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BHP Western Australia Iron Ore geotechnical open cut slope design system: a simple pragmatic process for slope risk decisions

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Abstract

A transparent, pragmatic geotechnical design system is outlined that presents a selection of risk options with associated risk/reward for decision makers. Risk options termed 'robust', 'balanced' and 'aggressive' have been defined appropriate to 'critical infrastructure', 'typical industry' and 'low risk' mining environments (where the safety risk and the consequences of failure on the budgeted mine plan are acceptably low), respectively. The geotechnical model includes 'most realistic' and 'reasonable lower case' conditions. A 'realistic' design principle requires reporting a Factor of Safety on the realistic case, rather than to reduce design inputs due to uncertainty. Uncertainty is transparently covered by the 'lower case' in sensitivity analyses. Indicative probabilities of failure are estimated and a simple empirical tool estimates the consequence of failure in terms of the area of mining floor impacted. These together with indicative value or tonnage estimates are presented to the decision maker (risk owner), with a selection recommendation. Post decisions, designs including any residual hazards are passed to the operational engineers to design risk-based slope monitoring, to ensure operational safety, and reconciliation programs, as required. Adoption of the realistic principle has facilitated risk owners taking decisions based on a more transparent presentation of risk since 2014 and made a material contribution to a step change slope angle increase in the mines of BHP Western Australian Iron Ore.

Keywords: *design, uncertainty, failure, risk*

1 Introduction

BHP Western Australia Iron Ore (WAIO) own and operate open cut iron ore mines in the Pilbara region of Western Australia. The pits are predominantly in Archean folded banded iron formations with some tertiary age sediments. Approximately 40 active cutbacks are mined at any one time, with ultimate design depths between 50 to 450 m but typically 100 to 150 m. The average mining depth across the portfolio in 2018 was only approximately 50–75 m. From 2000 to 2014, geotechnical design was outsourced to various parties, with differing design principles and variable levels of transparency on strength evaluation. Since 2014, designs were carried out to a common design philosophy with evolving design principles. This was largely based on common industry practices, however, it mandated realistic strength estimates for the most credible case and sensitivity analyses on lower cases with corresponding lower case acceptance criteria. In this paper, this slope design process for approving pits for construction is outlined and the high level results of implementation to date. Thereafter there is a discussion and conclusion.

2 Process overview

Figure 1 outlines the geotechnical design process, stepping through from data collection to model development, analysis, risk assessment and slope option selection. The main points of which are drawn out in the subsequent sections.

The focus in this paper is predominantly on approving designs for construction, particularly:

- A geotechnical model that provides realistic and credible lower case estimates for key parameters.
- Analysis that includes indicative probability of failure (PoF) estimates.
- Slope risk options with varying acceptance criteria.
- A simple assessment of risk and relative value of the options.
- Accountability for slope decisions.

3 Data collection

Each discipline (geotechnical, geology, hydrology) is accountable to collect data as an input to models that are fit-for-purpose for the design stage. Investigation designs are shared for cross-discipline comment to optimise data collection. For the rock mass model, for pits for construction, this typically involves a site-specific geotechnical ground investigation that aims to generate suitable data on the geotechnical units that are material to the design and to cover a reasonable geographic range. This typically includes site-specific diamond core and televiewer of reverse circulation (RC) and diamond holes.

4 Geotechnical model

As far as reasonably practical, the geotechnical model is based on the concept of a realistic design principle. The realistic design principle aims to present the most realistic representation of the in situ ground conditions that will control stability. This is assessed irrespective of data quantity or quality. Any uncertainty in this assessment is then covered by an estimate of what a lower reasonably credible case or 'lower case' estimate could be. The lower case is not the absolute minimum condition of a parameter or a combination of multiple lower case parameters, unless these are correlated. Notwithstanding that the combination of these multiple lower case conditions may occur, their probability of occurrence is considered to be sufficiently low as to not influence the design decision.

The geotechnical model is the synthesis of the major stratigraphic/structural, hydrological, rock mass and minor structural models.

The geoscience team provide major stratigraphic and structural (fault) models, typically based off 50 × 50 m exploration RC drilling. Confidence solids for the model are provided. Confidence is based on a rating matrix including drillhole spacing, interpretation confidence (logging, geochemistry, geophysics), supporting televiewer data and major structure intercepts.

Hydrology provides estimates of the groundwater pressure in 2D line sections or occasionally 3D models and representation again of the most realistic and lower case estimates.

