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# Development and application of a reliability-based approach to slope design acceptance criteria at Bingham Canyon Mine

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## Abstract

*In 2009, CSIRO published Guidelines for Open Pit Slope Design (Read & Stacey 2009). As with many high-quality guidelines, this publication became broadly accepted as a standard across the surface mining industry. Similarly, Table 1.1 of this guideline, which details typical Factor of Safety and Probability of Failure acceptance criteria values, has been adopted in terms of allowable mine slope design.*

*Following the 2013 Manefay slope failure event at Rio Tinto Kennecott's (RTK) Bingham Canyon Mine, scrutiny on how pit slopes were designed and approved across Rio Tinto increased, with a heightened focus on data reliability, consequence of slope failure and appropriate design peer review. Given that the mine has been in operation since the early 1900s, it has amassed an enormous amount of geological, geotechnical, hydrogeological, and slope performance data. Based on this data and the quality of RTK's component geotechnical models, the mine team challenged itself to see what could be done to refine its own in-house process for definition of slope design acceptance criteria.*

*RTK undertook a multi-disciplinary approach to development of defined levels of confidence for a range of model inputs to slope design. Once completed, these definitions were employed to allocate 'confidence scores' for each model element and specific pit slope design sector. These scores were then weighted and aggregated to provide an overall confidence score, which, when combined with a clear understanding of business risk during ongoing mine development, led to a more informed and technically defensible methodology for slope design acceptance.*

*This paper describes the reliability-based approach to design acceptance criteria developed at RTK and presents an example of its application in optimising slope designs relative to model confidence and associated business risk.*

**Keywords:** *Bingham Canyon Mine, design acceptance criteria, slope optimisation*

## 1 Introduction

For many years, engineers have used acceptance criteria in order to set thresholds for acceptance of a slope design to a given risk tolerance, prior to implementation. Dependent upon consequence of design failure and acceptability of risk, these criteria have varied significantly. Examples of typical mine slope design acceptance criteria (DAC) are set out in CANMET (1977), Priest & Brown (1983), and Swan & Sepulveda (2000), although numerous other papers have been published and used across the industry.

In 2004, the Large Open Pit (LOP) initiative was implemented with membership including many major mining companies, including Rio Tinto from 2006 to the present. Under the leadership of Dr John Read, a key focus for the LOP was creation and publication of *Guidelines for Open Pit Slope Design,* Read & Stacey (2009), to summarise and detail the essential information for the 'engineer on the hill'. These guidelines were to assist in definition and implementation of fit-for-purpose mine slope designs to deliver value and manage risk to levels acceptable to the relevant company or legislation. Table 1.1 of this guideline represents typical Factor of Safety (FoS) and Probability of Failure (PoF) acceptance criteria, as defined in a 'smoke-filled room' by a group of eminent mine geotechnical practitioners involved in the LOP project (Table 1).

**Table 1 Typical FoS and PoF acceptance criteria values (Read & Stacey 2009)**

| Slope scale | Consequences of failure | Acceptance criteria[a] | | |
|---|---|---|---|---|
| | | FoS (min) (static) | FoS (min) (dynamic) | PoF (max) P[FoS ≤ 1] |
| Bench | Low-high[b] | 1.10 | NA | 25–50% |
| Inter-ramp | Low | 1.15–1.2 | 1.0 | 25% |
| | Moderate | 1.20 | 1.0 | 20% |
| | High | 1.2–1.3 | 1.1 | 10% |
| Overall | Low | 1.2–1.3 | 1.0 | 15–20% |
| | Moderate | 1.30 | 1.05 | 10% |
| | High | 1.3–1.5 | 1.1 | 5% |

a: Needs to meet all acceptance criteria, b: Semi-quantitatively evaluated

The FoS and PoF criteria listed in Table 1 vary relative to generic levels of failure consequence although do not consider confidence in, or quality of, data inputs in the estimation of failure likelihood. As such, the values listed represent a blunt instrument, in terms of design, and rightly leave definition of confidence and levels of acceptable risk to the slope owner.

