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Mine slope design and the role of confidence and consequence

EK Jones *MineGeoTech, Australia*

J Player *MineGeoTech, Australia*

G Sweby *MineGeoTech, Australia*

Abstract

Geotechnical model confidence and consequence of failure are the two critical aspects when selecting appropriate stability design criteria. Geotechnical model confidence needs to be appropriate for the project, considering the scale of the pit, the geological setting and the study level. Consequence is express solely in its importance to the business.

This paper proposes an approach to help navigate how to apply which level of confidence and consequence to slope stability design when considering the geology, geotechnical and hydrogeology models, and how to apply this confidence to select the appropriate batter/berm design criteria.

When selecting the overall stability acceptance criteria both the model confidence and failure of consequence are utilised. Consequences for studies revolve around business loss (cessation of production), loss of licence to operate and the impacts of such to the operation.

This approach expands on the study guidelines and stability criteria as presented in Read & Stacey (2009) to allow for smaller pits or those that don't have a high consequence when it comes to instability occurrence.

Keywords: *slope design, geotechnical confidence, failure consequence*

1 Introduction

The level of confidence in the geotechnical model increases as a project progresses from scoping through to feasibility, followed by design and construction phases, and then closure. Achieving a high level of confidence early reduces the overall cost of a mine study through an earlier understanding of the geotechnical environment, resulting in less re-runs of mine designs and sequences (Varden et al. 2016). However, a balance is required between the study stage and what is a practical investment into the project, depending on geological model confidence. Additional specific company requirements need to be considered to align with company policies.

Several approaches for geotechnical frameworks to align to reporting codes for exploration results, mineral resources and ore reserves have been developed. These frameworks provide guidance to geotechnical engineers for equivalent 'data confidence' at various stages of a resource or project development.

A breakdown for geotechnical model requirements per the study stage is provided by Read & Stacey (2009). The amount of work and detail required for each model will vary depending on the site geotechnical complexity and key risks pertaining to the project. Read & Stacey further provide a recommendation for stability failure criteria based on failure of consequence for the slope scale. These are used worldwide and are considered best industry practice.

Navigating the design of a data program for study stages that meets industry best practice and company requirements, is adequate for the perceived risk and meets budgeting restraints can be a challenge. How to then relate the resulting model confidence to select an appropriate stability failure criterion can also be a challenge. This paper presents an approach to determine geotechnical model confidence across different scale operations and financial constraints for defendable stability assessment outcomes, providing mine planners with a level of confidence and risk regarding geotechnical outcomes. The levels of confidence have been developed to determine stability design criteria and are based on both reference documents and engineering experience.

2 Geotechnical model confidence

The geotechnical model comprises four components: geology, rock mass, structural and the hydrogeological sub-models. Each requires a different data collection strategy and the detail relative to the level of risk each poses for the project.

Input parameters are derived from these sub-models for slope stability analysis. Therefore, the higher level of confidence in these parameters, the higher the confidence is with stability outputs and, thereby, recommendations provided to mine planners. Figure 1 illustrates the components of these categories and parameters used for slope stability analysis.