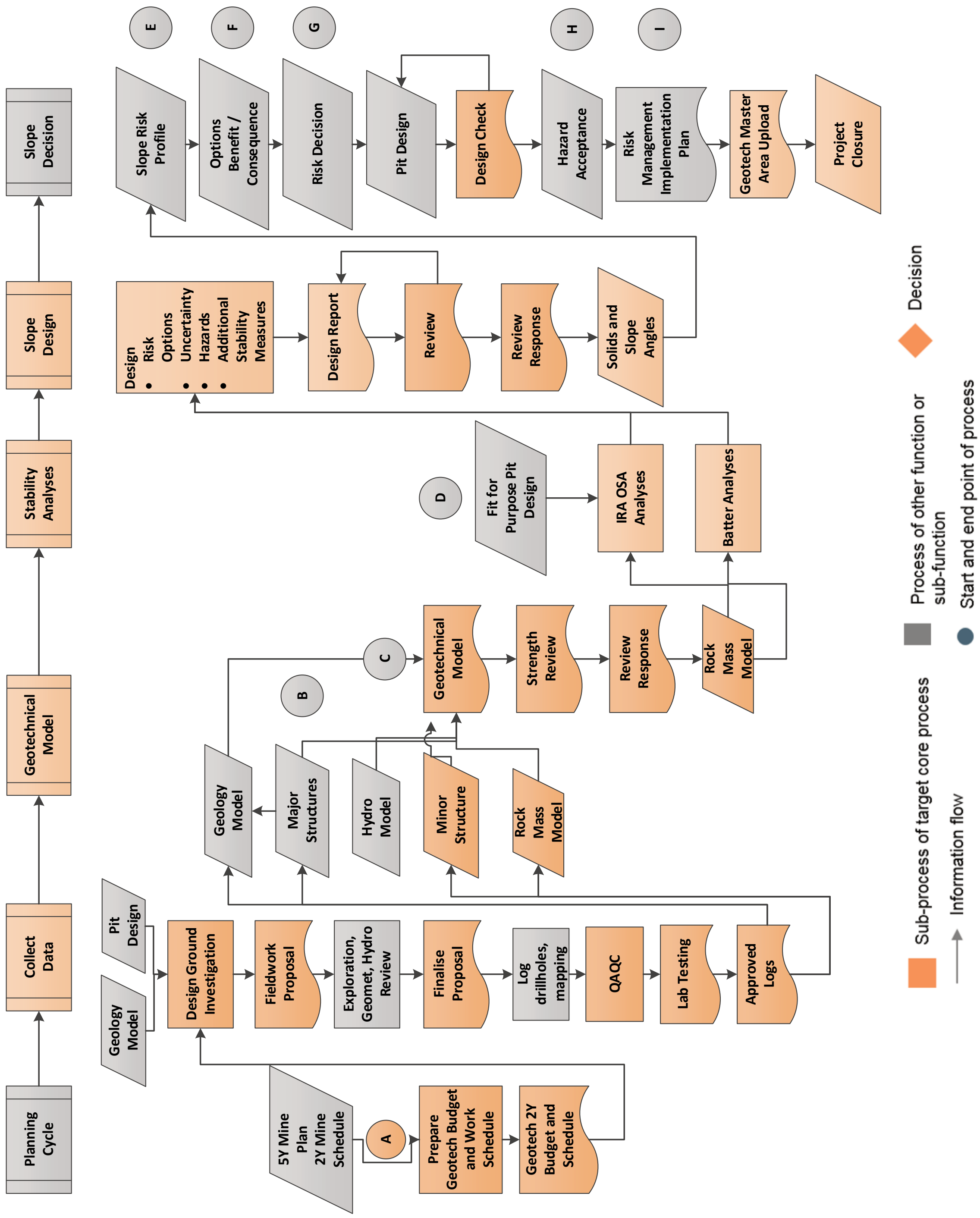

Figure 1 Western Australia Iron Ore slope design process overview

The geotechnical discipline constructs the rock mass and small-scale structural model. Where sufficient data exists, selection of central and lower cases, is typically performed from histograms. As a proxy for a lower case estimate in a 'homogeneous' material the 25th percentile lower case may be taken if data confidence is high (say a large number of drill metres in that unit) or a 16th percentile if low. If data is poor, benchmarks from other Pilbara designs or industry literature may be adopted. Lately, design values for defect strengths in high confidence units have been taken from a reliable statistical database (Maldonado & Haile 2015; Maldonado 2017).