# 2 Background

In April 2013, Rio Tinto Kennecott's (RTK) Bingham Canyon Mine experienced what is arguably the largest ever in-pit slope failure, namely the Manefay failure. This failure, although identified by monitoring and well managed from a safety perspective, was more extensive, and had a much larger run-out distance, than had been anticipated. The failure and the Bingham Canyon Mine recovery from it are presented in detail in Ross (2016). Post-failure, this event was subject to significant technical scrutiny with investigations identifying a number of key outcomes for both RTK as well as for Rio Tinto itself. One particular finding identified the need for increased scrutiny on how pit slopes were designed, peer reviewed and approved across the company.

The Bingham Canyon Mine has been in operation since the early 1900s, initially as a number of underground mining complexes and ultimately developing into one of the world's largest open pit mines. Over its period of operation, and as part of multiple investigation stages, it has amassed an enormous amount of geological, geotechnical, hydrogeological and slope performance data. Based on this data, the RTK team challenged itself to see what could be done to refine its own in-house slope design and associated acceptance criteria.

In 2015, RTK developed its reliability-based approach to definition of DAC.

# 3 Identification of slope geotechnical hazards and their consequences

Over its period of operation, the Bingham Canyon Mine has experienced failures ranging from single bench through to overall slope scale, and from thousands of failure tonnes to the 130 Mt of the Manefay failure. With this experience and based on the high-quality geotechnical monitoring practices in place, hazards are well understood and managed as part of current operations.

One of the findings of the Manefay failure investigations focused on the fact that the mine had a pre-conceived notion of the typical types of failure which occurred, and would continue to occur, at the mine. The Manefay failure mechanism and behaviour, particularly in terms of mass movement and run-out distance, was a significant departure from previous slope failure experience. A re-look and re-think of potential future failure mechanisms at the Bingham Canyon Mine was initiated, including consideration of scenarios to consider what if:

- An identified failure was much larger in height or extent than indicated by previous slope performance in the same slope sector?
- The failure occurred at a specific critical time within the mine development schedule?
- Additional geological structures, geotechnical low-strength zones, or high pore pressure zones were encountered leading to reduced slope performance?

This re-look at slope geotechnical hazards and their potential consequences to the Bingham Canyon Mine was termed the RTK supplemental hazard study (SHS) process. This comprised assessment of the representative (known) and what-if (as-yet unknown) slope geotechnical hazard scenarios by a team of internal and external specialists in various, relevant mine technical disciplines: primarily geology, geotechnical engineering, hydrogeology, and mine planning. Once geotechnical hazards were identified, this same team assessed the potential business consequence of the identified failure scenarios, in terms of loss or deferment of ore, loss or delay to production, impact on mine equipment and infrastructure, etc. Specific safety hazards were not considered as part of this process, on the assumption and understanding that these would be managed by the mine's slope monitoring and operational practices and procedures.

The outcome of the SHS process included locations of key failure scenarios and their changing impact on the business over the life of the mining operations, based on the current approved plans.

Since the first RTK SHS implementation in 2014, five cycles of this iterative process have been completed (Figure 1) to deliver a mature understanding of geotechnical hazards and their management over time at the Bingham Canyon Mine.

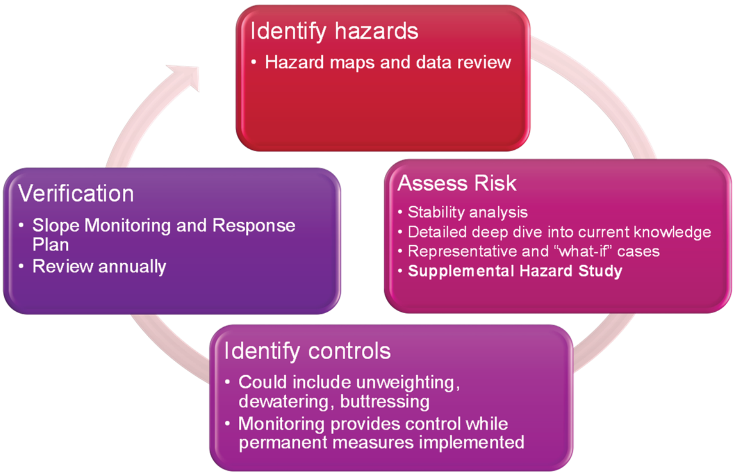


**Figure 1 Iterative improvement as part of supplemental hazard study process**

SHS outcomes represent the consequence element of the RTK reliability-based approach to DAC.

