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Observational method applied to pit slopes informing the characterisation, design and monitoring process for an open pit mine: a case study

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Abstract

This paper presents the application of the observational method (OM) to slope design in open pit mining, highlighting its effectiveness in managing geotechnical uncertainty and enhancing slope reliability. While widely applied in underground works, the OM remains underutilised in open pit environments. Through a structured cycle of predict–monitor–reconcile, the OM enables dynamic updates to design parameters based on actual slope behaviour. A case study at BHP's Escondida mine illustrates how the OM guided design adjustments following unexpected slope instability, particularly where rock mass properties deviated from initial assumptions. The methodology supported back-analysis, model reconciliation and outcomes such as reduction of inter-ramp angles, improving slope stability and increasing reliability in the mine plan. Such back-analysis and reconciliation are necessary considering the uncertainty in the critical geotechnical parameters that drive slope instabilities, impact the mine plan and may lead to a decrease or increase in inter-ramp angles if the actual slope performance is significantly worse or better that the expected one. Integrating reliability assessments and parameter uncertainty indices further weaker or strengthened the design process. This work advocates for the systematic implementation of the OM in open pit slope engineering as a best practice for managing geotechnical risk.

Keywords: *observational method, pit slope design, design guidelines, geotechnical monitoring, failure mechanisms, slope design process*

1 Introduction

The design of open pit slopes is a critical geotechnical process aimed at achieving safe and stable excavation geometries under an acceptable risk profile. This design constitutes the principal engineering control to prevent slope instabilities and their associated consequences. However, inherent uncertainties in geotechnical parameters – such as rock mass properties, structural controls and groundwater conditions – combined with the limitations of conventional stability analysis methods introduce a residual level of risk that must be carefully managed by geotechnical practitioners.

Although slope designs strive to balance safety with economic efficiency, actual slope performance can diverge significantly from initial predictions as the pit deepens, and geological variability is revealed. In this context, the observational method (OM) provides a structured and adaptive approach to managing slope performance. It enables continuous refinement of the design through an iterative process grounded in the principle of predict–monitor–reconcile. By systematically incorporating field observations and monitoring data into the design loop, confidence in the critical parameters influencing slope stability can be progressively

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improved. This adaptive methodology enhances both the robustness of slope designs and the responsiveness of geotechnical risk management throughout the mine life cycle.

The OM is essentially based on the working method of Professor Terzaghi (1943), and that of Ralph Peck, his student and disciple, who presented it at the 9th Rankine Lecture in 1969 (Peck 1969).

The OM is basically a geotechnical engineering technique of observation and modification of the design during execution. The OM in an open pit is a geotechnical process founded on design adjustment based on theoretical and empirical analysis of slope behaviour and instrumentation information, driven by slope design.

This methodology has evolved from relying purely on basic visual observations made on site to sophisticated procedures using geotechnical instrumentation and back-analysis. It has become an essential element in the design and construction of underground works, especially when excavating through variable and complex geology, rock masses, weak and deformable soils, and sections in very shallow or high overload conditions.

In open pit mining, slope stability is a critical concern; particularly in geologically complex environments where predicting failure mechanisms is inherently challenging. When a slope failure has occurred or is anticipated and the underlying causes remain uncertain – due to heterogeneous rock mass conditions, variable groundwater regimes or limited geotechnical data – the application of the OM becomes not only appropriate but essential.

In the context of mining slope design, the OM offers a proactive approach to managing uncertainty of the geotechnical inputs for slope design. By establishing acceptable performance thresholds, implementing robust monitoring systems (e.g. inclinometers, radar, piezometers) and preparing contingency measures or alternative designs in advance, engineers can respond dynamically to deviations between predicted and actual slope behaviour. This not only enhances safety and operational continuity but also aligns with modern risk-informed geotechnical design philosophies, as outlined in Eurocode 7 and in some references (such as Kovari & Lunardi 2000 and Dinesh 2006).

This paper explores the application of the OM in mining slope design, particularly when early-stage performance underperforms relative to design expectations. Through a synthesis of theoretical foundations, case studies and decision-making frameworks, we demonstrate how this methodology can reduce uncertainty, optimise resource allocation and improve the resilience of slope systems in complex mining environments.

The main concepts included in underground practice are outlined below and presented in Figure 1:

- identification of geotechnically relevant parameters
  - define key parameters that influence rock mass behaviour
  - use geological mapping, borehole logs, laboratory testing and geophysical surveys.
- development of geotechnical models
  - construct integrated models to represent site conditions
  - incorporate variability and uncertainty using probabilistic or parametric approaches.
- prediction of rock mass behaviour (pre-excavation)
  - estimate how the rock mass will respond to excavation or slope formation
  - use analytical, empirical (e.g. Q-system, Rock Mass Rating (RMR) and numerical methods (e.g. FEM, DEM)
- definition of performance requests and thresholds (limit of deformation rate, water table etc.)
  - establish acceptable limits for
    - displacement (e.g. slope movement using radar, prisms, inclinometers, and others)
    - support performance to control deformations and failures (e.g. bolt load, shotcrete strain, buttress)

        - groundwater inflow or pore pressure, measure in maximum flow or pressure.
    - define trigger values and action thresholds for monitoring systems.
- implementation of monitoring systems
    - deploy instrumentation to observe actual behaviour.
- evaluation of actual behaviour (during and post-excavation)
    - compare observed data with predicted behaviour.
- adaptive response and design modification
    - if behaviour exceeds thresholds
        - implement predefined contingency measures (e.g. additional support, drainage, excavation change, sinking rate or blasting volume to control the deformation rate)
        - update geotechnical models and framework plans, with added information and back analysis.
        - document decisions and rationale for traceability, to understand the parameters' effects, and historical behaviour.
- continuous feedback and model updating
    - integrate new data into the design process.

A procedure of geotechnical design for underground construction work using a cyclic approach is shown in Figure 1.