5 Stability analyses and optimisation

The pit is domained into sectors of reasonably similar geotechnical characteristics. For each domain, stability analyses are carried out at the batter scale using kinematic and limit equilibrium analyses, as required, using the most realistic case only.

At the inter-ramp angle (IRA) scale, typically 2D limit equilibrium analyses are carried out except in large scale complex environments where 3D numerical modelling may be adopted. Slopes are analysed to report a Factor of Safety (FoS) based on the most realistic case and sensitivity analyses on individual lower case elements, where these parameters are assessed as material to the design. The lowest stability result of the lower case elements analysed is reported. Slopes are optimised to dual acceptance criteria for designated slope risk options (Section 6).

From 2014–2017, indicative probabilities of failure were broadly inferred from typical industry FoS and PoF relationships, based on published data in Wesseloo & Read (2009). From 2018 onwards, a normal distribution of FoS was assumed. This normal distribution is constructed using the FoS results of the realistic case (typically the 50th percentile) and the percentile estimate of the 'controlling' lower case. From this the percentage of the curve at or below FoS 1 is taken as the PoF. This is illustrated in Figures 2 and 3.

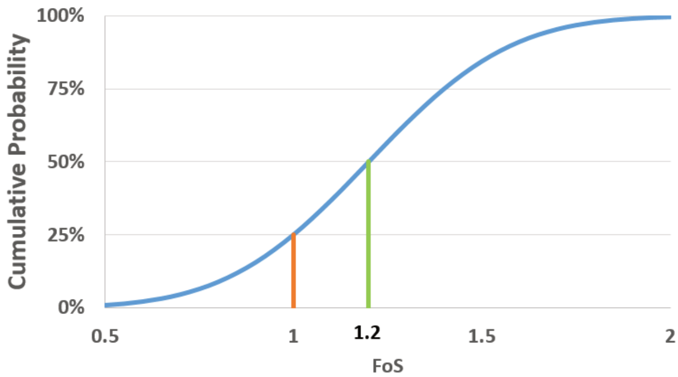

Figure 2 Cumulative probability for lower/central case FoS 1.0/1.2, where lower case is 25th percentile

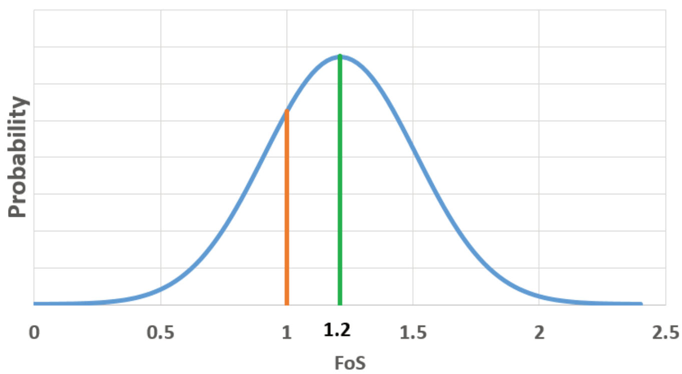

Figure 3 Normal probability density function for lower/central case FoS 1.0/1.2, where lower case is 25th percentile

Minimum berm widths are also assessed at this stage using empirical relationships after the Modified Ritchie criterion (Call 1992) and Ryan & Pryor (2000).

6 Acceptance criteria and slope options

Acceptance criteria have been set for:

- Batter stability (realistic case).
- Inter-ramp stability
  - Realistic case.
  - Lower case.
- Minimum berm width.

All must be satisfied in a particular domain. Some slopes are controlled by inter-ramp stability, whereas others by batter/berm configuration.

A range of acceptance criteria are provided to the business for different slope risk options. These are termed ‘robust’, ‘balanced’ and ‘aggressive’, which have been defined appropriate to ‘critical infrastructure’, ‘typical industry’ and ‘low risk’ mining environments respectively (Table 1). Note that in the context of ‘aggressive’, ‘low risk’ mining environments implies where the safety risk and the consequences of failure on the budgeted mine plan are acceptably low, notwithstanding that the likelihood of failure is higher than other options.