# 4 Assessment of reliability of constituent models

Assessments were undertaken to estimate the reliability of input data to the component models necessary to define a slope design. The geological, hydrogeological, geotechnical, and slope stability models were considered fundamental to design reliability and were assessed.

Examples of scoring criteria for the geological, hydrogeological, geotechnical and slope stability models are presented in Tables 2 to 5. Expert teams comprising internal RTK and external technical specialists developed standardised functional specifications to define the specific thresholds needed to attain a certain reliability score in each of the criteria. A scale from 1 to 5 was used, where 5 represents the highest data reliability.

## Table 2 Scoring criteria for the reliability of the geological model

| Input data | | | Reliability ranking 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| Data | Data density | Data density – drilling | Low reliability | | Medium reliability | | High reliability |
| | | Data density – mapping | | | | | |
| | | Data density – orientation | | | | | |
| | Data collection: drilling component | Standard operating procedure (SOP)/good logging manual | | | | | |
| | | Validated logging (re-logging/drillhole review) | | | | | |
| | | Quality of hole survey with validation (gyro, single shot, ATV) | | | | | |
| | | Standardisation of logging process and codes | | | | | |
| | | Quantity and quality of core orientation data (ATV, alpha angles, etc.) | | | | | |
| | | Logging detail (specific to critical geotech/hydro issues) | | | | | |
| | Data collection: mapping component | SOP/good mapping manual/coordinate system/conversion system | | | | | |
| | | Training/experience of mapper | | | | | |
| | | Validation of mapping | | | | | |
| | | Accuracy of mapping survey | | | | | |
| | | Standardisation of geology codes | | | | | |
| | | Mapping detail | | | | | |
| | Data management component | Standard Operating Procedure (SOP) | | | | | |
| | | Historic data cataloguing and management (paper/scanned copies of logs/maps/photos) | | | | | |
| | | Database validation (Acquire, MineSight, AutoCAD) | | | | | |
| | | Auditing. | | | | | |
| Characterisation and interpretation | Characterisation and interpretation | Proven history of understanding of geology units/geological style. | | | | | |
| | | Key lithological units or contacts have been recognised, defined and characterised by more than one method and location (mapping, drilling, underground mapping, geophysics, geochem) with consideration of nature of contacts (e.g. irregular = igneous; very stratiform, easily definable = limestone) | | | | | |
| | | Major structures. Understanding, capture and representation. Major structures, fabrics and orientation domain boundaries (e.g. major fold axial surfaces) | | | | | |
| | | Structural style. Understanding of variability and complexity: discontinuity types; planar fabrics; orientation domains; varying styles of deformation exhibited by individual rheological units or litho-stratigraphic packages | | | | | |
| | | Understanding and capture of spatial variability due to alteration, weathering including degree/scale of variability (may include lab reports, petrography, petrology, geochemistry) | | | | | |
| | | Geophysical characterisation (leave blank if not used for defining model) | | | | | |
| | | Updated to latest drilling and mapping data | | | | | |
| Modelling | Model quality and details component | Scope definition | | | | | |
| | | Compatible to orientation data (mapping, alpha angles, ATV) | | | | | |
| | | Effort/rigour of interpretation (including implicit versus explicit) | | | | | |
| | | Peer review and endorsement | | | | | |
| | | Deliverables (model files, report and memos, shape files for customer use) | | | | | |

**Table 3 Scoring criteria for the reliability of the hydrogeological model**

| Input data | | | Reliability ranking 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| **Data** | **Data density** | Geologic formations covered by piezometers | Low reliability | | Medium reliability | | High reliability |
| | | Lateral Distribution (proximity to area) | | | | | |
| | | Is the critical surface bracketed (vertical component) | | | | | |
| | **Data collection** | Piezometer data collection frequency | | | | | |
| | | Precipitation | | | | | |
| | **Data management** | Standard operating procedure (SOP) | | | | | |
| | | Data storage | | | | | |
| | | Validation process | | | | | |
| | | Auditing | | | | | |
| | **Quality downhole installation** | SOP | | | | | |
| | | Piezometer installation documentation | | | | | |
| | | Type of installation | | | | | |
| | | Location in rock mass | | | | | |
| | | Target geology achieved | | | | | |
| **Characterisation and interpretation** | **Drains** | Data collection quality | | | | | |
| | | Seepage maps | | | | | |
| | | Wells, sinks and flows | | | | | |
| | **Parameters** | Recharge | | | | | |
| | | Hydrogeologic units (HGU) - hydraulic conductivity | | | | | |
| **Modelling** | **Models** | Fit-for-purpose (porewater pressure for geotech models) | | | | | |
| | | Realisation (representation) of geology model (in hydrology model) | | | | | |
| | | Overall model calibration | | | | | |
| | | Model maturity (leave blank if not used for defining model) | | | | | |
| | **Model interpretation** | Peer review | | | | | |
| | | Communication | | | | | |
| | | Sensitivity | | | | | |