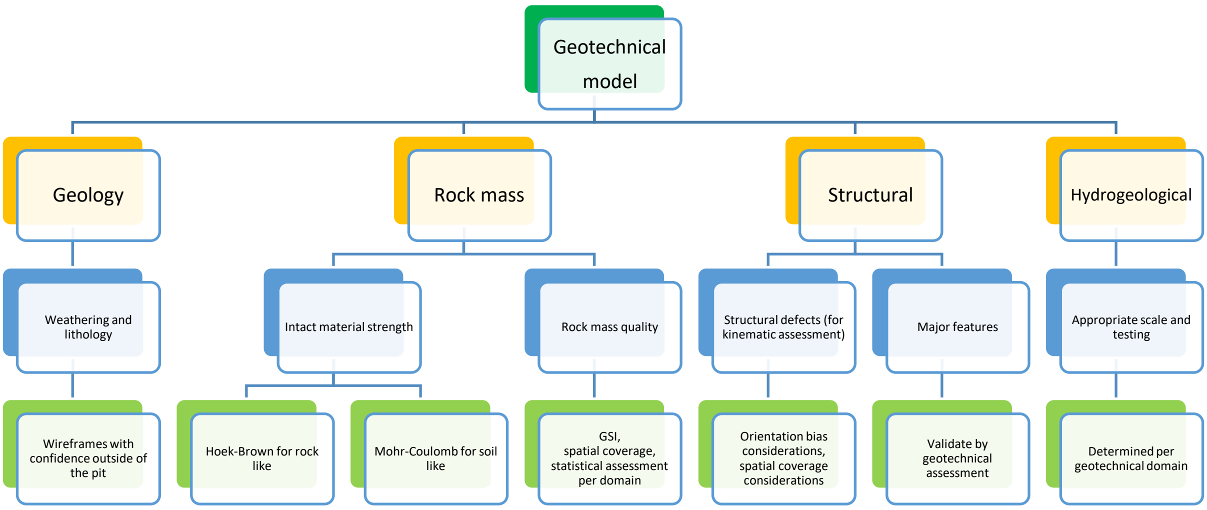

Figure 1 Geotechnical model with components and parameters for slope stability analysis

2.1 Geological confidence

The geological confidence for a particular project stage is regulated by codes that set out minimum standards, recommendations and guidelines for public reporting for solid minerals of exploration results, mineral resources and mineral reserves, i.e. Joint Ore Reserves Committee (Australian Institute of Mining and Metallurgy 2012), SAMREC (2016), NI43101 (Canadian Institute of Mining, Metallurgy and Petroleum 2011) etc. These codes require a level of drilling to defend resource models.

Geology model confidence for the geotechnical model also requires resource drilling coverage outside of the proposed pit design. High model confidence is attained when the resource drilling penetrates the proposed pit design to a depth of one-third of the slope height of the pit.

Confidence in the modelled wireframes representing the regolith, geological units and major structural features is dependent on drilling density. These wireframes are used as boundaries for populating geotechnical domains in stability analysis, and as the basis for identifying design domains for mine planners.

High confidence in the geology model results in the geotechnical engineer being able to enhance design domains, resulting in optimised outcomes for designs.

2.2 Rock mass confidence

The rock mass confidence has two components: intact material strength and rock mass quality.

2.2.1 Intact material strength

The intact material strength data confidence is based on the number of complete suites of triaxial/tensile strength data and their spread across the proposed pit design and geological domains. The authors recommend a minimum of five suites, with a well-defined Hoek–Brown or Mohr–Coulomb strength envelope, to achieve a high-confidence model. One suite comprises three single-stage triaxial tests with individual assigned confinements. Each geotechnical design domain would need similar levels of confidence. Datasets which show high variability require additional testing to better define the statistical spread. Anisotropic rock masses require at least 10 suites in order that enough samples which fail on foliation/bedding can be tested.

Hoek triaxial tests (HTRX) are completed on rock samples, both transitional and fresh domain types. This test defines the Hoek–Brown failure envelope and provides a means to determine the Hoek–Brown constant (m_i value) and intact rock strength (σ_{ci}) parameters. In triaxial compression, the rock sample is radially confined by a constant pressure as it is axially loaded. Failure occurs when the shear stress exceeds the shear strength as defined by the Hoek–Brown failure envelope. Linear variable differential transformers (LVDTs) are preferred to measure the axial strain change of the specimen and to assess the modulus of the complete sample as opposed to just where the strain gauges are mounted.

Single-stage HTRX tests are undertaken and test results per domain are used to generate a best-fit Hoek–Brown strength curve. This methodology provides a good estimate of the mean values of σ_{ci} and mi, but also quantifies the variability in intact material strength.

Failure mode is an important outcome of the results. Here, failure modes are used to determine and group intact versus structurally controlled results. Intact results are required to represent the material strength of the geotechnical domain in numerical modelling. Results from samples which failed on structure are used to quantify anisotropic strength for foliated or bedded materials. Outliers that represent misallocated lithology are also rejected.

