 SBlock FracMan	All available data: Joint sets and their orientation Persistence Spacing Joint cohesion Joint friction Statistical distributions	Visualisation of multiple failure blocks on slope Complex and more realistic failure mechanisms Advanced calibration based on actual slope performance	Considerable experience and engineering judgement in both modelling and interpretation are required Modelling and input selection can be time-consuming processes	Advanced stages or cutbacks Sufficient data from existing pit slopes are available for calibration, primarily derived from visual inspections and failure assessments

Note: Dips, RocPlane, Swedge, and RocSlope3 – Rocscience (2025), SBlock – Esterhuizen (2025), FracMan – WSP (2025), MWedge – Gibson (2015)

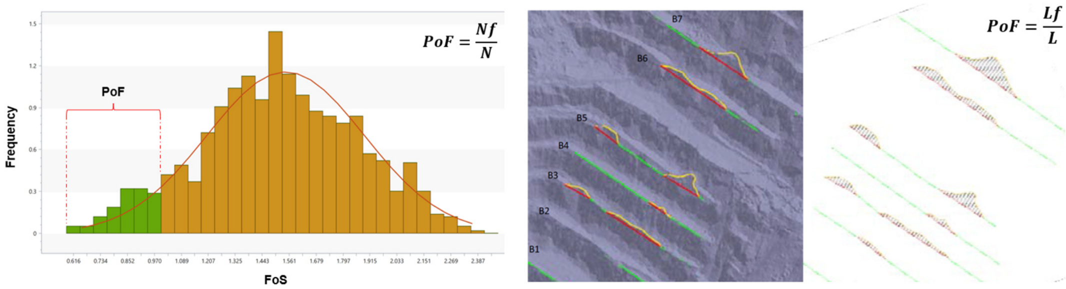
2.2 Design acceptance criteria

The guidelines provided by Read & Stacey (2009) recommend several design acceptance criteria (DAC) for assessing bench design:

- FoS: a minimum FoS of 1.1 is typically used for deterministic analyses.
- PoF: a PoF of 25–50% is generally acceptable; however, acceptable values may vary depending on the consequences of failure, operational risk tolerance, and the mitigation measures and strategies in place. Different DACs may be applied for specific pit sectors based on operational priorities.

There are 2 commonly used approaches to assess the PoF for benches (Figure 2):

- By the number of observed failures (Figure 2a)
- By the cumulative length of failure zones along the slope, representing a length-based PoF metric (Figure 2b).



(a) (b)

Figure 2 Methods to assess Probability of Failure (PoF) on benches: (a) By the number of failures; (b) Length-based PoF metric derived from the extent of failure zones observed or simulated along the bench (modified after Hormazabal et al. 2019)

where:

Nf = number of FoS values less than 1

N = total number of FoS values

Lf = total length of failures

L = total length of the considered benches (B1+B2+..+B7).

When considering berm width requirements, it is briefly noted in the guidelines that ideally 70–85% of any material from a failure block in the bench should be retained on the berm below, corresponding to a catch efficiency of approximately 80%. However, more conservative thresholds (e.g. 90%) may be adopted depending on site-specific risk tolerance, while more optimistic values may be acceptable where routine scaling or berm clean-up is practised. While a minimum berm width is not a mandatory design criterion in all jurisdictions, the empirical modified Ritchie criterion (Read & Stacey 2009) is commonly used:

$$BW = 0.2 \times BH + 4.5 \text{ m} \quad (1)$$

where:

BW = berm width (m)

BH = bench height (m).

Containment volume calculations and/or rockfall analyses should ideally be used to strengthen or refine berm width recommendations, particularly where a quantitative justification of catch efficiency is required. This is discussed in detail in Section 3.2.2.

3 Description of analysis methods

3.1 Stereographic analysis

Stereographic analysis is a relatively straightforward method for assessing bench instability from various failure mechanisms. However, it must be understood that a stereoplot can yield different interpretations when evaluating failure mechanisms. An example of this is provided for planar failure in Figure 3. The PoU can vary significantly depending on how it is assessed – whether based on all the poles plotted on the stereonet or restricted to a specific joint set. This variability occurs because many joint sets may be favourably oriented relative to the slope. When more joint sets are included in the analysis, the overall PoU tends to decrease due to a dilution effect – where favourable or random joint orientations dilute the influence of unfavourable ones.

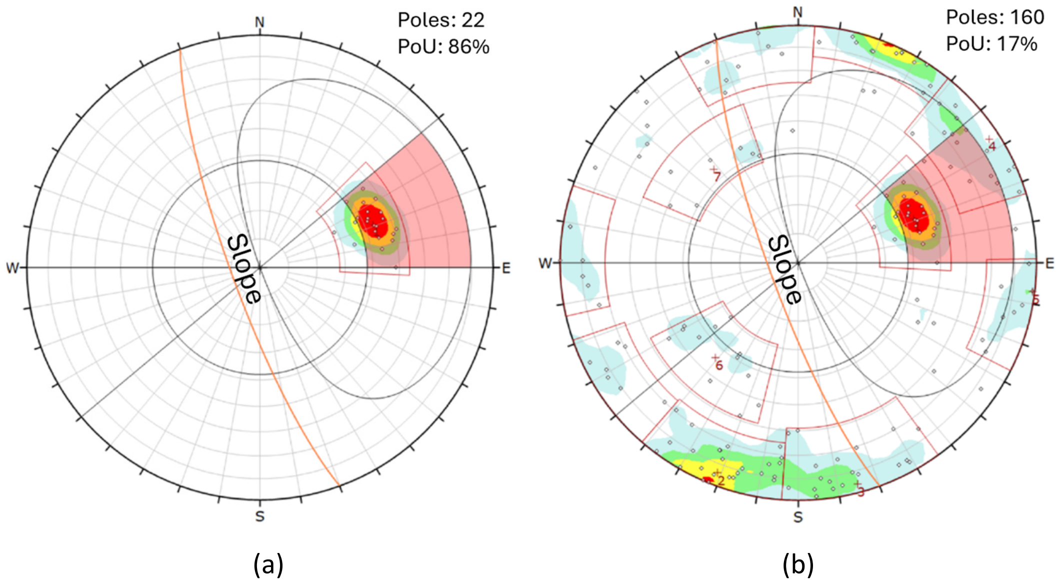


Figure 3 Effect of multiple joint sets on planar sliding Probability of Undercutting (PoU): (a) PoU calculation focused on the main joint set, resulting in higher potential (86%); (b) Inclusion of multiple joint sets dilutes the concentration of poles and reduces PoU to 17%

This dilution effect is particularly relevant in fractured rock masses, where several joint sets may be equally well developed. Prior to conducting any stability analysis, it is essential to identify and distinguish between the main structural sets – such as bedding/foliation and persistent joints – and minor sets. When multiple joint sets are equally developed in varying directions, all poles can be considered collectively in the analysis. Conversely, when a strong or dominant structural set is clearly present, the PoU should be assessed specifically for that set.