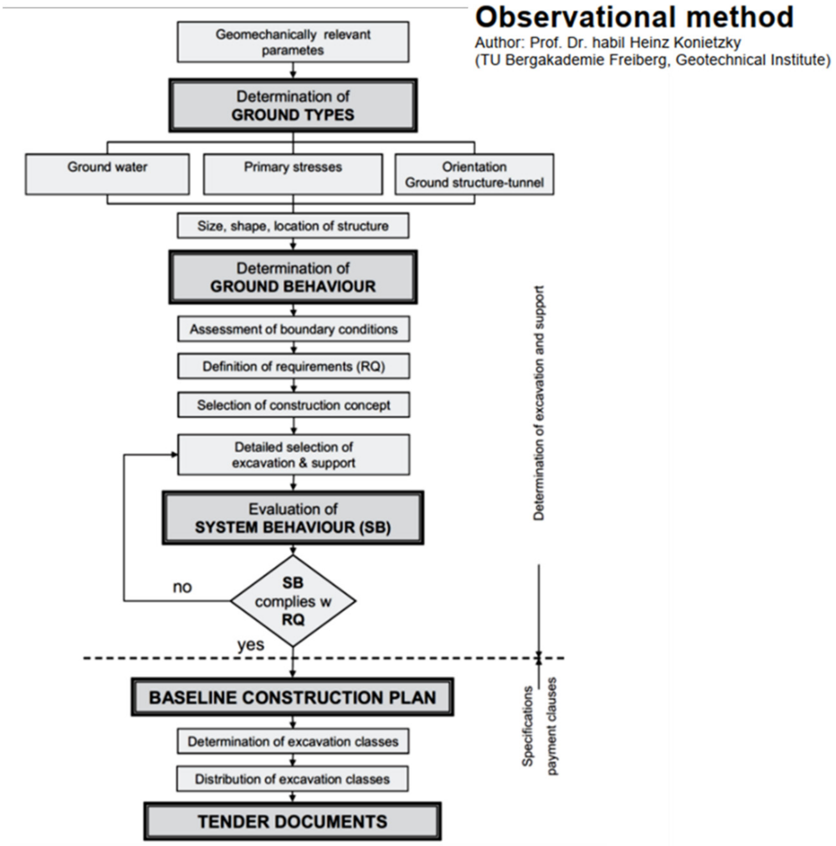


Figure 1 Flow chart of the geotechnical design procedure for underground construction work using a cyclic approach (Konietzky 2019)

2 Methodology of the observational method for an open pit

As mentioned above, the OM is built on three interdependent pillars:

- predict. Develop geotechnical models and forecast slope behaviour under excavation defined by geotechnical zones and mechanisms of failure
- monitor. Implement instrumentation, field observations and drilling data to track actual performance
- reconciliation. Compare observed behaviour with predictions and implement predefined contingency measures if thresholds are exceeded. Typically, prisms and radar data are the most significant sources of data for the definition of triggers.

This cycle is iterative and continuous, allowing for refinement of models and design decisions throughout the life of the pit.

2.1 Application to open pit slope design

2.1.1 Predict: geotechnical characterisation and behaviour forecasting

The predictive phase involves the development of robust geotechnical models that incorporate:

- lithological and structural models based on drilling, mapping and geophysics
- rock mass classification using systems such as rock mass rating (RMR), Q-system and geological strength index (GSI)
- hydrogeological models including pore pressure regimes and flow paths
- stress models of regional and excavation-induced stress fields.

From these models, engineers estimate potential failure mechanisms (e.g. planar, wedge, toppling, circular failure or a complex mechanism involving rock mass and structural condition), deformation patterns and critical zones. Probabilistic and numerical methods (e.g. limit equilibrium, finite element and discrete element as mentioned by Chiwaye & Stacey 2010) are used to simulate slope performance under various scenarios and design cases. Numerical tools are chosen according to the problem to be reproduced and are conditioned by the variables considered in the constitutive model and the boundary conditions, which are not always well known or correctly represented and need to be questioned and corrected continuously.

The approach of using stability modelling tools needs to be thought of as one that is highly dependent on the confidence of the input data. This requires input data like the orebody knowledge to go through sensitivity scenarios rather than one deterministic answer to define a slope design.

2.1.2 Monitor: instrumentation and field observations

The implementation of a geotechnical monitoring system is central to the OM and includes:

- Displacement monitoring: total station surveys, prisms, radar (e.g. SSR (Slope Stability Radar) , lidar) and InSAR
- Subsurface monitoring: inclinometers, extensometers, piezometers
- Visual inspections: crack mapping, rockfall logs and photographic documentation
- Characterisation data: information acquired by face mapping and drilling.

Monitoring plans must define:

- Trigger values: thresholds for displacement, velocity or pore pressure, depending on the expected mechanism of failure per geotechnical domain or geotechnical design zone

- Frequency and resolution: based on slope criticality and the potential failure mechanism
- Data integration: geotechnical databases and decision-support systems considering drilling and mapping data as part of the geotechnical characterisation cycle.

2.1.3 Reconciliation: decision-making and adaptive management

Reconciliation in the OM represents a critical feedback loop that ensures slope performance predictions remain aligned with actual geotechnical and hydrogeological conditions encountered during mine execution. This process is not limited to monitoring and instrumentation data alone but is deeply grounded in the systematic integration of multiple field-derived data sources into the geotechnical model.

While monitoring systems such as radar, prisms and piezometers provide essential performance indicators, by the time displacement or pore pressure anomalies are detected the slope may already be exhibiting symptoms of instability. Therefore, reconciliation must begin earlier – at the predict stage – by proactively updating geotechnical inputs through the continuous validation of model assumptions.