**Table 4 Scoring criteria for the reliability of the geotechnical model**

| Input data | | | Reliability ranking 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| **Data** | **Data density** | Geotechnical mapping | Low reliability | | Medium reliability | | High reliability |
| | | Geotechnical core drilling | | | | | |
| | | Data density strengths testing | | | | | |
| | **Data collection methods** | Geotechnical mapping | | | | | |
| | | Standard operating procedure (SOP)/good logging manual | | | | | |
| | | Validated logging (QA/QC, re-logging/drillhole review) | | | | | |
| | | Quantity and quality of core orientation data (ATV, alpha angles, etc.) | | | | | |
| | | Standardisation of logging process and codes | | | | | |
| | | Core handling | | | | | |
| | | Sampling methods | | | | | |
| | | Lab testing and reporting | | | | | |
| | | Validation/audit and process/standard | | | | | |
| | **Data management component** | SOP | | | | | |
| | | Data storage | | | | | |
| | | Database validation based on SOP (AcQuire, MineSight, AutoCAD) | | | | | |
| | | Auditing | | | | | |
| **Data analysis and interpretation** | **Data analysis and interpretation** | Domaining confidence | | | | | |
| | | Rock mass strength estimation (isotropic and anisotropic) | | | | | |
| | | Discontinuities strength estimation (large-scale explicit structures) | | | | | |
| | | Performance and condition verification | | | | | |
| | | Peer review of geotechnical characterisation | | | | | |

**Table 5 Scoring criteria for the reliability of the slope stability model**

| Input data | | | Reliability ranking | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 |
| **Slope stability modelling** | **Stability model** | 2D or 3D - capable of realising conceptual model<br>Model construction<br>Model calibration and input calibration | Low reliability | | Medium reliability | | High reliability |
| | | Model runs<br>Modelling comparisons<br>Peer review and QA/QC | | | | | |
| **Model results and communication category** | **Model outputs component** | Communication to stakeholders (FoS, SRF, PoF, Convergence, predicted deformation)<br>Deliverables (model files, report and memo's, shape files for customer use) | | | | | |
| | **Endorsement component** | Endorsement | | | | | |

Functional specifications sit below each row in Tables 2 to 5.

An example of the detail for each table and functional specification is shown in Table 6. The example shown is for the geotechnical model reliability (Table 4) and is qualitative; other criteria have semi-quantitative thresholds. The descriptions ensure scoring is consistent across categories and over time.

**Table 6 Functional specification example: geotechnical data collection methods subcategory**

| Criteria | Very low reliability | Low reliability | Moderate reliability | High reliability | Very high reliability |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| Quantity and quality of core orientation data (ATV, alpha angle, etc.) | No orientation data collected | Limited orientation data as alpha angles | Moderate oriented data and alpha angle data | Numerous alpha angles and quality-oriented data | High amount of quality-oriented data. ATV data available during logging. Cross-match between ATV and core logging features. ATV orientation verified with secondary measure |

The functional specifications are then used to score each input to the geology, hydrogeology, geotechnical and stability models on a design sector basis. Individual input scores are weighted and combined to assess reliability scores for each model. The model scores themselves are then weighted and combined with a weighting of 30% being applied to the geological model, to acknowledge that it underpins all other models. The remaining three models equally share the remaining 70% weighting, at 23.3% each. The combined weighted scores represent the overall reliability score for the subject slope design sector.

Scoring the models using the functional specifications allowed a repeatable and auditable way to assess model reliabilities.

# 5 Definition of design acceptance criteria

In defining DAC for RTK's DAC process, the ranges of values detailed in the *Guideline for Open Pit Slope Design* were considered (Table 1). These were mapped by RTK relative to their five defined levels of data reliability for a given slope sector and their five levels of consequence for a failure in that same sector. This mapping is shown as Figure 2, with the RTK DAC values presented in Table 7.