The Brazilian test is an indirect tensile test which is combined with the HTRX results to improve the Hoek–Brown curve-fit. One uniaxial tensile strength (UTS) test is completed for each HTRX suite. An example of a high-confidence Hoek–Brown strength envelope for rock-like material is shown in Figure 2.

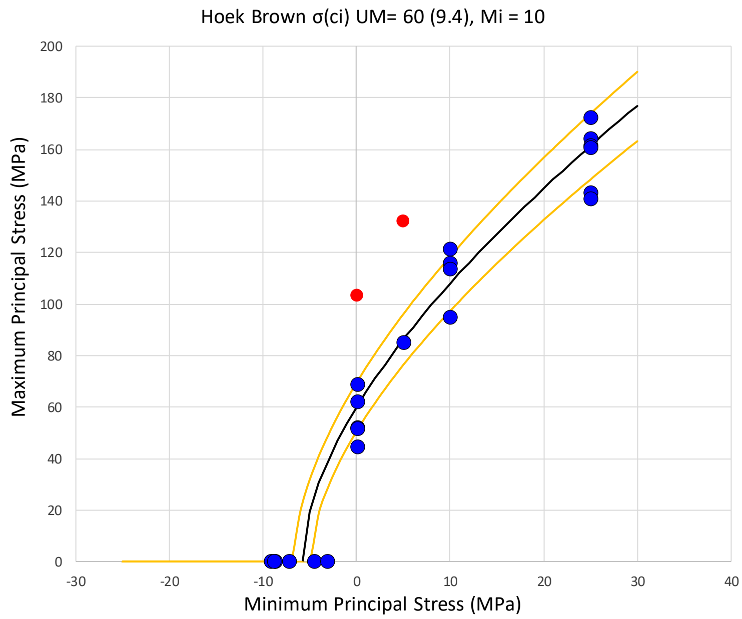

Figure 2 Example of a high-confidence rock-like material strength envelope (red dots represent outliers)

Consolidated-drained triaxial testing is a method to test low-strength cored samples to determine the effective strength of the material. The specimen is first saturated and then subjected to a confining pressure. Dissipation of the excess porewater pressure (consolidation) is allowed to occur over time. Mohr–Coulomb failure envelopes are produced by fitting a linear regression to a plot of shear stress versus normal stress (at failure). An example of a high-confidence Mohr–Coulomb strength envelope for soil-like material is shown in Figure 3.