At the inter-ramp scale, acceptance criteria were determined as follows. Firstly, central case factors of safety for ‘critical infrastructure’, ‘typical industry’ and ‘low risk’ conditions, were taken from a review of typical industry values published in Wesseloo & Read (2009). Secondly, where a published acceptance criteria in Wesseloo & Read (2009) contained both a FoS and a corresponding PoF, these were plotted as data points on a graph with FoS and PoF as x and y axes. Fit curves corresponding to low, moderate and high uncertainty were plotted, again based data published in Wesseloo & Read (2009). Finally, the spread in FoS between central case and lower case was taken from the typical uncertainty in the distribution of input parameters for a low uncertainty environment. Low uncertainty was assumed given typical WAIO conditions where slope heights are <150 m, repetition of the same geology / geotechnical units, failure mechanisms and broadly similar strengths.

Table 1 Acceptance criteria for robust, balanced and aggressive slope options (H = batter height)

Acceptance criteria	IRA likely case (FoS)	IRA lower case (FoS)	Batter likely case (FoS, PoF)	Berm width (m)
Robust	>= 1.3	>= 1.1	>= 1.2, <= 15%	0.2H + 4.5
Balanced	>= 1.2	>= 1.0	>= 1.1, <= 30%	0.2H + 4.5
Aggressive	>= 1.15	>= 0.95	>= 1.0, <= 50%	0.17H + 3

An example summary of balanced case IRA results for a typical cutback are presented in Figure 4.

Once the final slope design has been reviewed, and revised if required, 3D slope solids representing each domain and a set of batter berm configurations for each slope risk option are provided to mine planners for high level pit design optimisation. Hazards (defined as sub-slope areas not meeting the acceptance criteria) can be provided for risk owner consideration, where reasonably manageable and with reasonable benefit. Such may be a local area within a domain with a low FoS that would otherwise control the domain, or allowing single batters as hazards provided sufficient corresponding berm width ‘compensation’ is provided. The design report also calls out specific design uncertainties and /or residual hazards. This is then made available to the site based geotechnical engineers to design risk-based slope monitoring and reconciliation programs, as required.