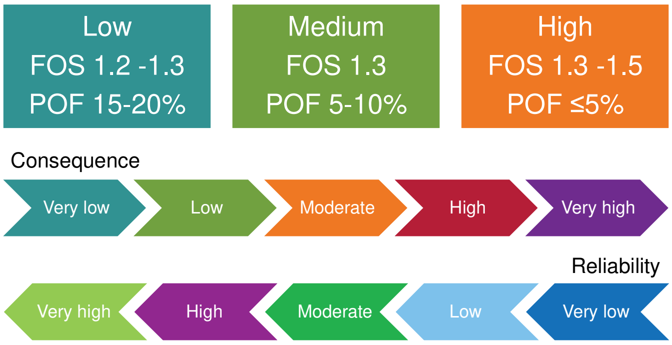


**Figure 2 Consequence and reliability relative to Read and Stacey design acceptance criteria**

**Table 7 RTKC reliability-based design acceptance criteria table of Factory of Safety for overall slope design assessment**

| Reliability | Descriptor | Consequence | | | | | Comments |
|---|---|---|---|---|---|---|---|
| | | Very low | Low | Moderate | High | Very high | |
| 1 | Very low reliability | 1.35 | 1.4 | 1.5 | X | X | Limited knowledge |
| 2 | Low reliability | 1.3 | 1.3 | 1.4 | 1.45 | 1.5 | Reasonable knowledge: bottom of Large Open Pit (LOP) range |
| 3 | Moderate reliability | 1.25 | 1.25 | 1.3 | 1.35 | 1.4 | LOP approach: central case |
| 4 | High reliability | 1.2 | 1.2 | 1.25 | 1.3 | 1.3 | Top of LOP range |
| 5 | Very high reliability | 1.15 | 1.2 | 1.2 | 1.25 | 1.25 | Detailed knowledge |

The process flow for design acceptance at RTK for a given slope stability sector is presented as Figure 3. The required FoS to meet DAC (DFoS, or Design FoS) is defined using the reliability of the model inputs to the slope designs coupled with the business risk (consequence) to each analysed case, as defined by the RTK SHS process. This is then compared with the calculated FoS value from stability analysis (MFoS, or modelled FoS) in the subject slope sector to assess whether acceptance of design has been achieved or exceeded.

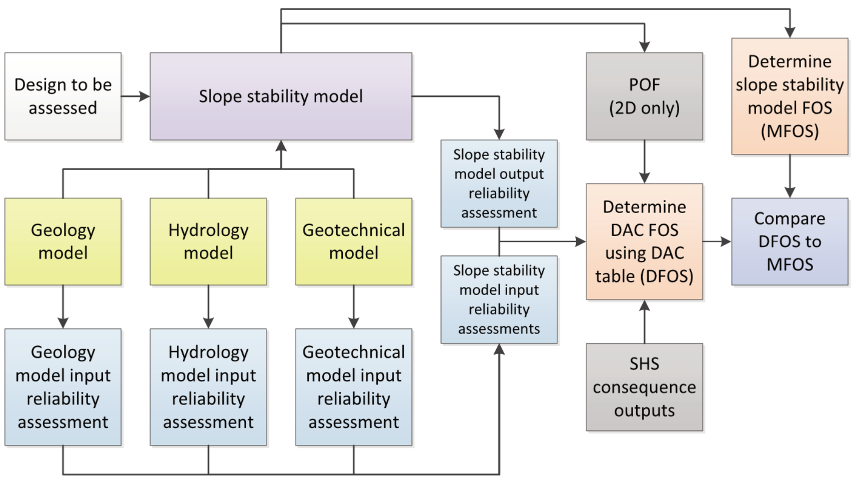


**Figure 3 Process flow for Rio Tinto Kennecott design acceptability**

# 6 Example of reliability-based design acceptance criteria at Bingham Canyon Mine

As part of ongoing expansions, multiple generations of slope designs have been completed at the Bingham Canyon Mine. In this example, application of the DAC approach for part of a mine south wall expansion is discussed.

## 6.1 Context

As part of future south wall pit expansion, RTK developed a slope design that was constrained by overall stability to satisfy the 'industry-accepted' standard design acceptance criterion of FoS = 1.30 (Table 1). However, the mine recognised the significant economic opportunity to locally steepen the slope and recover more ore if a lower FoS value could be technically justified and associated geotechnical risks managed or accepted.