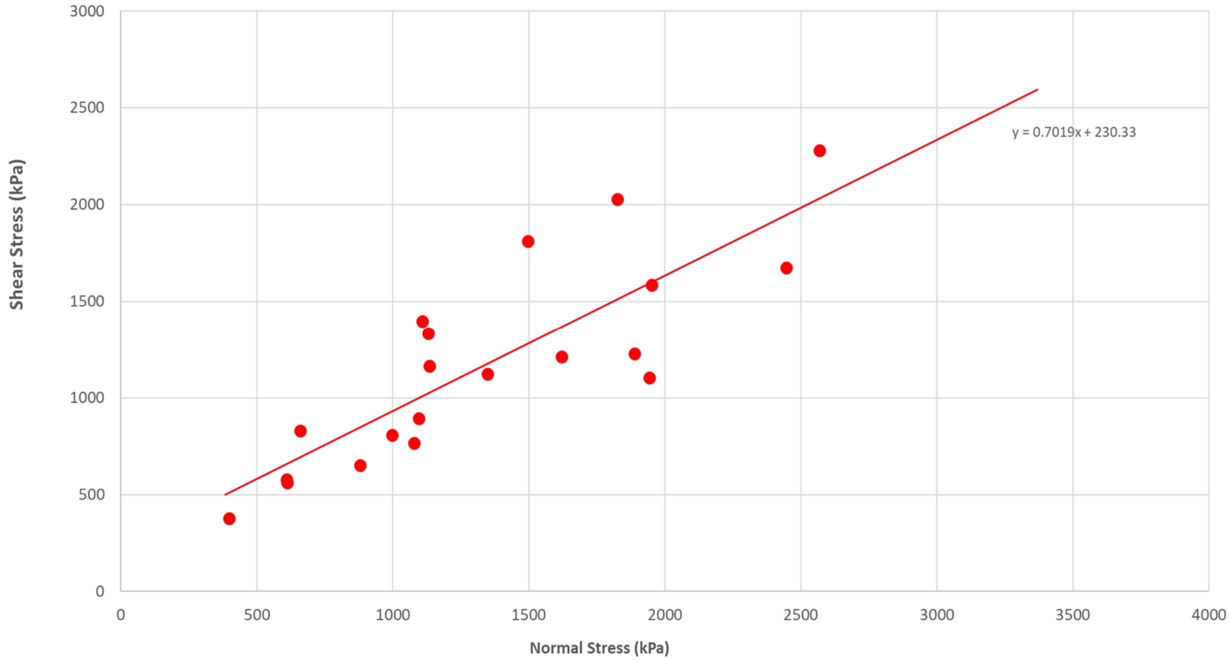

Figure 3 Example of a high-confidence soil-like material strength envelope

2.2.2 Rock mass quality and structural defect data model

The rock mass and structural defect data model confidence is based on geotechnical drilling coverage and considers three main components:

1. Orientation of drillhole to mitigate bias.
2. Spatial cover around the pit.
3. Extension outside of the proposed pit design to confirm geological setting.

2.2.2.1 Drillhole bias

Understanding the drillhole bias analysis enables identification of dominant defect sets that are over-represented and/or highlights blind spots where potential data gaps exist. Rock mass quality also can suffer from bias and over-representation of the quality in one direction. Rock mass quality is to be described statistically and account for variable interval lengths used in geotechnical logging of core. An example box plot with distribution for geological strength index (GSI) from Hoek et al. (2013) is shown in Figure 4. The box plots report the recorded minimum and maximum (either ends of the line), the 10th and 90th percentile (dots), the 25th, 50th and 75th percentile (the components of the box), and the weighted mean.