3.2 Simple block-based analyses and stochastic joint network analyses

3.2.1 Block generation and geometric constraints

For simple block-based analyses and stochastic joint network analyses, several block generation approaches provide the conceptual framework for the methodologies. These are discussed by Gibson et al. (2006), Hormazabal (2013), and Goodman & Shi (1985).

In simple block-based analyses, block shapes are typically simple (e.g. planar or wedge), and failure volumes are constrained by geometric limits such as BH, BW, joint persistence, and joint spacing (Figure 4). Properly accounting for the actual persistence of joints ensures more realistic estimations of block size and potential failure volume.

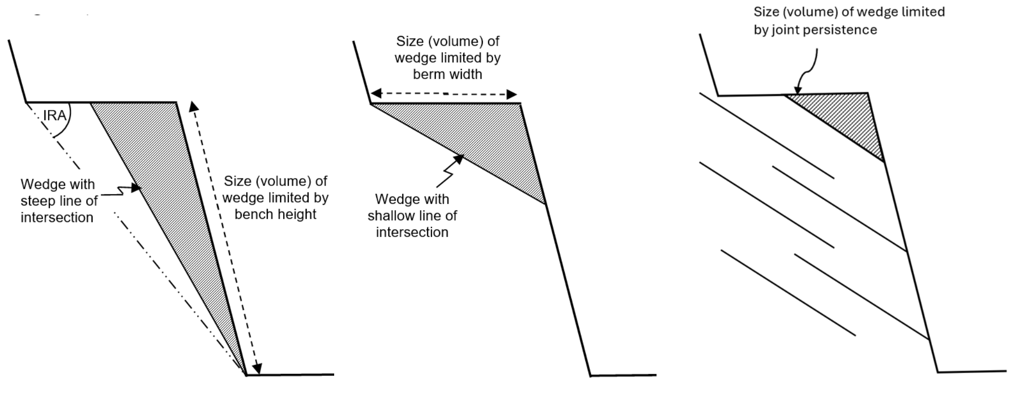


Figure 4 Failure volume limitations in simple block-based methods (modified after Gibson et al. 2006): (a) Block volume limited by bench height; (b) Block volume limited by berm width; (c) Block volume limited by joint persistence

Stochastic joint network analyses can produce blocks with irregular and complex geometries, as joints can interconnect in unexpected ways. Block size is not limited by any pair of joints but rather by the combined geometry of multiple intersecting joints. Figure 5 illustrates this concept: the block near the crest is relatively small due to limited joint persistence, while the larger block can form because a backward-oriented joint set enables the block to be fully separated. This highlights how DFN modelling can identify failure mechanisms and volumes that are not easily captured by simpler block generation techniques. Stability is assessed only for blocks that are fully joint-defined, in contact with the slope surface, and not structurally locked (i.e. removable blocks; Goodman & Shi 1985).

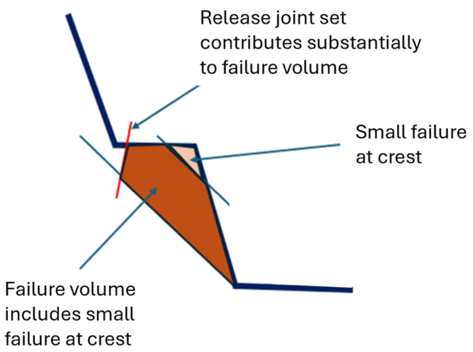
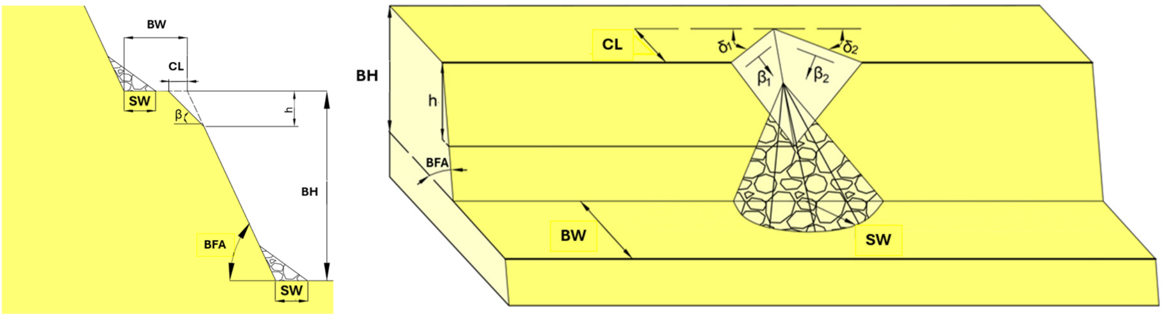


Figure 5 An example of failure volumes in stochastic joint network analyses (figure and concept provided by Gabriel [Essie] Esterhuizen)

3.2.2 Minimum berm width

Minimum berm width is assessed to ensure berm retention capacity, which depends on the anticipated volumes of failed material and expected rockfall trajectories. These are assessed using quantitative approaches, in contrast to empirical approaches such as the modified Ritchie criterion, which is geometry based. Figure 6 illustrates key considerations related to berm retention capacity for volumes of failed material. Alternative equations for estimating berm retention in cases of planar failure are provided in the RocPlane manual (Rocscience 2022) and produce equivalent results.



$$V = \frac{h^2}{2}\left(\frac{1}{\tan(\beta)} - \frac{1}{\tan(BFA)}\right)$$

$$CL = h\left(\frac{1}{\tan(\beta)} - \frac{1}{\tan(BFA)}\right)$$

$$SW = \left(2VK\left(\frac{1}{\tan(\phi)} - \frac{1}{tan(BFA)}\right)\right)^{1/2}$$

(a)

$$V = \frac{h^3}{6}(cot(\psi') - cot(BFA))^2(\cot(\delta_1) + \cot(\delta_2))^2$$

$$\cot(\psi') = \frac{sin\,\delta_1\,cot\beta_2 + sin\,\delta_2\,cot\beta_1}{sin(\delta_1 + \delta_2)}$$

$$CL = h\left(\frac{1}{\tan(\psi')} - \frac{1}{\tan(BFA)}\right)$$

$$SW = \left(\frac{6VK}{\pi}\left(\frac{1}{tan(\phi)} - \frac{1}{\tan(BFA)}\right)\right)^{1/3}$$

(b)

Figure 6 Berm retention capacity considerations (modified after Gibson et al. 2006; Rylnikova & Zoteev 2022): (a) Planar failure; (b) Wedge failure

where:

BFA = bench face angle

BH = bench height

BW = berm width

CL = crest loss (the distance between the design bench face and the apex of the failure)

SW = spill width (the minimum berm width required to retain the volume of potential failures)

V = volume of failed material

h = failure height

K = swelling factor (e.g. K = 1.35)

ø = angle of repose of failed material (ø = 38° is a typical value for granular material; Bowles 1990)

β = structure dip angle

δ = angle of obliqueness of the structure relative to the slope

π = constant (3.14)

ψ’ = auxiliary constant.