Given the many years of operation at the mine, the reliability of key components of pit slope design are well understood, particularly when contrasted with that for less mature operations which also employ a FoS DAC of 1.30 as a target.

## 6.2 Reliability assessment

A baseline reliability assessment of all models was performed at the beginning of the design process to assess input quantities and qualities, and to identify areas of lower model confidence in the design sector. This led to development and implementation of a data collection campaign comprising additional drilling, mapping and materials testing to improve data density and ultimately the reliability of the geological, hydrogeological, and geotechnical models. Following completion of the program the reliability assessment was repeated using the updated data from the data collection campaign.

Figure 4 shows the geological cross-section through a selected design sector and the borehole coverage used in the updated reliability assessment. The location of the cross-section is shown in Figure 5.

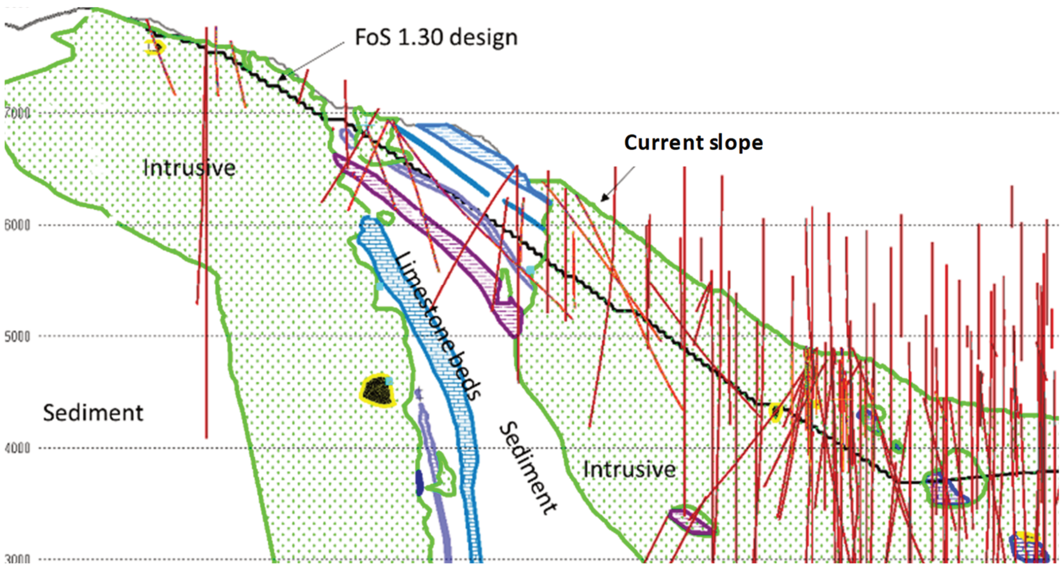


**Figure 4 Analysed cross-section with geology and drill holes coverage**

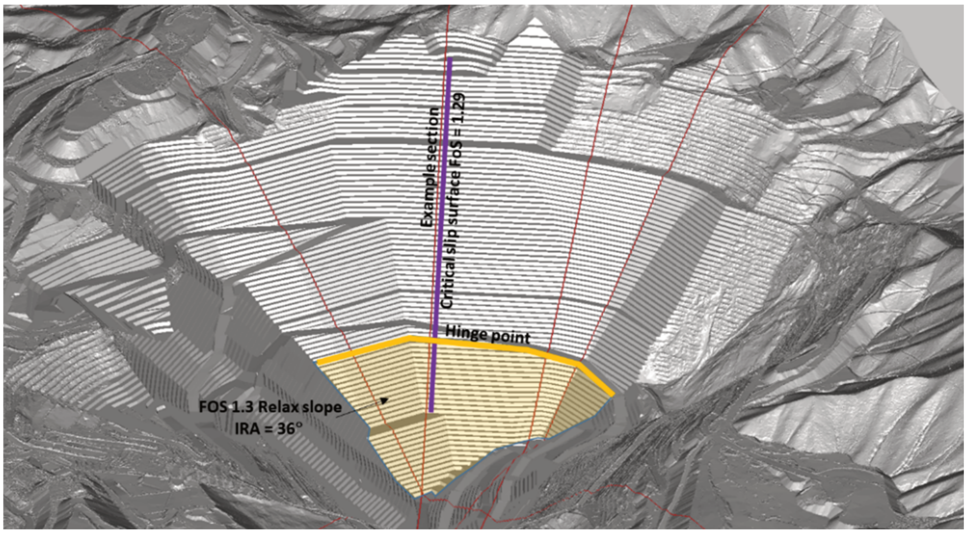


**Figure 5 Line of cross-section through slope of interest**

Reliability assessments were undertaken for all models with Table 8 presenting the results for the geotechnical model as an example. Assessments include numeric values for each criteria within a category. These numbers are then weighted to produce a single overall reliability number for the subject model. The criteria with lower rankings are considered by RTK in targeting future data collection and analysis for improving model confidence.

**Table 8 Example of reliability assessment of the geotechnical inputs for the design sector**

| Input data | | | Reliability ranking |
|---|---|---|---|
| **Overall geotechnical reliability score** | | | **3.7** |
| | | | **3.8** |
| Data | Data density | Geotechnical mapping | 4.0 |
| | | Geotechnical core drilling | 4.0 |
| | | Data density strengths testing | 3.0 |
| | Data collection methods | Geotechnical mapping | 4.0 |
| | | SOP/good logging manual | 4.5 |
| | | Validated logging (QA/QC, re-logging/drillhole review) | 4.5 |
| | | Quantity and quality of core orientation data (ATV, alpha angles, etc.) | 3.0 |
| | | Standardisation of logging process and codes | 4.5 |
| | | Core handling | 3.0 |
| | | Sampling methods | 4.5 |
| | | Lab testing and reporting | 4.0 |
| | | Validation/audit and process/standard | 4.0 |