This includes:

- Lithological reconciliation: updating the lithological model using new exposures from pit walls, blast holes and operational drilling campaigns. Variability in rock type and alteration intensity often becomes evident only during active mining, necessitating refinement of the lithological domains
- Structural reconciliation: systematic face- and bench-scale mapping of faults, joints, bedding planes and fold structures to refine the structural model. This helps confirm or challenge previously assumed failure mechanisms and daylighting conditions
- Geotechnical cell mapping: detailed in-pit geotechnical cell mapping is essential to classify local rock mass conditions. These cells are used to spatially track GSI, RMR, Q-values and discontinuity characteristics – particularly in high-risk zones or where ground conditions deviate from the design model
- Hydrogeological reconciliation: groundwater models are updated with real-time piezometric data, dewatering observations and flow regime assessments. These updates are especially critical in domains where pore pressure is a key driver of failure mechanisms or where depressurisation efforts are underway
- Operational drilling campaigns: new drilling data, particularly from angled and infill holes, can significantly change the understanding of subsurface conditions. Integration of drilling logs, core photos and televiewer data allows for dynamic refinement of geotechnical domains and material property estimates.

Together, these elements form the foundation of a reconciliation process that is not reactive but predictive – a forward-looking framework that captures the evolving reality of ground conditions before instability occurs. By integrating reconciliation as a core component of the OM cycle, practitioners can reclassify domains, adjust design parameters and recalibrate numerical models in a timely and traceable manner.

Ultimately, reconciliation links field evidence to design response, bridging the gap between assumed geotechnical conditions and observed slope behaviour. Its continuous application improves the reliability of slope designs and enhances the effectiveness of trigger action response plans (TARPs) and slope management plans across the mine life cycle.

When monitored behaviour deviates from predictions, the OM requires a structured response:

- TARPs: predefined actions for various threshold exceedances
- Data acquisition: additional geotechnical information integrating face mapping and drilling data is required
- Design adaptation: slope angle modification, berm redesign, drainage installation or reinforcement. Depending on the outcome of the reconciliation, the adaptation can be positive if the observed geotechnical conditions are more favourable than originally expected. Otherwise, the adaption can impact negatively in the design
    - if the slope performance is worse than expected, the design adaptation can add value in terms of increasing the reliability of the mine plan (generally decreasing inter-ramp angles or adding step-outs in the slope design) for operational continuity while minimising operational disruptions due to instability issues.
    - if the slope performance is significantly better than expected, the design adaptation can add value by increasing the inter-ramp angles or optimising the overall slope angle.
- Operational controls: evacuation protocols, exclusion zones or mining sequence changes
- Model updating: back-analysis to refine geotechnical models and improve future predictions.

This reactive capability transforms slope design from a static to a dynamic process, improving safety and operational flexibility.

2.2 Integration with geotechnical design guidelines

To effectively apply the OM in open pit slope design it is essential to embed it within a structured and traceable geotechnical design process. This begins with a thorough characterisation of the ground conditions and a prediction of slope behaviour based on geological, hydrogeological and structural models, where the conceptualisation of potential failure mechanisms becomes critical. As excavation progresses, real-time monitoring data must be systematically compared with these predictions to assess performance. When deviations occur, the design must be updated accordingly. Maintaining clear documentation of assumptions, observations/monitoring and decisions ensures transparency and supports adaptive management. This continuous feedback loop not only enhances safety and efficiency but also provides a consistent framework for managing geotechnical risk throughout the life of the mine.

2.3 Relevant parameters and alignment to open pit design guidelines

In development and analysis of the geotechnical model, the relevant parameters (which could affect the rock mass behaviour) and their uncertainties must be identified, as shown in Figure 2.

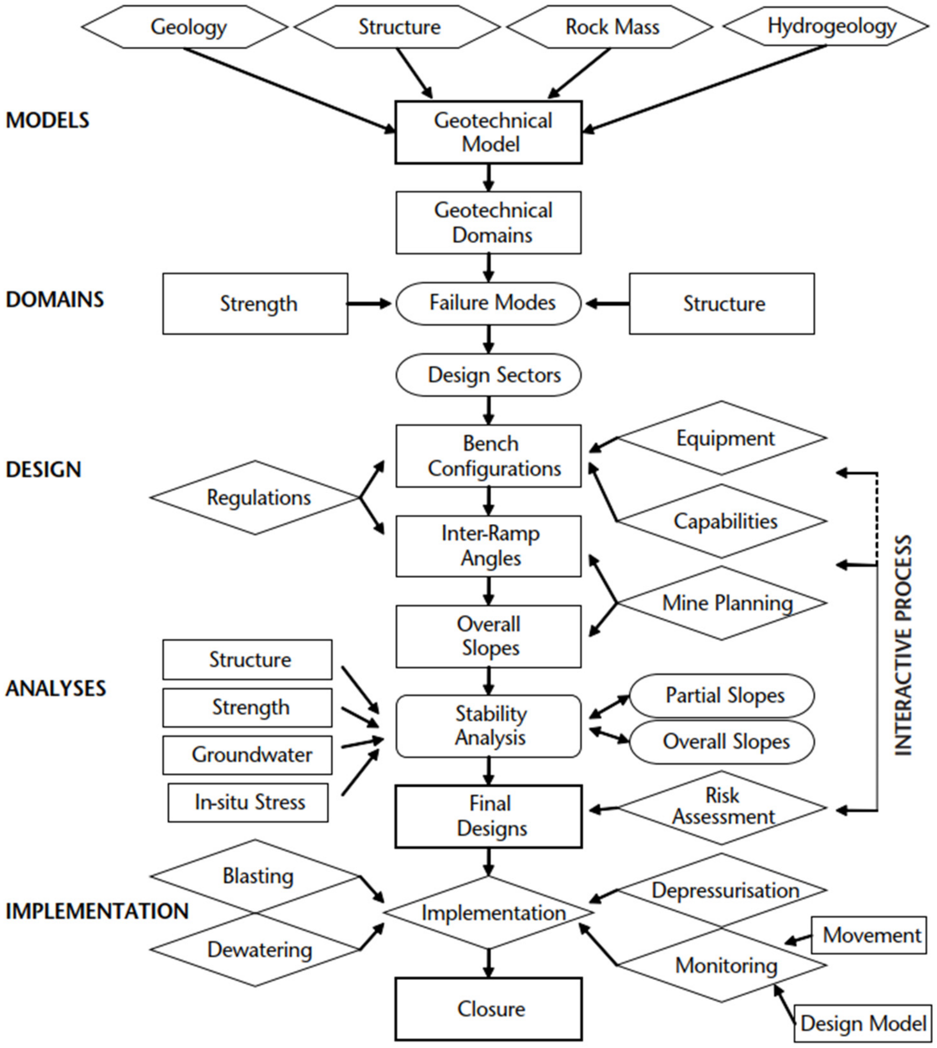


Figure 2 Slope design process (Read & Stacey 2009)