Berm retention capacity is assessed by comparing the BW with the SW; CL may also be included in the assessment. To evaluate this, a derived parameter — the ‘free berm width’ (FB) — can be defined as the remaining berm width after accounting for both SW and CL. For adequate retention, FB should remain greater than or equal to zero:

$$FB = BW - SW - CL \geq 0 \quad (2)$$

As outlined in Section 2.2, this calculation is typically based on design parameters selected with an acceptable overspill in mind, with berms generally intended to retain about 80–90% of failure volumes. Because the SW and CL values are based on representative rather than most conservative conditions, a limited overspill may still occur even when FB ≥ 0. In some cases, CL may be excluded or replaced with a fixed allowance (e.g. 1–2 m) to avoid overly conservative outcomes when the wedge apex is considered.

3.2.3 Relationship between Probability of Failure and spill width

When a DFN is used to stochastically simulate block formation, the outcomes (such as V, CL, and SW) can vary significantly, even when the same slope geometry and joint parameters are applied (Figure 7). This is due to the way the stochastic simulation generates discontinuities in a spatial sense; each generated DFN is unique, and not every block or wedge generated is the maximum size it could potentially be. In Figure 7a, a small failure volume poses minimal risk and may have no impact on slope design. In contrast, the example in Figure 7b shows a larger failure volume that can entirely fill and overspill the berm, potentially resulting in a critical design issue.

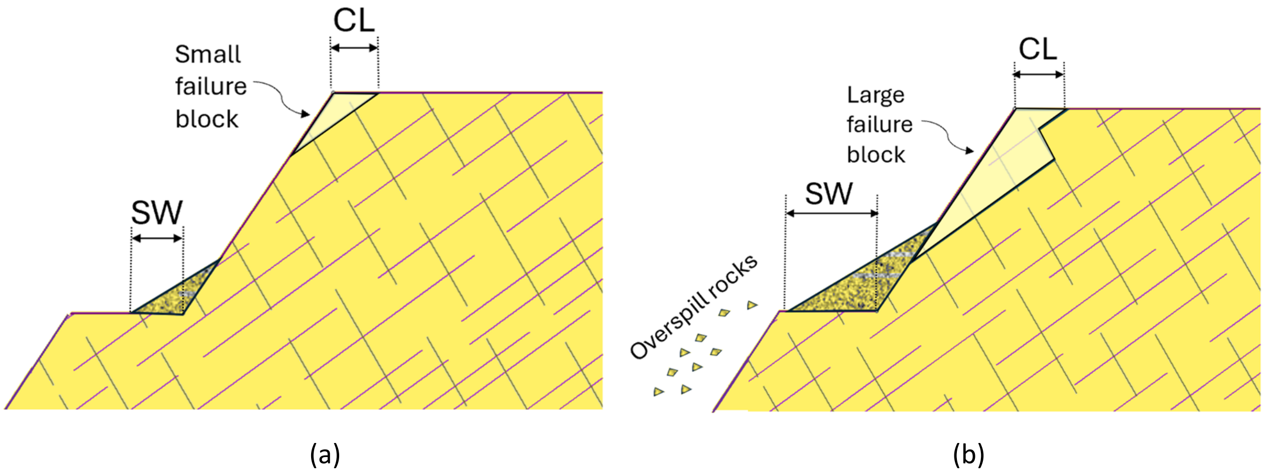


Figure 7 Effect of different stochastic discrete fracture network realisations on the same slope geometry: (a) Small failure – low potential risk; (b) Large failure – increased potential risk due to insufficient berm catchment

Numerous studies have demonstrated that fractures of small persistence generally occur far more frequently than ones of large persistence in natural rock masses (Bonnet et al. 2001). Consequently, large failure blocks are inherently less likely to develop, while smaller failures are more common. Furthermore, smaller blocks are more likely to be dislodged during blasting and scaling, and often have negligible design and operational impact. Importantly, there is an inverse relationship between failure volume and PoF – larger failures are associated with lower PoF, whereas smaller failures tend to occur more frequently and have higher PoF. As a result, PoF and SW do not always increase together, and high PoF does not necessarily imply a critical design threat if the associated spill volume remains low. This highlights the importance of jointly considering both PoF and SW metrics during bench–berm performance assessment.

When assessing multiple stochastic joint network generations, the resulting distributions for bench failure depth and SW may appear as shown in Figure 8, with the following key observations:

- PoF distribution: the figure shows PoF across the bench profile as shaded contours, with values decreasing from ~50% near the slope surface to ~10% at full depth. PoF is calculated using a 10 × 10 grid, where each cell indicates how often it is included in failed blocks across multiple DFN realisations. This length-based approach is conceptually similar to that shown in Figure 2b but applied across the entire bench profile.
- SW distribution: the figure also presents the estimated accumulation of failed material (SW) at the slope toe, based on the mean failure volume. The upper and lower bounds represent the SW range associated with large and small failure volumes, respectively.

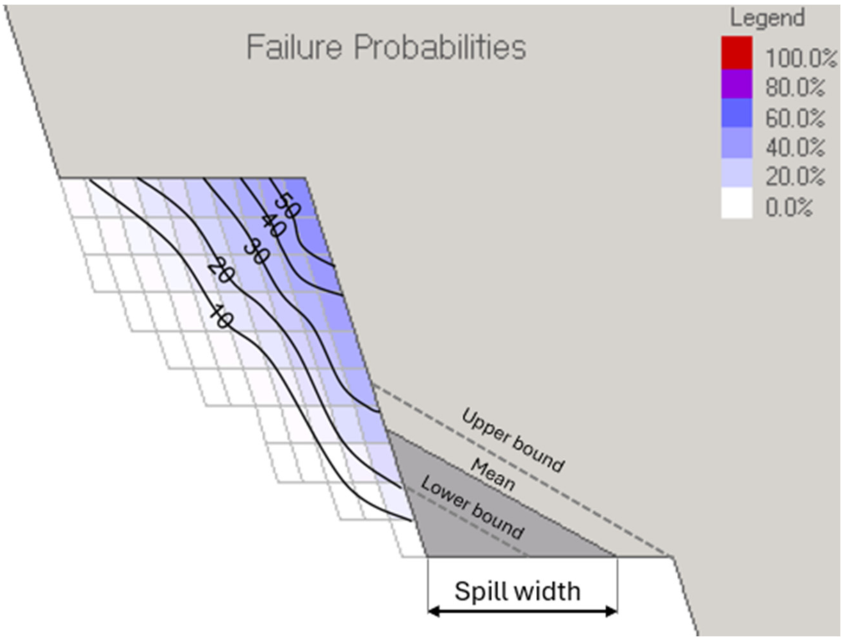


Figure 8 Depth of bench failure and spill width shown as Probability of Failure contours (modified after Hormazabal 2013)

While FoS and PoF are commonly used to guide the selection of BFA, BW is primarily justified based on expected failure volume, SW, and CL. Overall, the goal of bench–berm optimisation is to balance these parameters to ensure both bench stability and adequate berm retention performance.