| | Data management component | SOP | 4.5 |
| | | Data storage | 4.5 |
| | | Database validation based on SOP (AcQuire, MineSight, AutoCAD) | 4.5 |
| | | Auditing | 4.5 |
| | | | **3.4** |
| Data analysis and interpretation | Data analysis and interpretation | Domaining confidence | 3.5 |
| | | Rock mass strength estimation (isotropic and anisotropic) | 3.5 |
| | | Discontinuities strength estimation (large-scale explicit structures) | 3.0 |
| | | Performance and condition verification | 3.0 |
| | | Peer review of geotechnical characterisation | 4.0 |

Following weighing of the constituent model reliabilities, the overall updated reliability assessment for the cross-section/design sector returned an overall score of 4.0 (high) (Table 9).

**Table 9 Reliability assessment for the design sector**

| Design sector | Model reliability ratings | | | | Design sector reliability score |
|---|---|---|---|---|---|
| | Geology | Geotechnical | Hydrogeology | Stability model | |
| South | 3.9 | 3.7 | 3.8 | 4.5 | 4.0 |

## 6.3 Consequence assessment

The consequence of an instability on the controlling design mechanism was assessed using the RTK SHS methodology. Considering the potential failure scenario volume and the location of mine infrastructure, a consequence category of 'very high' was identified.

## 6.4 Stability models and design acceptance criteria minimum Factor of Safety

The DAC assessment for the example design sector considered the reliability ranking of 4.0 (high) and design sector consequence of 'very high'. When using the chart shown in Table 7, this suggests a minimum DAC for the sector of FoS > 1.30 (Table 10).

**Table 10 Reliability and consequence ratings with resulting design acceptance criteria minimum Factor of Safety**

| Design sector | Design sector reliability score | Design sector consequence | Design acceptance criteria minimum Factor of Safety (FoS) | Stability model FoS |
|---|---|---|---|---|
| South | 4.0 | Very high | 1.30 | 1.29 |

2D limit equilibrium analysis of the subject slope design, which has an inter-ramp angle (IRA) of 36°, was undertaken. These returned an FoS of 1.36 for the overall slope stability and a critical slope mechanism with FoS of 1.29 (Figure 6, with line of cross-section shown in Figure 5). The FoS of 1.29 was considered acceptable to RTK despite it being below the target FoS of 1.30 (difference of only 0.01) following review of 2D and 3D numerical model results in the same design sector, and with consideration to model accuracy.