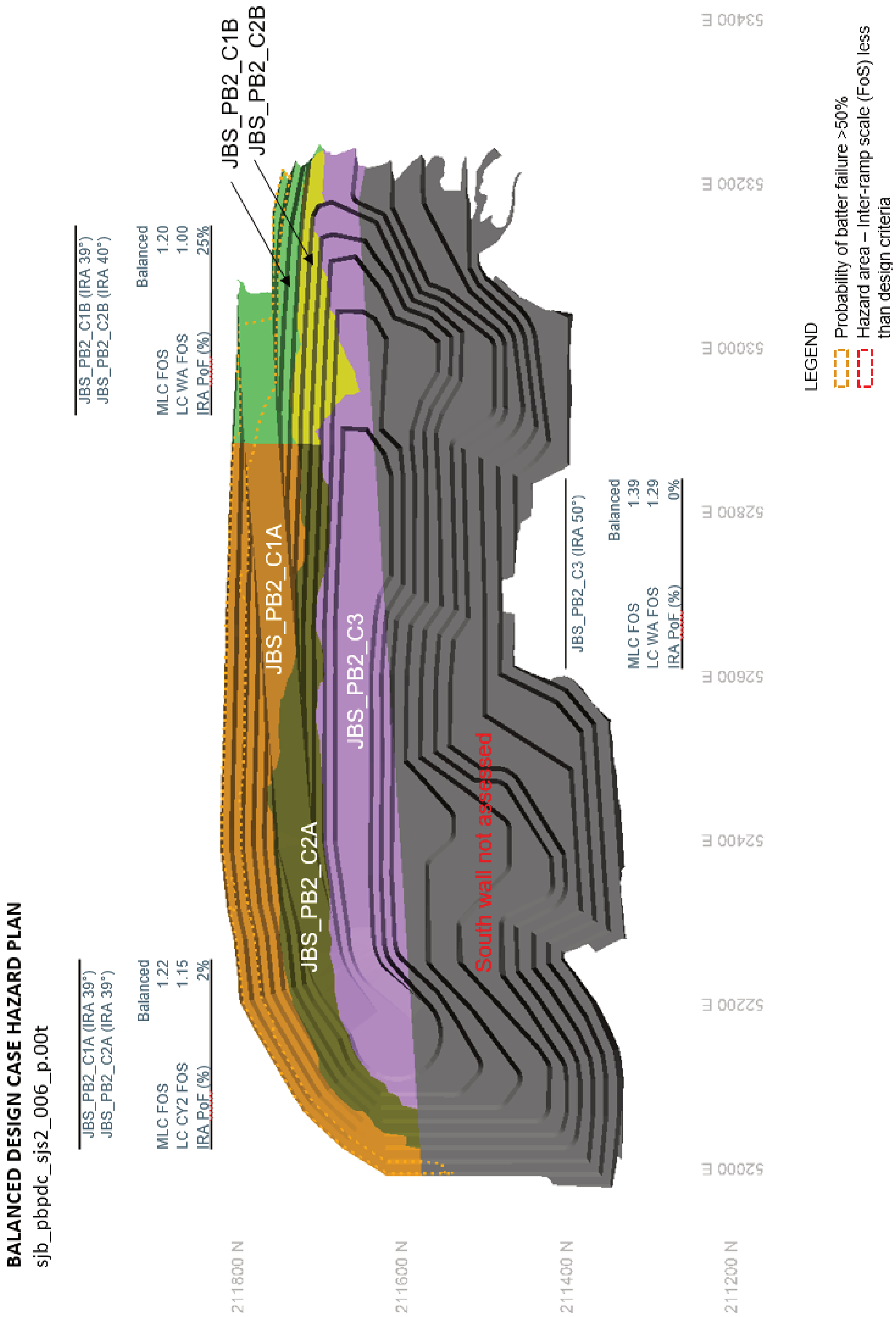

Figure 4 Example inter-ramp angle stability results for a typical balanced case (MLC = most likely (realistic case); LC = lower case; CY2/WA = material controlling lower case)

7 Simple risk assessment and value proposition

Risk assessment is performed at a high level in terms of likelihood and consequence.

For slopes controlled by batter/berm configuration, qualitative guidance is given on key risk aspects impacting expected slope performance; for example, failure to achieve design on steeper slopes with minimum berm widths can lead to an elevated safety risk profile, with the risk of 'step-ins' that sterilise ore. Lately, berm reliability, reported in monthly compliance to design has been quoted to inform this risk.

For likelihood in slopes controlled by inter-ramp stability, this is assessed on the basis of PoF (as derived from assumed statistical relationships between the central case and lower case FoS as described in Section 5). Consequences for slopes controlled by inter-ramp stability are assessed using the in-house slope risk profile tool. In the absence of incremental slope height analyses the tool factors the PoF against the exposed pit depth, up to the maximum PoF at the full 'daylight' elevation. This is based on typical generic geotechnical settings and failure mechanisms of the Pilbara. Run-out distance is based on an empirical best fit of models by Finlay et al. (1999) and two models by Whittall (2015) namely the optimised model and his interpretation of the stratified Fahrboschung angle for weathered weak rock. These assessments are based on a typically representative generic 40 degree inter-ramp slope.

This is then factored by the representative strike length of the domain (it is assumed that strike length fails) and the estimated PoF to return an indicative risk weighted impact in terms of expected metres squared of mining area impacted by failure material by elevation. Risked impacts of each elevations are then summed for all domains to show the cumulative risked impact area as a proportion of the total mining area for that slope risk option. Figure 5 shows an example comparing balanced and aggressive results for a particular cutback.