The combination of BFA, BW, and BH defines the bench–berm configuration, which in turn influences the IRA – a critical parameter for overall slope optimisation.

4 Example of practical application

4.1 Deposit description

A design review was conducted for the Big Mack and Radio Hill pit cutbacks at the Woodie Woodie manganese mine, located 400 km southeast of Port Hedland in the East Pilbara region of Western Australia. The review focused on bench–berm analysis in moderately weathered to unweathered dolomitic rock within the lower pit slopes. The major structures hosting ore are observed to crosscut the deposit but do not significantly affect slope stability. Most minor structures were logged as joints occurring in multiple orientations, but generally lacking high persistence. In dolomite, bedding is not well defined, and as a result, there is no clear dominant anisotropy in the lower sections of the pits. However, the most frequently logged structural set is treated as bedding in the analyses.

The existing bench–berm parameters for the pit slope design in dolomite were BH = 18 m, BW = 8 m, and BFA = 70°, resulting in an inter-ramp angle of 51°. The potential for further optimisation was assessed, but this is subject to uncertainty due to limited calibration data, as the dolomite that will comprise a significant part of future cutbacks is currently exposed only in the lower parts of the present slopes.

The bench–berm design in dolomite slopes was reviewed using the following methods:

- stereographic analyses for planar, wedge and toppling failure mechanisms using Dips software (Rocscience 2025)
- simple block-based analyses for wedge instabilities using MWedge (software internally developed by SRK, Gibson 2015)
- stochastic joint network analyses for block instabilities using SBlock software (Esterhuizen 2025).

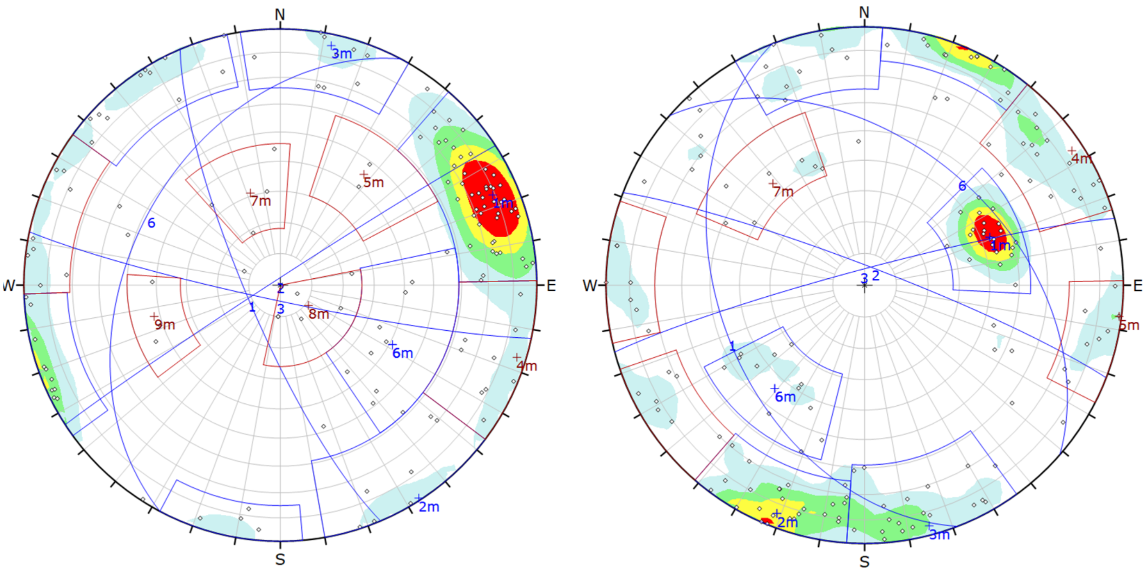
DACs for bench stability were applied in accordance with industry standards, specifying a PoF ≤ 30%. Based on the Ritchie empirical criterion the required BW is 8.1 m for a BH of 18 m. This initial berm width value was further assessed and refined through quantitative analysis to achieve a target catch efficiency of about 90%, ensuring retention of the potential failure volumes.

Statistical parameters were derived for each structural set identified in the pits using surface photogrammetry mapping and laboratory testing. These parameters included dip and dip direction (with corresponding standard deviations), as well as the minimum, maximum, and mean values for spacing, persistence, cohesion, and friction angle. The structural set inputs for the dolomite were:

- Bedding: spacing = 1–5 m, persistence = 10–30 m.
- Joint sets: spacing = 2–5 m, persistence = 15 m.

Joints were typically characterised by undulating, smooth surface roughness, either unfilled or with minimal mineral coating. Shear strength parameters for defects were estimated based on direct shear tests conducted on dolomite samples. The adopted shear strength values were joint cohesion (Cj) = 0, joint friction angle (ϕj) = 38°.

Structural data for the Big Mack and Radio Hill pits within the dolomite unit are shown as stereonet plots in Figure 9. While multiple joint sets are visible, only those considered sufficiently 'strong' – highlighted in blue – were included in further analysis. 'Weaker' sets, unlikely to contribute meaningfully to block formation, were either disregarded or modelled in DFN simulations with low persistence and wide spacing to reflect their limited influence on bench stability. Strong sets were selected based on frequency, traceability across the slope face, and geometrical relevance to expected failure mechanisms. However, due to potential data collection bias, interpretation of joint reliability requires broader structural geological understanding. For example, in Figure 9a (Big Mack), joint set 6 m – dipping westward – is likely more prominent than its representation on the stereonet suggests, based on background geological information. Therefore, this set has been carefully considered for its potential impact on the east wall, which may be undercut by this structure.