Figure 2 presents the slope design process, including the relevant parameters that are included in the geotechnical model. This in turn has an input to the geological, hydrogeological, structural and rock mass models. For the OM application it is necessary to know the variables associated with each model and their uncertainties. The main parameters for the models, taken from the large open pit project guidelines (Read & Stacey 2009), are presented in Figure 3.

Figure 4 shows the proposed application of the OM in open pit slope design following a structured, iterative process centred on the principles of predict–monitor–reconciliation. Initially, geotechnical domains are defined based on the assumption of which are the main drivers for slope failure. Therefore, it is expected to initially identify the relevant/critical parameters for mine design. These domains inform the conceptualisation of failure mechanisms and the development of slope designs, supported by numerical modelling and design acceptance criteria.

During mine execution, actual slope behaviour is monitored using a geotechnical monitoring system. This includes displacement tracking (typically through prisms and radars), pore pressure monitoring and visual inspections. The observed behaviour (excavation data – ED) is then compared to the predicted behaviour (conceptual expectation – CE) to assess whether the slope is performing as expected.

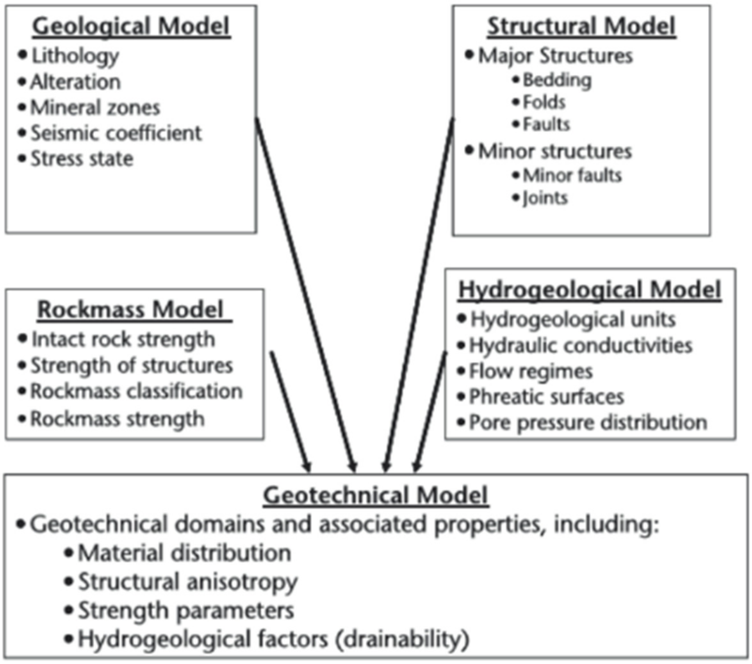


Figure 3 **Information needed to build a geotechnical model (Read & Stacey 2009)**