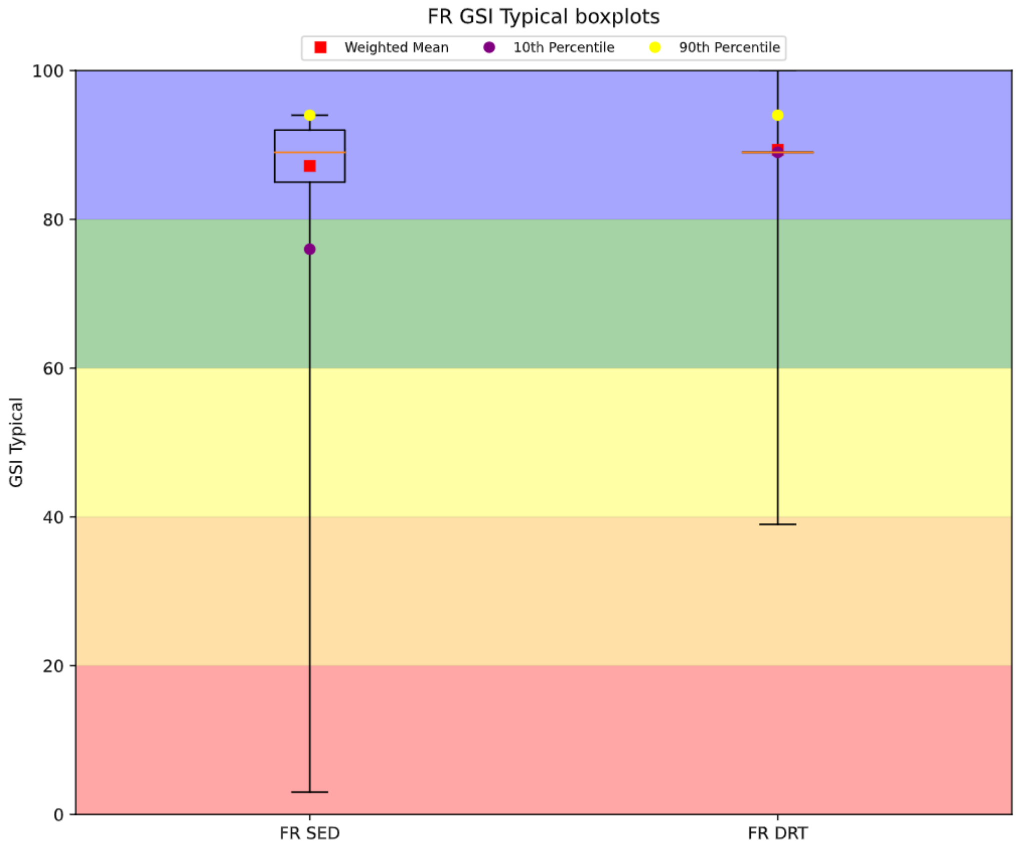

Figure 4 Box plot for GSI for two different domains

Confidence will also be dependent on the perceived risk of the poorly sampled orientation, i.e. this area might be a highwall or potentially the orientation is not critical to stability.

Bias is easily assessed by plotting the drillhole orientation and sample length. Software programs are available to produce effective figures for reporting (i.e. AGSW 2023 explained by Thomas 2021). An example of a moderately confident defect database is shown in Figure 5, which represents poor sampling of moderate to steeply dipping northwest defects.

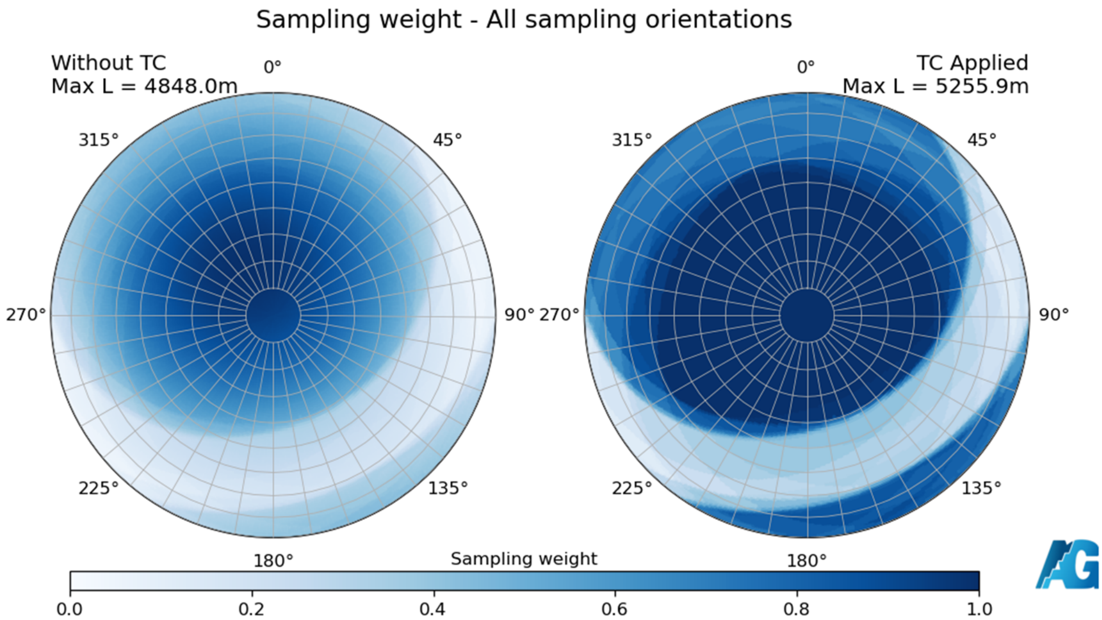

Figure 5 Sample and orientation bias plot using AGSW (2023) software

2.2.2.2 Spatial coverage

Spatial cover around the pit complements the bias analysis, ensuring the project is spatially represented appropriately to the level of confidence required. Orebody coverage for a resource estimate is never achieved in a geotechnical program of the proposed walls.

Fillion & Hadjigeorgiou (2018) investigated the influence of drillhole density on the resulting interpretation of the geological model.