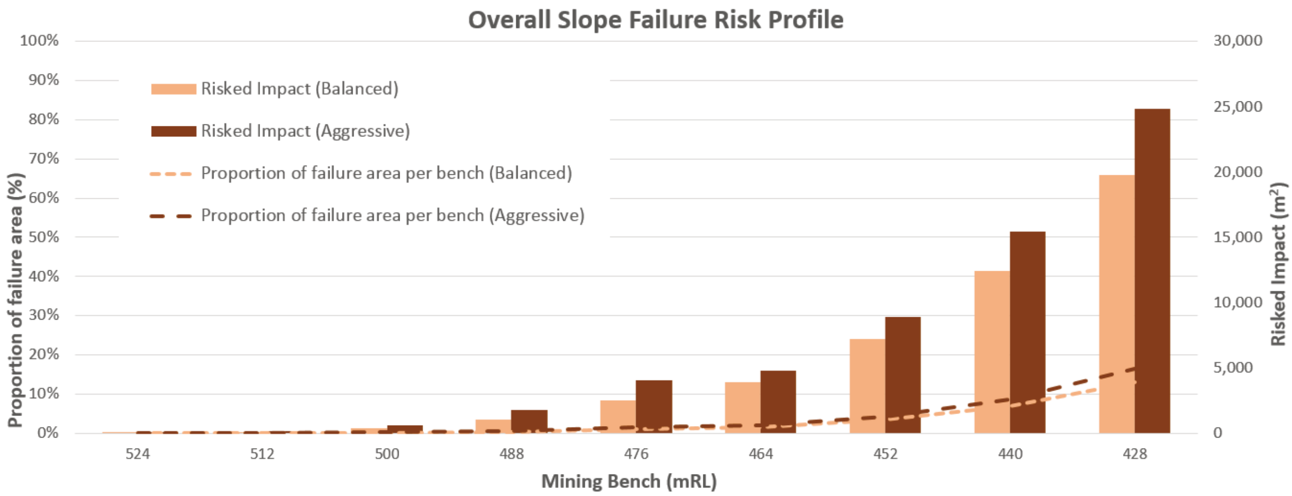

Figure 5 Example slope risk profile

These 'simplistic' analyses are considered suitable for the strategic level of the slope selection decisions; however, more 'optimised' analyses should be conducted on site-specific parameters where these 'generic' relations are not considered suitable for strategic slope selection decisions. For example, impacts on critical infrastructure such as a single access to the pit should be considered separately.

In terms of value proposition, since approximately 2017, mine planners have provided high level net present value (NPV), or related tonnage estimates, for each slope risk option so that the relative value proposition between them can be compared.

8 Slope decisions

From 2014 to 2016, the operations based manager of production planning would select the slope option for each domain. They would be supported at a meeting attended by key site, mine planning, geotechnical and hydrological stakeholders. Each domain would be reviewed and particular issues raised such as indicative PoF, hazards and particular consequences of failure, such as critical infrastructure (e.g. crusher or rail line), single or dual pit accesses, interim or final wall or impacts of failure to achieve rockfall capacity or production targets.

Since 2017, the process is similar in that the geotechnical team provide the slope options; however, the strategic mine planners now use these, with multi-disciplinary input, as the basis to make a single recommendation for endorsement by the production manager. The production manager is the final decision maker, being the single point of accountability for safety and production onsite. The main principle behind the mine planners making a recommendation is that they can better inform production contingency planning in the event of failure. In other words, they understand whether exposed ore is likely to be available elsewhere in the event a slope were to fail and therefore the additional risk worth taking. An example of slope selection presentation slide, for a single domain for typical cutback, is included as Figure 6. Table 2 shows the high grade feed difference for the cutback in Figures 4 and 5. The aggressive design allowed an additional bench of pit depth to be mined compared to the robust / balanced designs.

Table 2 High grade feed difference for a cutback relative to aggressive design

Slope risk option	Ore feed difference (%)	Ore feed (tonnes)
Aggressive	0	0
Balanced	-ve 3	-ve 702,000
Robust	-ve 3	-ve 774,000

9 Results

A review of slope option selection in 2017 found that typically 70% of slope options selected were 'aggressive', 29% 'balanced' and 1% 'robust'. On average, design slope angles have increased approximately 7 degrees since pre-2013. As a rule of thumb, balanced slopes were steepened by 5 degrees and an additional 2 degrees was achieved for the aggressive option. The uplift in the 'balanced' slope option is primarily attributed to the introduction of the new design philosophy in 2014, with new common design principles incorporating:

- Realistic design principle including:
  - Central estimate strengths.
  - Reduction of 'a' value of 5 to 1 in the Snowden Linear Anisotropic Strength model (Mercer 2012).
- Inferred waviness at inter-ramp scale in bedding controlled slopes.
- Adoption of more double batters.
- The disturbance factor of D = 0.7 was constrained to the slope nearfield rather than across the whole model.

In terms of outcomes, multi-batter slope failures have been few. Some sites have had issues in achieving designs controlled by aggressive narrow berms and now tend not to select these.