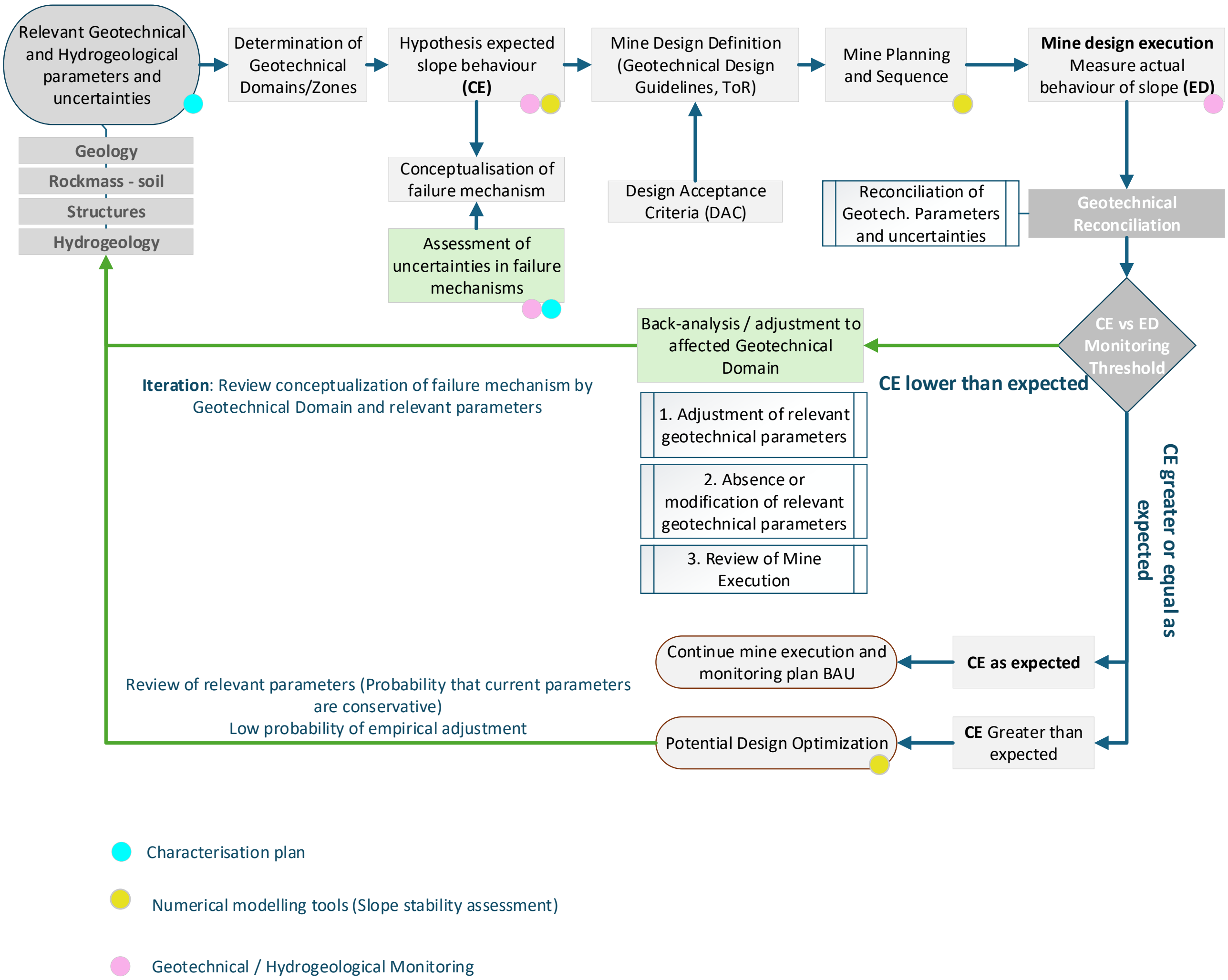


Figure 4 **Proposed geotechnical process flow for applying the observational method to an open pit**

If actual performance aligns with expectations, mining continues under the current design or eventually there is a potential optimisation (if actual performance exceeds expectations). However, if performance is worse than predicted, a back-analysis is triggered. This involves reviewing and adjusting geotechnical parameters, updating failure mechanism hypotheses and refining the geotechnical model through reconciliation with field data.

This iterative cycle ensures that slope designs remain responsive to an evolving understanding of ground conditions. By continuously integrating new data and refining assumptions, the OM enhances slope stability, reduces geotechnical risk and supports safer, more adaptive mine planning.

Understanding the uncertainty of the critical parameters, as represented in Figure 3, is an essential part of this process to interpret and attempt to predict the expected mechanism of failure per geotechnical domain zone. The following Table 1 represents the qualitative assessment of the uncertainty of these parameters and their weight in the predicted failure mechanism. This assessment gives us an uncertainty index for the failure mechanism with respect to the parameters that govern it, which must be filled in for each geotechnical domain zone of the pit.

Table 1 Reliability assessment of critical parameters by geotechnical domain zone, modified after Read & Stacey (2009) and Gaida et al. (2021)

		Reliability in relevant parameters (rating)					Relative weight	
Item		**1**	**2**	**3**	**4**	**5**	**Weight**	**Value**
A	**Geology model**							
1a	Lithology							
2a	Alteration						10%	0
3a	Mineral zones							
4a	Seismic coefficient							
5a	Stress state							
B	**Structural model**							
	Major structures							
1b	Bedding							
2b	Folding							
3b	Faults						10%	0.3
	Minor structures							
4b	Minor faults						20%	0.4
5b	Joints							
C	**Rock mass model**							
1c	Intact rock strength							
2c	Strength of structures						10%	0.3
3c	Rock mass classification							
4c	Rock mass strength						40%	0.8
D	**Hydrogeological model**							
1d	Hydrogeological units							

Item		Reliability in relevant parameters (rating) 1	2	3	4	5	Relative weight Weight	Value
2d	Hydraulic conductivities							
3d	Flow regimes							
4d	Phreatic surfaces							
5d	Pore pressure distribution						10%	0.2
	Total						**100%**	**2**

Another uncertainty in predicting failure mechanisms is the type of stability analysis used and whether this analysis can reproduce the failure mechanism we have identified. This assessment can be 2D or 3D and can be performed through a limit equilibrium analysis or a numerical analysis. The assessment template is shown in Table 2 Reliability/applicability in the LEM (Limit Equilibrium Method) or SRF (Strength Reduction Factor) stability analysis based on the modelled failure mechanism.

Table 2 Template for uncertainty assessment

Note: 5 very high confidence – 1 Very low confidence	**Relative certainty in tools for stability analysis** **1**	**2**	**3**	**4**	**5**	**Relative weight in the failure mechanism** **Weight**	**Value**
The LEM or SRF stability analysis (2D or 3D) clearly represents the expected failure mechanism							
The failure mechanism is not conditioned by the disturbance factor?							
There is enough information to calibrate the analysis							

*When Hoek–Brown failure criteria applies.

3 Case study: application of the observational method in the Escondida pit slope design

The following example represents the application of the OM in the Escondida pit to consider two design cycles for a long-term mining plan. The exercise will show the design cycles as iterations following the flow chart in Figure 4.

3.1 Relevant geotechnical and hydrogeological parameters and uncertainties

The Escondida pit is a large-scale copper porphyry deposit that has been in continuous operation for over 35 years. As a result, there exists a comprehensive understanding of the key geotechnical and hydrogeological parameters that contribute to slope instabilities.

An annual review is conducted to assess whether the current conditions influencing slope stability remain consistent with the historically identified critical parameters.

The primary factors influencing slope stability are generally recognised as:

- rock mass alteration

- major fault structures
- minor fault structures
- rock mass strength
- pore pressure distribution.

It is important to emphasise that the influence of these parameters varies across the different geotechnical zones within the Escondida pit. As will be discussed in subsequent sections, the relevance of each parameter is closely linked to the dominant failure mechanisms anticipated in each geotechnical zone.

3.2 Determination of geotechnical zones

The geotechnical zoning of the Escondida pit has been established through an integrated approach that overlays lithological data with alteration zones derived from the geological model (Flores & Karzulovic 2003). This framework is further refined by incorporating assessments of rock mass quality and structural domain characteristics. The outcome of this methodology is the delineation of 14 distinct geotechnical zones across the Escondida pit, as shown in Figure 5.