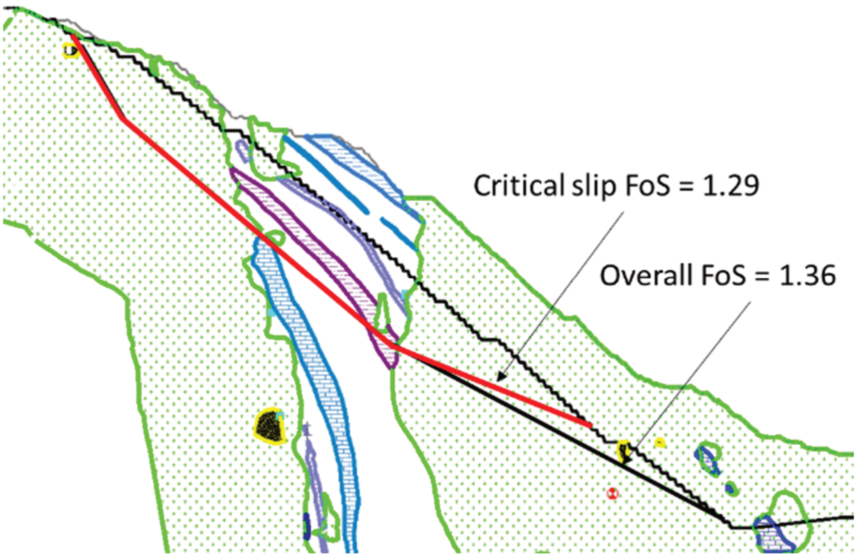


**Figure 6 2D limit equilibrium model results**

### 6.5 Design optimisation

An optimised design was developed for the subject cross-section to meet a DAC of 1.25. This required steepening the IRA from 36–39° in the lower slope (Figure 7). The original and optimised designs are identical until a hinge point approximately 457 m (1,500 ft) above the design pit floor (Figures 5 and 7). This potential optimisation allows continued mining on the current plan and collection of further slope performance and geological, geotechnical, and hydrogeological data until the hinge point elevation is achieved. RTK plans to collect additional data in the time available to improve the calculated model reliability from 'high' to 'very high' (level 4 to level 5), which in turn would allow a DAC FoS of 1.25 for the same slope failure consequence.

Acceptance of this optimised design (from FoS 1.30 to 1.25) would result in mining of 14.5 Mt of additional copper ore. The increased revenue from mining of additional ore significantly exceeds the cost of further data collection and therefore allows mine management to make an informed decision regarding the estimated expenditure for additional revenue.

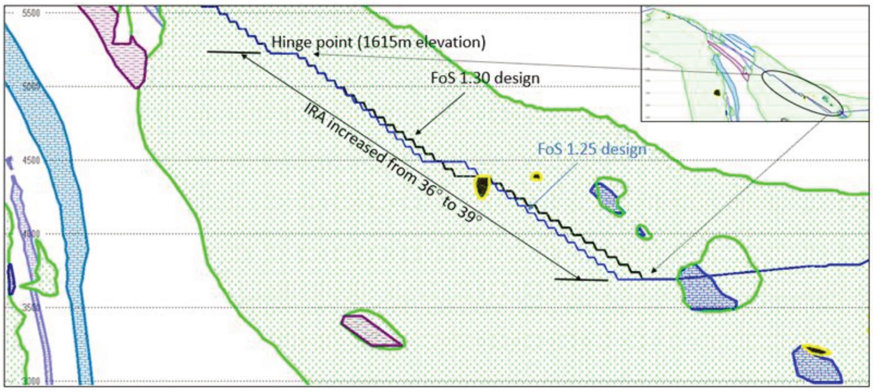


**Figure 7 Optimised design with FOS of 1.25 achieved by steepening lower slope inter-ramp angle**

## 7 Conclusion

In order to define what can be accepted in terms of a mine slope design, an understanding of the quality and quantity of input data is essential, as is an appreciation of the risks than can be tolerated by a business.

The RKC DAC process is a means of defining model reliabilities (confidence) versus consequence for a given slope design sector and allows Rio Tinto and RTK to make informed decisions on design acceptance. Equally, the process provides a means for RTK to communicate how expenditure on, and collection and interpretation of, additional data can lead to improved model confidence and potentially a change to a DAC. Allowance of a lower DAC can in turn lead to steeper acceptable slope angles and improved mine economics as a function of reduced strip ratio.

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