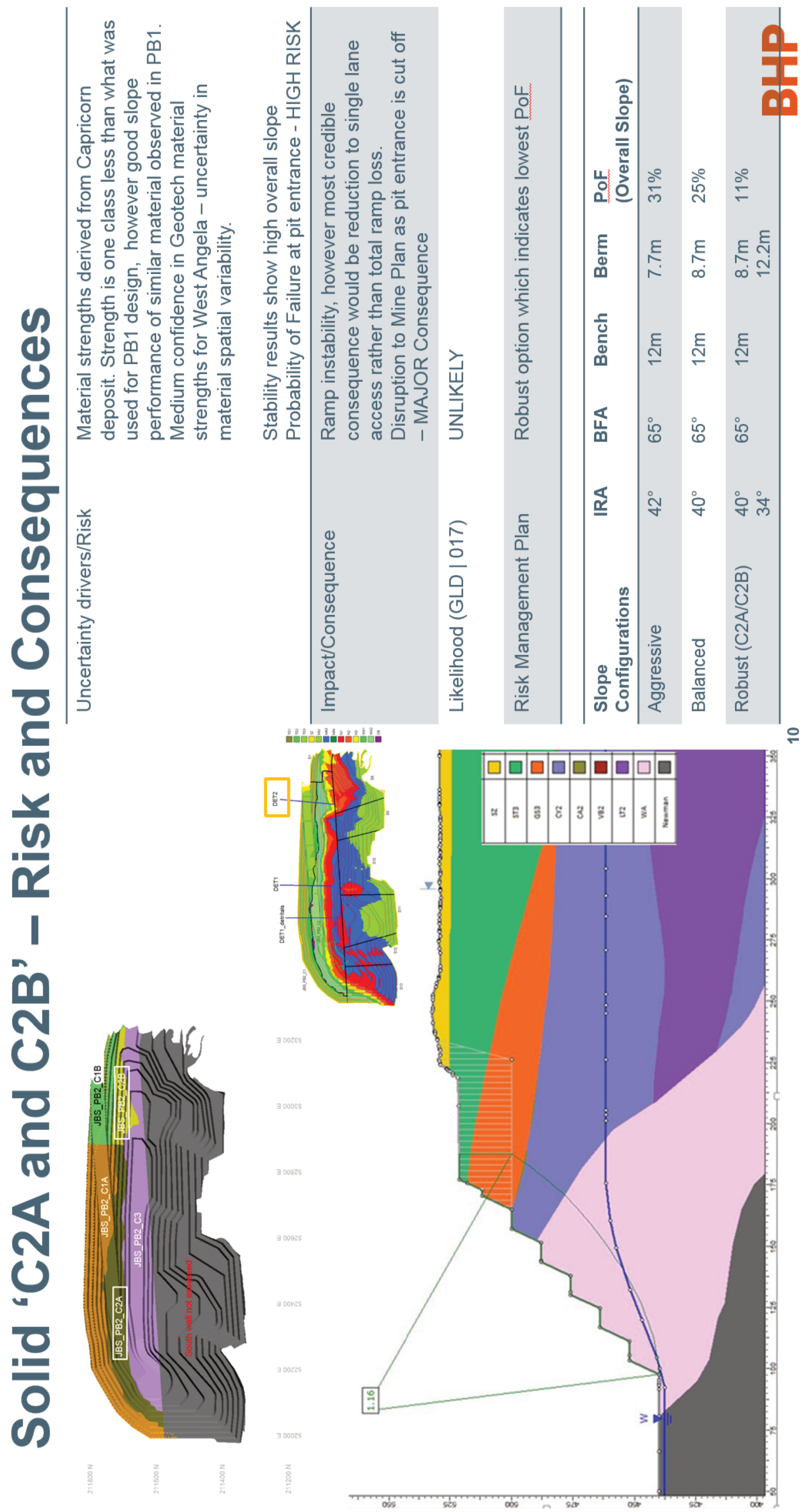

Figure 6 Example domain slope risk profile communication slide

10 Discussion

In some pre-2014 designs, the reported FoS was based on the 25th percentile due to uncertainty, or in other cases the basis of a selected design value was not fully reported. The introduction of the realistic and lower case design principles and clearer parameter derivation has made uncertainty transparent.

In addition, moving to consistent design principles the designs are altogether more consistent. This not only offers a more realistic and consistent expression of risk but also in time generates a large, consistently designed as-built dataset of pits, where design principles can be reconciled and improved (i.e. comparing apples with apples).

Despite introducing lower case sensitivity analyses and associated acceptance criteria, where the lower case criterion can control the slope selection, with the realistic case significantly exceeding the acceptance criteria, overall designs have steepened. This is predominantly due to the various factors described in Section 9.

A further advantage of the lower case is that it offers flexibility to proceed to construction in areas of poor data by drawing on lower cases estimated from benchmarks or literature.