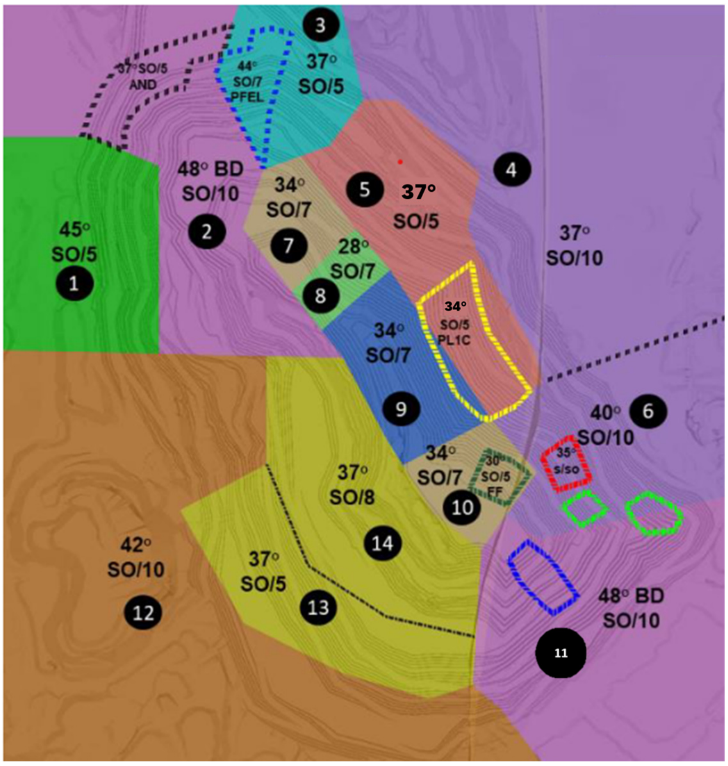


Figure 5 Geotechnical domain zones for the Escondida pit (Vasquez & Ledezma 2024)

3.3 Hypothesised expected slope behaviour and conceptualisation of failure mechanisms

The conceptualisation of failure mechanisms needs to be assessed considering the impact of each geotechnical and hydrogeological parameter listed in Section 3.1. This assumption considers a minimum level of knowledge about the expected mechanism driven by available information and the geotechnical assessment done at this point (as a first iteration in this case study), supported by a stability assessment.

The following image (Figure 6) shows a representative section of geotechnical zone 5, where the expected mechanism of failure is mainly driven by a poor-quality rock mass in combination with sub-vertical faults, forming non-daylighting wedges or non-daylighting planar failures leading to a shallow slope instability at the inter-ramp scale,

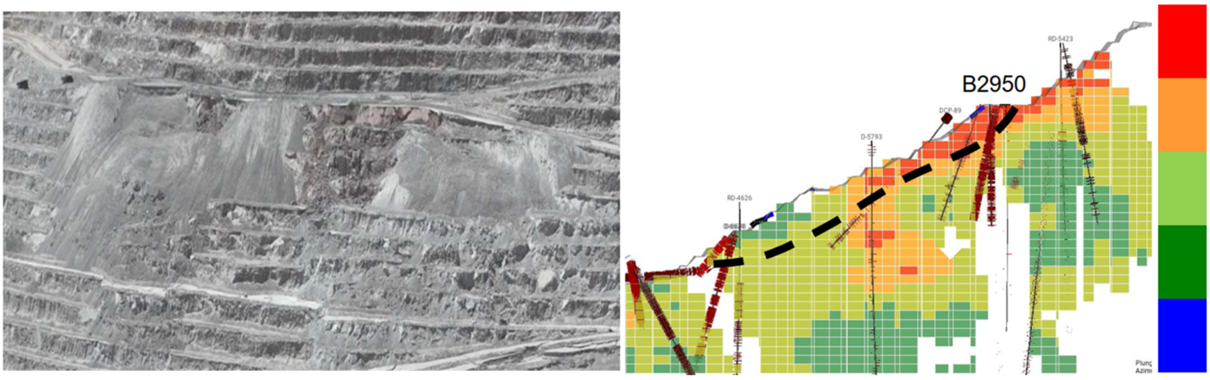


Figure 6 **Representative section of geotechnical zone 5 (courtesy of Escondida mine), legend in fracture frequency**

3.3.1 Conceptualisation of failure mechanisms

Considering the initial geotechnical assessment (first iteration in the diagram shown in Figure 4), the result of the conceptualisation of mechanisms by geotechnical domain is shown in Table 3.

Table 3 **Mechanism of failure assessment for the Escondida open pit by geotechnical domain zones (Hypothesis 1)**

Geotechnical zones	Mechanism of failure	Comments	PP*
1	Non-daylighting wedges with one main plane	Mid GSI with small areas of low GSI	No
2	Non-daylighting wedges with one main plane	Mid GSI with small areas of low GSI	No
3	Non-daylighting wedges with one main plane + rock mass	Mid GSI with small areas of low GSI	No
4	Rock mass failure and non-daylighting wedge with one main plane	Low GSI	No
5	Rock mass failure and non-daylighting wedge with one main plane	Low GSI	No
6	Non-daylighting wedges with one main plane	Mid GSI with small areas of low GSI	No
7	Mainly rock mass failure induced by anisotropy	Low GSI	Yes
8	Mainly rock mass failure induced by anisotropy	Low GSI	Yes
9	Non-daylighting wedge with two main planes	High GSI, impacted by major structures	Yes
10	Non-daylighting wedges with one main plane + PP	Impacted by PP	Yes
11	Brittle non-daylighting wedges with two main planes (high GSI) + PP	High GSI, impacted by major structures	Yes
12	Brittle non-daylighting wedges with one main plane (high GSI)	High GSI, impacted by major structures	No
13	Brittle non-daylighting wedges with one main plane (high GSI)	High GSI, impacted by major structures	No
14	Non-daylighting wedge with one main plane	Mid GSI, high impact of PP	Yes

*PP = pore pressure. GSI = Geological Strength Index.