The International Society for Rock Mechanics' (ISRM) recommendations on site investigation techniques (International Society of Rock Mechanics 1975) specify that the number of borings depends on the geological homogeneity of the area to be investigated. Where inhomogeneity is encountered, the complexity and continuity of the proposed geotechnical domains should be practically considered in relation to recommendations for mine design. Determining the number of geological lithology units and structural domains, and thereby the complexity of the project area, are required steps to derive geotechnical domains and targets for boreholes.

Fillion & Hadjigeorgiou (2018) reviewed a number of boreholes used to interpret the geological and geotechnical database, comparing the before-mining model interpretation and the after-mining interpretation. From this work an empirical quantitative guideline was derived with respect to the minimum drillhole density per domain complexity. A classification system was provided that recognises three levels: low, medium or high complexity. They then built off Read & Stacey (2009) study guidelines to present a drillhole density per domain complexity for the anticipated maximum variation from the real model.

Using this work and the authors' experience, recommendations for hole density for rock mass and structural data confidence are made. Using spatial and sampling bias tools to assess residual data gaps highlights where model weaknesses remain and allows recommendations for additional data collection to be undertaken.

An example of spatial presentation of drillhole pierce points on a pit design is shown in Figure 6. This figure is coloured to highlight a 100 m radius as an example of high confidence.