Moving to estimates of PoF, although initially very simplistic, has been powerful in communicating relative likelihood of failure between options. This has been more illuminating than quoting FoS alone, which some parties, if not guided appropriately, can interpret as 'this slope will not fail'. PoF also supports operational staff tasked with designing monitoring and reconciliation programs. Such PoF estimates are now becoming more refined (Section 7), however high probabilities of failure for IRA slopes controlled by rock mass have not transpired into a proportional number of IRA failures to date. Investigation of this may bring more refinement and confidence in the design process.

The different slope risk options 'robust', 'balanced' and 'aggressive', again support consistency and common understanding across the business of both the 'sensitivity' of the slope to mining practice and the likelihood of business disruption. However, the risk profile and necessary controls for successful implementation requires careful communication, documentation, handover and regular refreshing to risk owners (managers of production).

In practice, slopes can be implemented 2 to 10 years after taking slope option decisions. Records of slope decisions are recorded; however, Production commitments to monitor and modify excavation practices as required were not. Most managers taking slope decisions move before construction and commitments can be lost. Understanding of the terms has improved, but it has taken several separate ore sterilisation events for these lessons to be learnt.

Managers also need to be kept up to date with their risks. Having said that, despite being informed of leading indicators on poor design compliance by geotechnical staff, this has not always led to successful resolution. This is considered to be due to the inherent flexibility and optionality of the Pilbara iron ore mining environment, such that sterilisation events typically do not immediately impact budgeted production. Finally, incoming Managers need to be brought up to speed with the risk options, their risk profile and the controls they own to be able to manage it appropriately.

None-the-less, the options of 'robust', 'balanced' and 'aggressive' are found to be fit-for-purpose to fulfil their design intent of protecting critical infrastructure, enabling a typical mining environment and realising more opportunity, respectively. In actuality, 'robust' has rarely been used; again due to the inherent flexibility in mining operations and the remoteness of critical infrastructure from the influence of most pits.

We are still dependent on engineering judgement and compliance to design reconciliation to inform the likelihood of ore sterilisation due to the cumulative loss of catch capacity in aggressive narrow berm designs. A lot of value can be gained from tracking slope performance, e.g. berm reliability to inform corrective actions, future slope decisions and investigation of slope over-performance, as described above.

In terms of assessing the consequences of slope failure, the risk profile tool is a simplistic representation of the estimated run-out distance, based on a generic pre-failure 40 degree IRA, and assumes all the representative length of the domain fails and the impacted areas are not cleaned up (worst case scenario). As these consequences are factored by likelihood (PoF), it does not represent the actual impact of a failure event. However, for business planning purposes across BHP WAIO situation this would average out across all deposits. Although simple, it does communicate indicative differences between risk options and can semi-quantitatively highlight when to schedule availability of contingent ore (e.g. 2 benches above floor). It does not capture narrow berm and specific ramp risks. Clearly, these should be called out separately.

Turning to slope decisions, in the early stages, without a value proposition, decision makers bemoaned a lack of economic assessment (provision of NPV or ore tonnage differences) to support their decisions. Having such information available is extremely valuable. Finally, the decision sits with the right person, they own the safety risk and they are empowered to implement the controls. It is not a geotechnical accountability to pick the risk profile for the company.

11 Conclusion

Since the implementation of the WAIO Geotechnical Design System in 2014:

1. The realistic design principle allows for
   a. Transparency of known risks; and
   b. Offers flexibility to proceed to construction in areas of poor data (acknowledging that with more data the design could potentially be optimised further).
2. The risk profile and necessary controls requires careful communication, documentation, handover and regular refreshing to existing and incoming risk owners.
3. Designs are consistent, offering a more reliable, transparent basis to take decisions, manage the risk in operations and to reconcile and further optimise the system.
4. The system, particularly the new design principles, including the realistic design principle and introduction of the ‘aggressive’ option, have steepened slope designs on average by about 7 degrees.
5. In execution, as a generalisation, inter-ramp stability has over-performed whilst aggressive narrow berms in steeper slopes have under-performed and impacted on some of the anticipated savings.
6. Reconciliation offers the opportunity to highlight emerging risks and to refine reliability in the design principles and methodology.
7. The risk profile tool, whilst simplistic, communicates the indicative difference between slope risk options, which can semi-quantatively highlight when to schedule availability of contingency ore. It does not however capture risks associated with narrow berms and specific ramps, which need to be called out separately.
8. Decision makers struggle to take slope risk decisions without some indication of the economic difference between risk options.
9. The risk owner, who is typically the Manager mining is formally engaged in collaborative discussions with mine planning and geotechnical staff and has final say to endorse or reject the recommended risk profile.

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