3.3.2 Reliability assessment for mechanisms of failure by geotechnical zone

According to the outlined methodology, the subsequent step involves conducting a reliability assessment of the critical parameters influencing each geotechnical zone. It is important to recognise that the relevance and impact of these parameters may vary depending on the specific location within the pit..

Table

Table 4 presents the qualitative assessment approach applied in this case study, specifically for geotechnical zone 5.

Table 4 Qualitative reliability assessment by geotechnical parameters (example of geotechnical zone 5) – iteration 1

		Reliability in relevant parameters (rating)					**Relative weight**	
Item		**1**	**2**	**3**	**4**	**5**	**Weight**	**Value**
A	**Geology model**							
1a	Lithology					5		
2a	Alteration		2				10%	0.2
3a	Mineral zones					5		
4a	Seismic coefficient				4			
5a	Stress state							
B	**Structural model**							
	Major structures							
1b	Bedding							
2b	Folding							
3b	Faults			3			10%	0.3
	Minor structures							
4b	Minor faults		2				20%	0.4
5b	Joints							
C	**Rock mass model**							
1c	Intact rock strength				4			
2c	Strength of structures			3			10%	0.3
3c	Rock mass classification							
4c	Rock mass strength		2				40%	0.8
D	**Hydrogeological model**							
1d	Hydrogeological units				4			
2d	Hydraulic conductivities				4			
3d	Flow regimes			3				
4d	Phreatic surfaces				4			
5d	Pore pressure distribution		2				10%	0.2
	Total						**100%**	**2.2**

The table below presents an example of classification for the key parameters in geotechnical domain zone 5, organised into four sections in accordance with the guidelines outlined by Read & Stacey (2009), and followed by the work done by Gaida et al. (2021) and Creighton (2022). At this stage of the assessment, the objective is to evaluate the relevance of each parameter in relation to the expected failure mechanism (previously defined in Table 3) for each geotechnical zone.

As discussed earlier, the dominant factors contributing to slope instability in this domain are rock mass strength and the structural model.

This assessment process was applied across all 14 geotechnical zones, with each zone incorporating a distinct set of geotechnical parameters and associated weightings reflecting the variability in geological and structural conditions throughout the pit.

3.4 Mine design and stability analysis

In accordance with the workflow, the next step involves incorporating the mine design and extraction sequence into the slope stability assessment. At this stage it is essential to select an appropriate slope stability analysis method that can accurately represent the physical characteristics, conceptual mechanism and anticipated behaviour of the slope.

Table 5 provides a qualitative assessment, by geotechnical zone, reliability/applicability in the LEM (Limit Equilibrium Method) or SRF (Strength Reduction Factor) stability analysis based on modelled failure mechanism, of the key factors relevant to slope stability analysis. This includes considerations such as slope geometry, failure mechanisms and the suitability of numerical modelling tools for each zone.

Table 5 Reliability on the application of slope stability tools (example of geotechnical zone 5)

Note: 5 very high confidence – 1 very low confidence	**Relative certainty in tools for stability analysis**					**Relative weight in the failure mechanism**	
	1	**2**	**3**	**4**	**5**	**Weight**	**Value**
The LEM or SRF stability analysis (2D or 3D) clearly represents the expected failure mechanism		2				40%	0.8
The failure mechanism is not conditioned by disturbance (D) factor?				4		30%	1.2
There is enough information to calibrate the analysis			3			30%	0.9
					Total	**100%**	**2.9**

*When Hoek–Brown failure criteria apply.

This rating was done for each of the 14 geotechnical zones in the Escondida pit. For practical purposes, the table shows the example of geotechnical zone 5 as the modelling results there are highly impacted by the disturbance (D) factor, which was addressed by running a sensitivity analysis over D. In the case of the Escondida pit, when the numerical results are impacted significantly by D, the FoS tends to be less reliable than in areas where the D factor is less sensitive.

3.5 Mine design execution

As outlined in Figure 4, the implementation of a geotechnical monitoring system during mine execution is a critical component of the observational method. The effectiveness of this approach relies heavily on the ability to observe and interpret slope behaviour in real time, which is made possible through robust monitoring systems.

At the Escondida pit, a comprehensive geotechnical monitoring network has been established. This system integrates multiple technologies including ground-based radars, robotic total stations, global navigation satellite systems and satellite InSAR, and a range of sub-surface instruments such as time domain reflectometers, shape-acceleration arrays and in-place inclinometers.

3.5.1 Slope performance monitoring

Monitoring slope displacements enables geotechnical practitioners to distinguish between planned and unplanned deformations, both of which may indicate the onset of slope instability.

During mine execution, geotechnical domain 5 experienced several unplanned geotechnical instabilities. The image (Figure 7) below illustrates an example of a multi-batter inter-ramp failure. Although the initial failure mechanism was anticipated (as outlined in Table 3), the reliability assessment of critical parameters (Table 4) indicated that rock mass strength had a low level of reliability at the time of evaluation, which likely contributed to the observed instability. This was triggered by a previous definition of maximum acceptable velocity in the TARP.

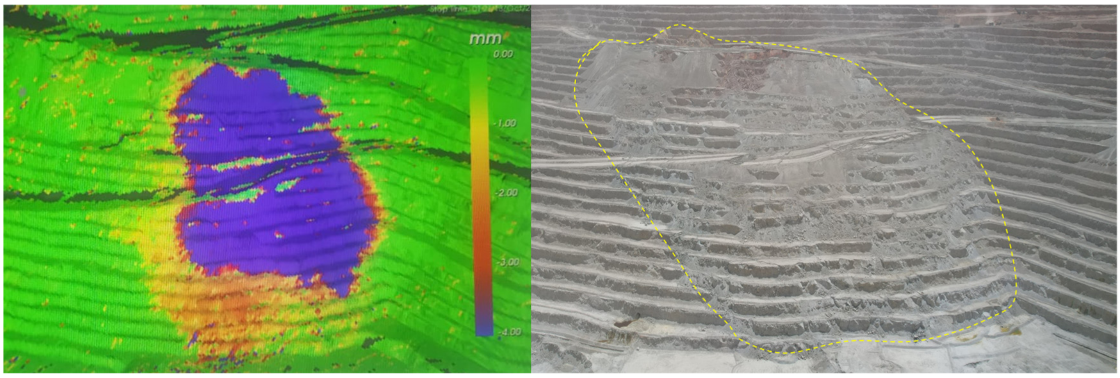


Figure 7 Instability during mine execution in geotechnical zone 5 (courtesy of Escondida mine)

The difference between the actual failure compared to the expected design was mainly due to the actual rock mass strength being significantly lower than the one used in the slope stability analysis for this geotechnical zone.