(a) (b)

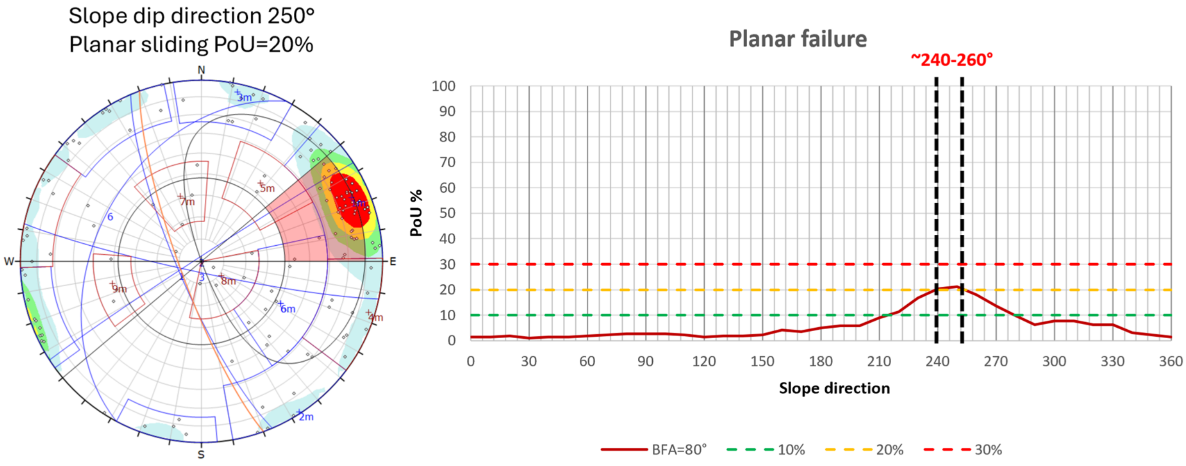
Figure 9 Stereonet plots from surface mapping of the dolomite unit: (a) Big Mack; (b) Radio Hill. Note: strong joint sets are highlighted in blue. Stereonet plots use the lower hemisphere projection

4.2 Stereographic analysis

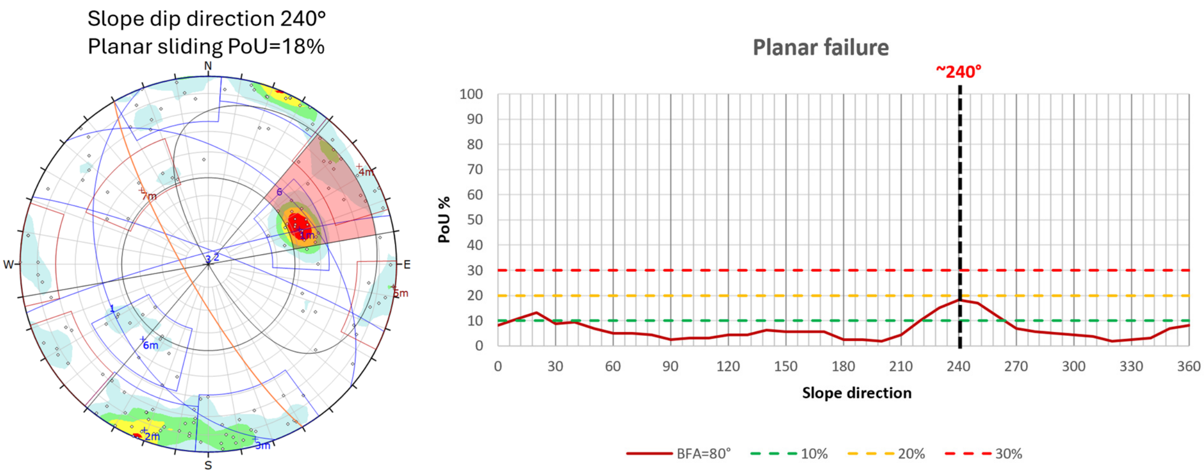
Stereographic analyses for planar, wedge, and toppling failure mechanisms were conducted using Dips software. The results of the planar failure analysis are presented in Figure 10; all poles were used to assess PoU.

The potential for planar failure at the Big Mack and Radio Hill pits is highest where the pit wall dip direction is ~240–260°. For a BFA of 80°, potential for planar failure is indicated to be about 20%, which is below the DAC. However, moderately west-dipping joint set 6 m (Figure 9a) has not been adequately captured due to limited data, as previously discussed. If the presence and strength of this joint set are confirmed, it could have a significant impact on slope stability, especially on walls with dip directions aligned toward ~300°.

Wedge failure analysis plots are shown in Figure 11; grid data intersections were used to assess PoU. For a BFA of 80°, wedge potential is high for pit wall dip directions of ~200–300° (east wall); however, for a BFA of 75°, the potential for wedge failure is at the DAC.



(a)



(b)