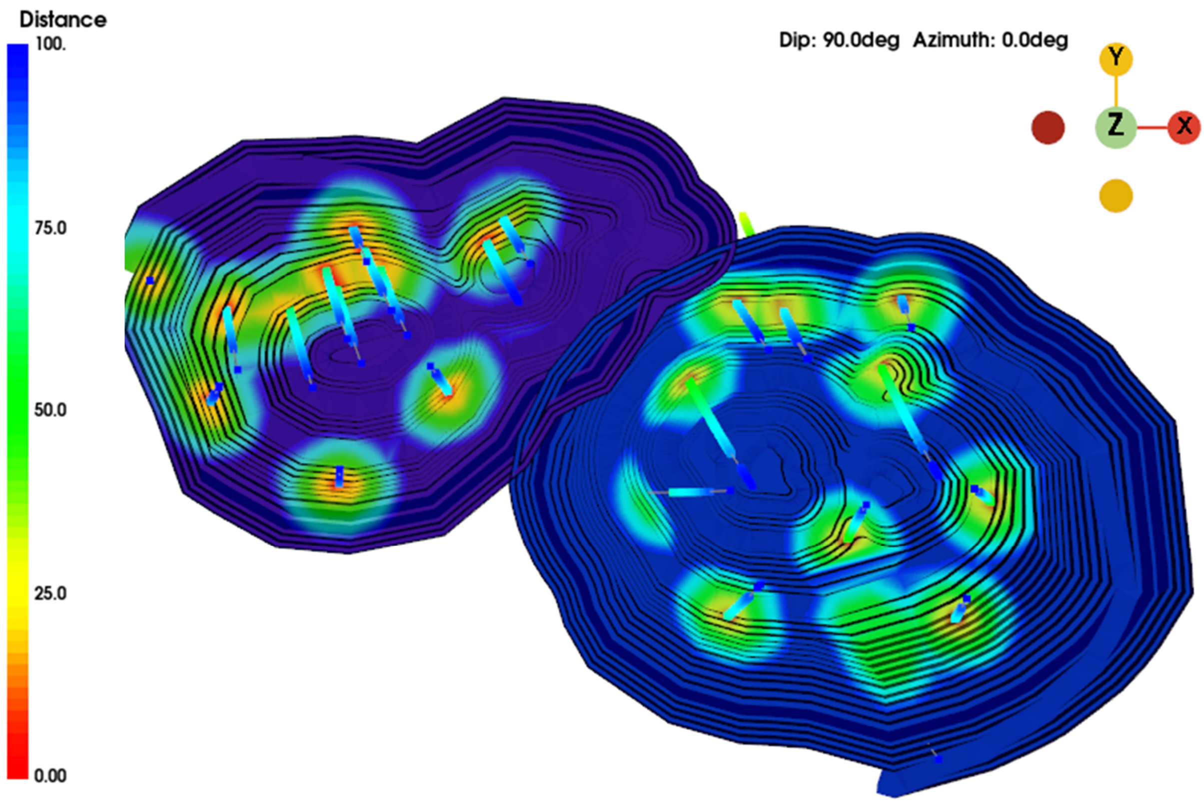

Figure 6 Example of spatial distribution of geotechnically logged drillholes

2.2.2.3 Extension beyond pit profile

The geotechnical drilling program can sometimes take place parallel to resource definition. In these cases, pit optimisation shells are used to design geotechnical drilling programs. When designing a program, understanding the potential expansion due to either resource increase or metal price, is important to ensure drilling depths cater for any increase in the pit size.

A good rule of thumb for depth of a geotechnical drillhole is to target 1/3 of slope height beyond the pit or optimisation shell outline. Adjusting the depth for practicality is a given, however, this depth will ensure that geological features and geotechnical ground conditions behind potential walls are intercepted.

2.2.3 Major structural features

Major features account for faults, shear zones and dominant fabric (bedding, foliation) that will influence global stability and are included in the stability numerical model assessment. These major features are assessed for:

- Persistence, extent of the feature.
- Orientation and undulation.
- Slip potential – characteristics of the feature, planarity, roughness, infill type and thickness.

It is noted here that major faults and shears can have different characteristics across the regolith profile. Bedding orientation is important to understand when targeting drilling to obtain samples for assessing material strength, intact and shear/foliation/bedding strength.

Resource holes should also be used to review and assess features to verify persistence across the project area.

2.3 Hydrogeological confidence

The hydrogeological model confidence is based around coverage of field-testing bores, the type of testing undertaken, water level measurements across the project area and whether or not hydraulic conductivities of key geotechnical design domains (with respect to wall stability) have been determined from the fieldwork.

Depending on the complexity of the environment and assessed impacts, this model may be simple or detailed. It may include features such as water-bearing structures, paleochannels or other features that might hold water or allow for recharge, and which need to be modelled and characterised.

Consideration of the hydrogeological environment in general, including flooding conditions, position of water systems, overall risk of water to the project, potential environmental impacts and proposed water management strategy, is necessary when determining the level of model confidence and consequence.

2.4 Proposed levels of confidence

Based on these four components, levels of confidence are presented in Table 1.

Table 1 Confidence levels per model

	Geology	Rock mass	Structure			Hydrogeological
		Material properties	Rock mass quality	Minor defects	Major structures	
High	High model confidence is attained when the resource drilling penetrates the proposed pit design to a depth of 1/3 the slope height of the pit.	At least five suites of tests that result in a well-defined Hoek–Brown or Mohr–Coulomb strength envelope. Sufficient spatial coverage for sample collection to determine material properties.	<200 m spacing of rock mass logged drillholes piercing the proposed pit design to a depth of 1/3 the slope height of the pit. These must cover all geology and weathering domains at a range of orientations to allow mitigation of drillhole bias for structural setting which determines kinematic failure mode.		Major features that will dictate inter-ramp angle or large-scaled failures have been interpreted from multiple drilling intercepts, and slip potential and strength investigated.	Permeability data is obtained per geotechnical design domain to define transient groundwater drawdown as mining progresses.
Medium	Geology interpretation completed but still data gaps and inconsistencies between wireframes and drilling data.	Material properties are sufficient to defend the failure mechanism but do not capture the full wall exposure.	200–400 m spacing of rock mass logged drillholes piercing the proposed pit design to a depth of 1/3 the slope height of the pit. Medium confidence is achieved for correcting drillhole bias (i.e. a non-critical blind spot for kinematic failure mode).		Major features that will dictate inter-ramp angle or large-scaled failures have been identified but not fully investigated, i.e. continuity unknown or characteristics unknown.	Watertable obtained from drillholes and is below the saprolite. Bulk permeability obtained from site testing.
Low	Significant gaps for geology wireframe interpretation. Estimations make up the majority of the wireframe interpretation.	One or more material types that influence the outcomes of the stability analysis has/have not been defined.	Data gaps present. One or more blind spots exists that do not allow kinematic failure analysis to be completed.		Drilling shows indications of major features but no interpretation completed and/or major features have been interpreted based on geological knowledge and have no drilling intercepts.	No hydrogeological data available. Referenced literature and/or engineering experience used.