Figure 10 Stereographic analysis – planar failure: (a) Big Mack; (b) Radio Hill

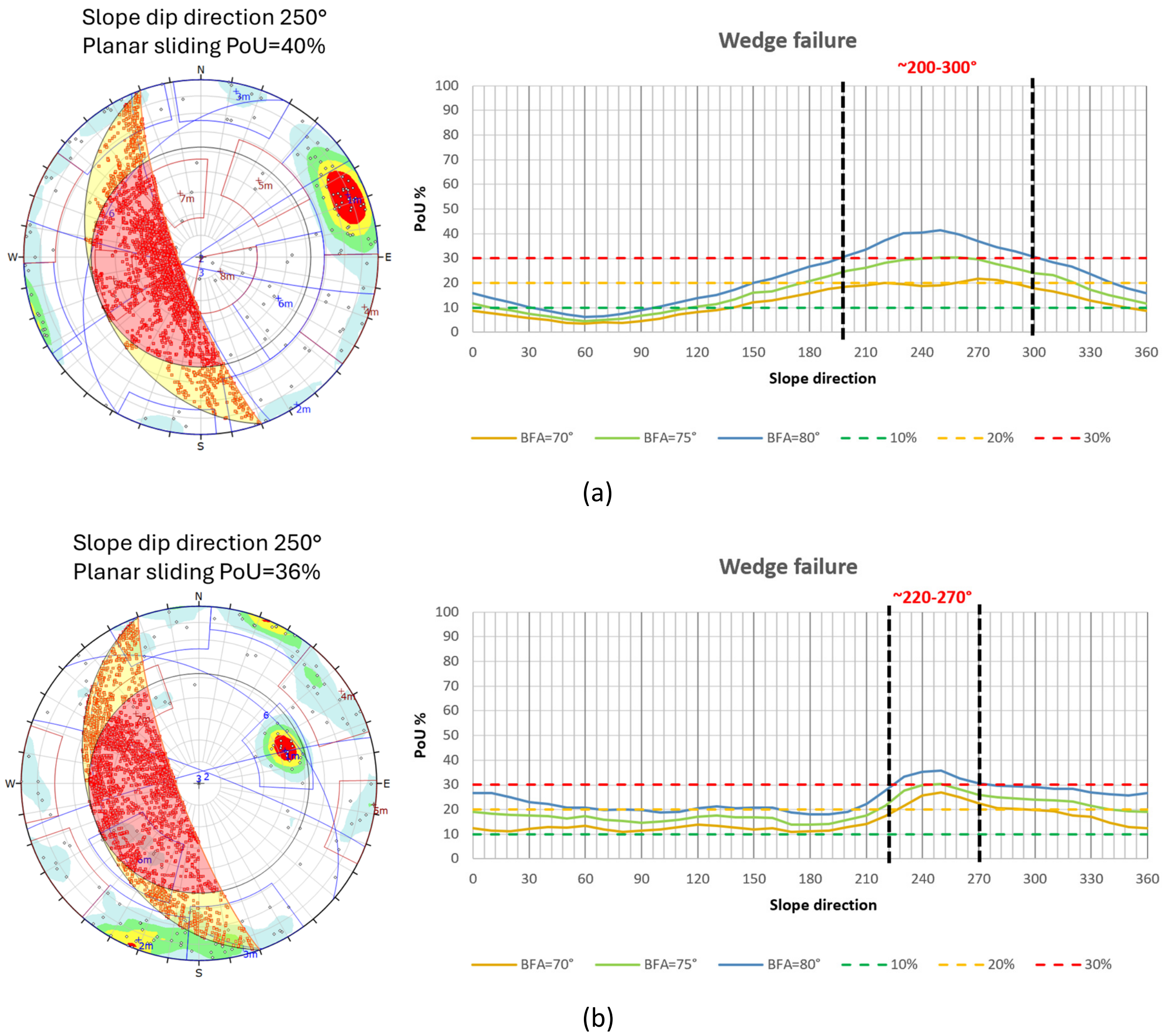


Figure 11 Stereographic analysis – wedge failure: (a) Big Mack; (b) Radio Hill

At Big Mack, joint set 1 m (79°/247°), which dips steeply to the southwest, shows clear potential for planar sliding if bench faces are designed at 80°. Although less evident on the stereonet, joint set 6 m (41°/298°), dipping moderately to the northwest, is also considered influential for planar failure potential in the east wall. The combination of sets 6 m and 1 m may further contribute to wedge failure mechanisms within the same sector.

At Radio Hill, the dominant joint set 1 m (43°/249°) dips moderately to the southwest and is expected to significantly influence planar failure potential in the east wall. Additionally, the combination of joint sets 1 m (43°/249°) and 3 m (86°/345°) contributes to wedge failure mechanisms in the same sector.

Based on planar and wedge stereographic failure analyses, a BFA of 80° is suitable for all slope orientations except those with dip directions between 200 and 300° in the east wall, where a reduced BFA of 75° is required.

Stereographic analysis using Dips was undertaken as an initial step to identify pit sectors with a high PoU, which highlighted the east wall as less stable. Other slope orientations were indicated to be more stable. As a result, more detailed and advanced stability assessments focused primarily on the east wall, while assessment of the west wall was included mainly for comparison purposes.

4.3 Simple block-based analyses

Analyses using MWedge calculate key wedge parameters, including PoF, FoS, CL, SW, volume of failed material and the distribution of these parameters, which allow for percentage-based assessment.

While FoS was also calculated deterministically for individual wedge configurations based on specific joint set combinations, greater emphasis was placed on the probabilistic analyses. Summary results for the Big Mack and Radio Hill pit sectors are presented in Table 2.

Table 2 Probabilistic analysis results using MWedge

		Bench–berm configuration				Berm required (m)				Failure volume	
Pit sector	Slope dip direction (°)	BH (m)	BFA (°)	BW (m)	IRA (°)	CL (mean) (m)	SW (mean) (m)	SW 90% (m)	PoF (%)	V 90% (m^3)	V (Max) (m^3)
Big Mack-W	90	18	80	8	58.2	2.0	2.0	3.5	18.5	20	176
Big Mack-E	290	18	70	8	51.0	2.0	2.0	4.5	25.5	50	441
Radio Hill-W	60	18	80	8	58.2	4.0	4.5	5.0	18.4	45	295
Radio Hill-E	260	18	70	8	51.0	3.2	4.9	6.0	27.6	110	554

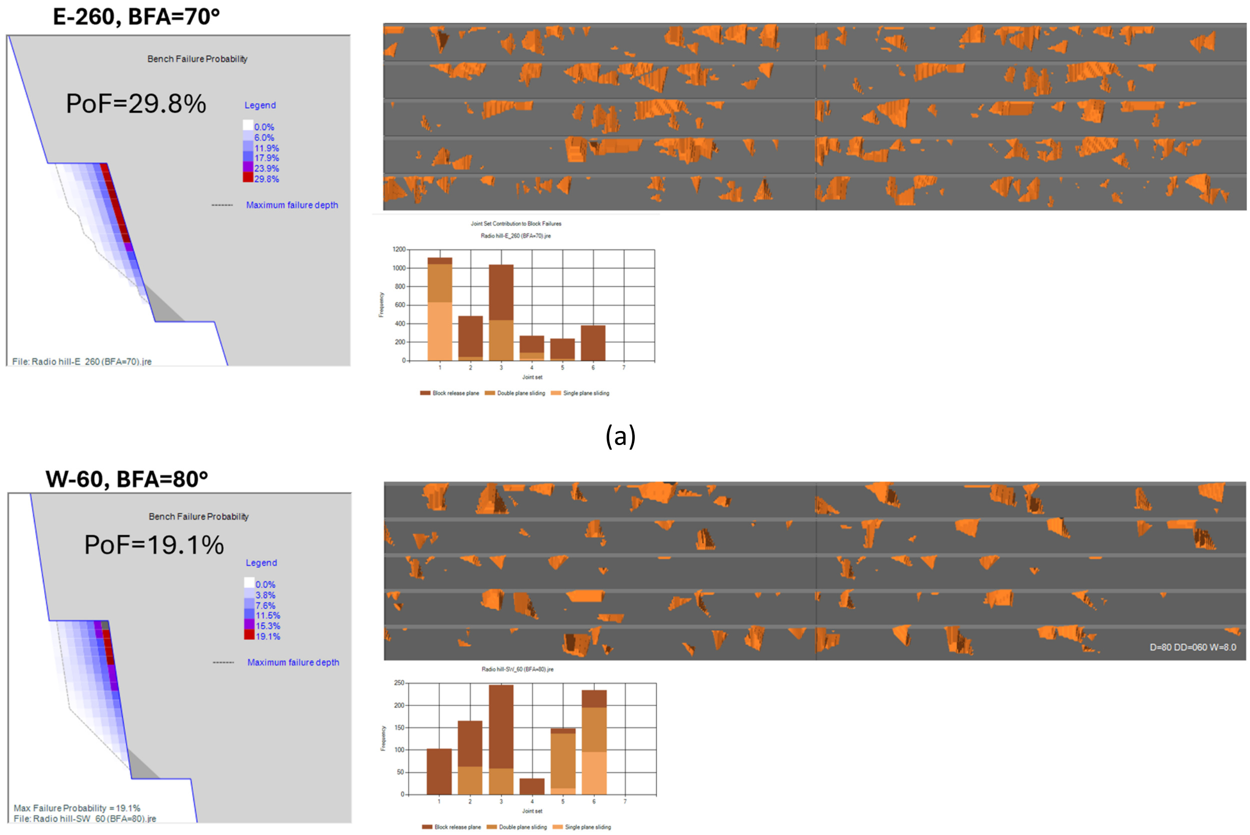
Note: values in red text indicate relatively high Probability of Failure and failure volume.

Based on the outcomes, a design BFA of 70° was considered acceptable for the east walls to meet the DAC criterion of PoF ≤ 30%. A steeper BFA of 80° was recommended for the west walls, which also satisfies the DAC requirement. These results were deemed sufficient to support design decisions for a berm width of 8 m, ensuring the retention of at least 90% of the potential spill SW. CL was not considered in berm retention capacity to avoid overly conservative outcomes when the wedge apex is considered in this method.

4.4 Stochastic joint network analyses

Although more advanced (stochastic joint network) analyses were not strictly required, they were nonetheless conducted for comparison purposes and to support more refined berm width adjustments. Analyses were carried out using SBlock software. SBlock analysis results are presented in Table 3.

An example of SBlock result plots for the Radio Hill pit is presented in Figure 12, comparing the east (slope dip direction of 260°) and west (slope dip direction of 60°) sectors. The PoF is higher in the east sector, despite the application of a flatter BFA of 70°, compared to a steeper BFA of 80° in the west sector. This is also supported by block visualisation of the slope (looking horizontally at the slope face), which shows a noticeably greater number of failure blocks in the east sector. The predominant failure mechanism in the east sector is planar sliding associated with joint set 1 m, along with wedge failures involving joint sets 1 m and 3 m, as illustrated in the joint set histogram in Figure 12a.



(a)

(b)

Figure 12 SBlock result plots for Radio Hill pit sectors. (a) East; (b) West

Table 3 Probabilistic analysis results using SBlock

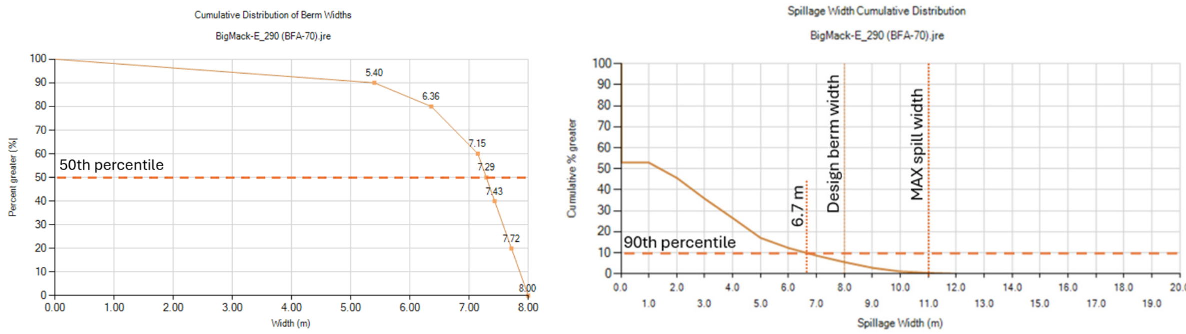
Pit sector	Slope dip direction (°)	Bench–berm configuration				Berm required (m)				PoF (%)	Failure volume (mean) (m^3/m)
		BH (m)	BFA (°)	BW (m)	IRA (°)	CL (mean) (m)	SW (mean) (m)	SW 90% (m)	FB (m)		
Big Mack-W	90	18	80	7	60.5	0.4	3.1	5.5	1.1	15.0	12.2
Big Mack-E	290	18	70	8	51.0	0.7	3.7	6.7	0.6	29.6	10.2
Radio Hill-W	60	18	80	8.5	57.0	0.6	4.0	7.5	0.4	19.1	16.9
Radio Hill-E	260	18	70	8.5	50.1	0.7	4.1	7.4	0.4	29.8	12.1

Note: values in red text indicate relatively high Probability of Failure and spill width.

The results were interpreted based on the PoF and berm catch capacity, which were assessed using the mean CL and the 90th percentile of SW (SW_{90}). For example, in the Big Mack east sector, the mean crest loss is approximately 0.7 m, resulting in a post-failure berm width of 7.29 m (Figure 13a). The SW_{90} is approximately 6.7 m (Figure 13b). Based on these values, the FB was calculated as follows:

$$FB = BW - CL - SW_{90} = 8 - 0.7 - 6.7 = 0.6 \text{ m} \tag{3}$$

As the resulting FB is slightly above zero, berm adjustment is not required. Therefore, a berm width of 8 m for Big Mack-E was considered acceptable.



(a) (b)

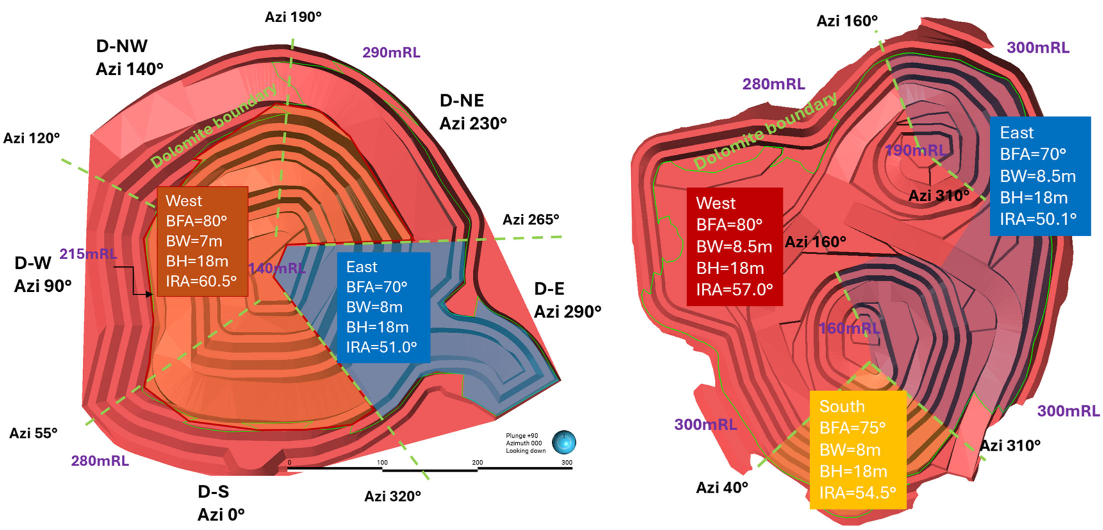
Figure 13 Histograms for berm width assessment in the east sector of Big Mack. (a) Berm width after failure (reflecting crest loss); (b) Spill width

Although the outcomes from the stochastic joint network analyses differed slightly from the direct simple block-based analyses, the overall conclusions remained consistent. The east wall benches were confirmed to be less stable due to unfavourably oriented joint sets that promote undercutting, with PoF approaching 30% for BFA = 70°. In contrast, the west wall benches demonstrated acceptable stability, even with steeper bench face angles (BFA = 80°), maintaining PoF well below 30%.