3 Consequence

Consequence of an instability is relative to the impact on the company or operation's economic, social or governance aspirations. At worst, the mining licence is revoked or the company becomes bankrupt; at best, there is little impact and mining carries on. This chapter presents scales of instability accounted for in the proposed failure criterion, the consequence of an instability and categorising these for use.

3.1 Consequence of instability

The impact of instability is dependent on the scale of operation. To understand the scale of the operation and thereby the consequence of instability, the following require consideration:

- Size of pit.
- Production strategy – how critical is production from this pit to the operation?
- Singular pit or are there multiple sources of ore available?
- Stakeholder confidence importance.
- Impact on company commitments to environmental, social and governance (ESG) factors.

Pit wall instability occurs at varying scales.

Bench and inter-ramp scale instabilities can result in the following:

- Loss of catchment.
- Loss of access to berms for clean-up and monitoring.
- Increase of rockfall hazard.
- Unbudgeted ground support i.e. mesh drapes or catch fences.
- Mine design adjustment to manage rockfall hazard.
- Risk of equipment damage, injury or fatality.

Inter-ramp and overall wall stability can result in the following:

- Loss of production.
- Loss of stakeholder confidence – potential for loss of investors.
- Additional mining required – impacting ESG commitments.
- Risk of equipment damage, injury or fatality.
- Closure of operation.
- Insolvency of company.

Understanding the sensitivity and tipping points of these in relation to the scale of an instability is required to enable selection of the appropriate failure criterion.

3.2 Categorising consequence

Two categories of failure consequence are considered, as follows:

- High consequence: business loss (cessation of production), loss of licence to operate.
- Low consequence: production is able to continue from other sources while remediation takes place.

4 Design acceptance criteria

The design acceptance criteria were developed individually for bench stability and overall wall stability. Both criteria were designed utilising levels of confidence and consequence as presented in Table 1. Table 2 is the bench configuration stability acceptance criteria based on model confidence. Table 3 is the overall stability acceptance criteria based on model confidence and failure consequence.

Table 2 Bench configuration stability acceptance criteria

Batter face angle (BFA) and inter-ramp angle (IRA) design				
Confidence of geotechnical and geological model		High		Low
		Low	High	
Consequence of failure/risk acceptance	BFA PoF (kinematic)	<50%	<25%	<25%
	BFA FoS (finite element)	>1.1	>1.3	>1.3
	IRA PoF (kinematic)	<25%	<10%	<10%

Table 3 Overall slope stability acceptance criteria

		Model confidence		
		Low	**Medium**	**High**
Failure consequence	Low	FoS (Mean) > 1.5 FoS (Lower bound) > 1.2 PoF < 5%	FoS (Mean) > 1.3 FoS (Lower bound) > 1.1 PoF < 10%	FoS (Mean) > 1.2 FoS (Lower bound) > 1 PoF < 20%
	High			FoS (Mean) > 1.3 FoS (Lower bound) > 1.1 PoF < 10%

5 Conclusion

This paper presented a framework to use levels of geotechnical model confidence and consequence as defined by Read & Stacey (2009) to select an appropriate slope stability design failure criterion.

Geotechnical model confidence is dependent on the type and quantity of data collected, bias and spatial coverage for the four components (geology, rock mass, structure and hydrogeology). The data collection programs are designed by balancing study-level recommendations, geotechnical site complexity, company risk profile and economic confidence in the project.

Consequence is operation-specific and dependent on the scale of operation, sensitivity to instabilities, production schedule and impacts on ESG commitments.

Linking model confidence to select failure criterion used in stability analysis provides a defendable method for selected failure criterion; thereby providing mine planners with informed geotechnical recommendations and constraints.

Further adjustment to the presented tables is expected as this method is applied and learnings are used to improve the system.

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