One key distinction highlighted by the stochastic joint network analyses was the prediction of higher spill volumes. For example, in the east wall sectors, the SW required to retain 90% of the failed volume could reach up to 7.5 m (see Table 3), whereas previous analyses suggested values of up to 6 m (see Table 2). The berm width estimated from the stochastic joint network analyses is considered more realistic and accurate, as it accounts for the influence of multiple joint sets contributing to failure mechanisms.

4.5 Outcomes

The recommended slope design geometries for the Big Mack and Radio Hill pits in dolomite rock are summarised in the Figure 14. An overall slope stability analysis confirmed that the proposed configuration remains stable under steeper bench geometry.



(a) (b)

Figure 14 Slope design recommendations for the pits in dolomite rock. (a) Big Mack; (b) Radio Hill

An example of the current Big Mack cutback pit excavated using the recommended bench–berm parameters is shown in Figure 15.

Figure 15 Examples of slope performance with recommended bench–berm parameters at Big Mack

To address design uncertainties, further structural mapping, laboratory testing, and reassessment of the bench–berm configuration – based on calibrated structural data and observed slope performance – may be required. While berm widths were quantitatively assessed as an alternative to the empirical Ritchie criterion, the approach focuses on bench-scale failure volumes. In addition, the potential for increased rockfall from smaller blocks – particularly where narrower berms are used – should be acknowledged.

5 Summary and conclusion

This paper has presented key theoretical considerations and practical methodologies for bench–berm design, discussing stereographic analyses, simple block-based analyses and stochastic joint network analyses. This was followed by a case study demonstrating the application of these analyses – supported by engineering judgement and site-specific experience.

Stereographic analysis was initially conducted to identify pit sectors with a PoU and to determine the structural sets contributing to potential failure mechanisms. This preliminary assessment allowed for early identification of geotechnically sensitive sectors and confirmed areas with minimal potential for structurally controlled failure.

Simple block-based analyses were then conducted to assess the PoF, failure volumes and SW. These results helped validate the designed berm width and guided adjustments to the BFA to satisfy the required DAC for PoF in the sectors under consideration. The outcomes from this method were sufficient to support design decisions, particularly in cases where reliable calibration data on slope performance was limited.

Stochastic joint network analyses were performed to validate and cross-check the outcomes. While the results from the methods showed slight differences, the conclusions remained consistent in identifying the sectors with benches that are less stable due to unfavourably oriented joint sets that promote undercutting, and those sectors with benches demonstrating acceptable stability, even with steeper BFAs. Stochastic joint network analyses indicated a larger spill volume potential due to the contribution of multiple joint sets to the failure mechanisms. Accordingly, SW estimates from stochastic joint network analyses were considered more accurate to serve as a basis for berm width refinement. These assessments can be further improved once site-specific calibration data – based on observed slope performance – is available.

The choice of design analysis method depends on data reliability and the stage of the project – more advanced analyses become viable as input confidence improves. Regardless of the approach, a clear understanding of the structural fabric is essential, with emphasis on consistent, primary joint sets. Key parameters such as shear strength, discontinuity orientation, persistence, and spacing must be well defined. When assessing berm width quantitatively, the technical team should determine acceptable SW tolerances and whether crest loss should be considered, and if so, whether it is systematic or variable. If narrower berms are adopted, the potential increase in rockfall risk from smaller blocks should also be considered.

Acknowledgement

The authors thank Consolidated Minerals for granting permission to present this paper, and acknowledge Esteban Hormazabal and Gabriel (Essie) Esterhuizen for their review and valuable comments.

References

Bonnet, E, Bour, O, Odling, N, Davy, P, Main, I, Berkowitz, B & Cowie, P 2001, 'Scaling of fracture systems in geological media', *Reviews of Geophysics*, vol. 39, no. 3, pp. 347–383.

Bowles, JE 1990, *Foundation Analysis and Design*, 4th edn, McGraw-Hill, New York.

Esterhuizen, GS 2025, *SBlock*, computer software, https://sites.google.com/view/ayzprojects

Gibson, W 2015, *MWedge*, computer software.

Gibson, W, de Bruyn, I & Walker, D 2006, 'Considerations in the optimisation of bench face angle and berm width geometries for open pit mines', *Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering*, The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 559–578.

Goodman, RE & Shi, GH 1985, *Block Theory and its Application to Rock Engineering*, Prentice-Hall, Englewood Cliffs.

Hoek, E 2009, 'Fundamentals of Slope Design', *Slope Stability 2009: Proceedings of the International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, 9–11 November 2009, Santiago, Chile*, Australian Centre for Geomechanics, Perth.

Hormazabal, E 2013, 'Bench berm design using probabilistic key block analysis', in PM Dight (ed.), *Slope Stability 2013: Proceedings of the 2013 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 227–236, https://doi.org/10.36487/ACG_rep/1308_10_Hormazabal

Hormazabal, H, Prudencio, M & Cofre, M 2019, 'Design and performance of rock slopes at bench scale', paper presented at 1st Bolivian Congress on Rock Mechanics, CONBOLMER, Cochabamba.

Read, J & Stacey, P (eds) 2009, *Guidelines for Open Pit Slope Design*, CSIRO Publishing, Collingwood.

Rocscience 2022, *RocPlane – Persistence and Bench Design Theory Manual*, viewed 3 August 2025, https://www.rocscience.com/help/rocplane/verification-theory/theory-manuals

Rocscience 2025, *Dips*, computer software, https://www.rocscience.com/software/dips

Rylnikova, MV & Zoteev, OV 2022, *Guidelines for Determining the Parameters of Pit Slopes, Benches, and Waste Dump Slopes*, IPKON RAS, Moscow.

WSP 2025, *FracMan*, computer software, https://www.wsp.com/en-gl/services/fracman