The difference between the actual failure compared to the expected was mainly due to the actual rock mass strength being significantly lower than the one used in the slope stability analysis for this geotechnical zone. This deviation highlights a critical limitation in the initial geotechnical model, which underestimated the extent and spatial distribution of poor-quality rock mass and clay-rich zones within geotechnical zone 5. While the original conceptual design did anticipate the possibility of localised instabilities, which is normally manageable through operational controls, the actual, broader scale and continuity of weak material encountered during mine execution exceeded those assumptions. As a result, the slope performed from a planned locally unstable scenario to an actual domain-wide instability condition.

Under the framework of the OM, particularly its emphasis on early reconciliation and proactive model updates, this failure could have been anticipated or, at minimum, its impact significantly reduced. Had a more rigorous operational drilling campaign or in-pit geotechnical characterisation been conducted earlier in the design process, the condition and prevalence of poor rock mass would have been anticipated earlier. This would have allowed for a more conservative initial design, potentially involving reduced inter-ramp angles from the outset.

The OM methodology supports this level of adaptability by embedding field validation and continuous reconciliation into the design process. In this specific case, the methodology successfully captured the deviation through early warning signs and subsequent back-analysis, allowing the design team to mitigate further risk. However, had these critical geotechnical conditions been identified earlier in the predict phase

– via enhanced data acquisition and domain refinement – the magnitude of the uncontrolled event and its associated operational disruption could have been substantially minimised.

This underscores the value of the OM framework not only as a responsive tool post-failure, but as a proactive design philosophy that can adjust slope geometries before adverse performance occurs, improving overall geotechnical reliability in large-scale mining operations.

3.6 Geotechnical reconciliation

Continuing with the example from geotechnical domain 5, the reconciliation process revealed a significant discrepancy between the geotechnical model and field observations; specifically, the GSI where values mapped in the field were found to be 10 to 20 points lower than those assumed in the initial stability assessment (iteration 1).

This variance highlights the importance of ongoing reconciliation between modelled and observed geotechnical conditions, ensuring that slope designs remain aligned with actual ground conditions as mining progresses. This difference between actual versus planned conditions triggers an action plan in terms of specific geotechnical mapping and characterisation with a focus on confirming the relevance of the critical parameters defined in the initial hypothesis and the mechanism of failure. Figure 8 shows the difference between the expected rock mass condition (bottom right) and the actual rock mass condition (upper right) coming from face mapping.

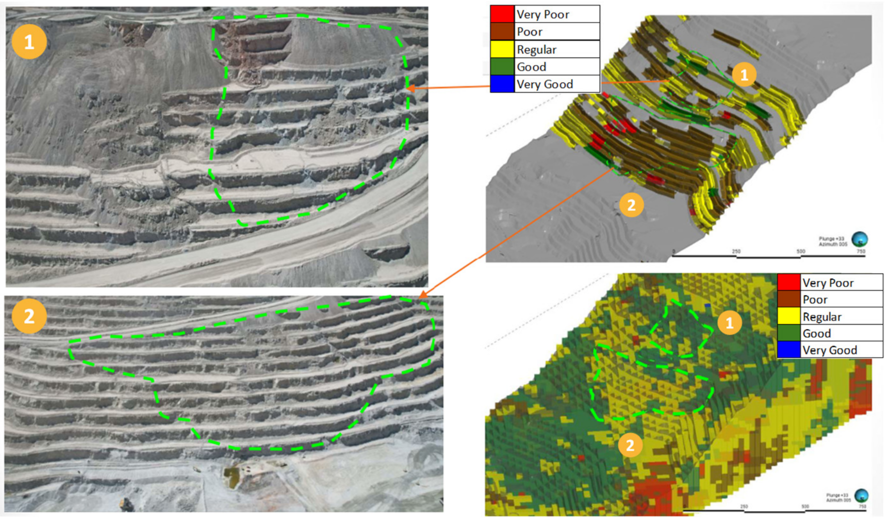
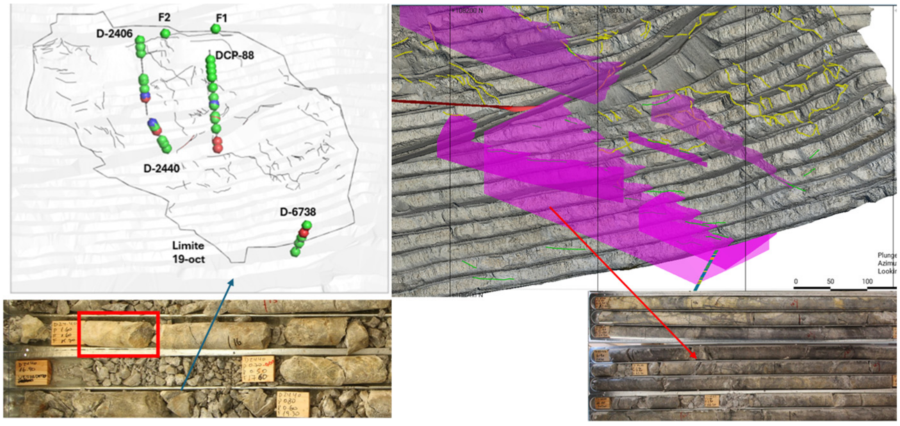


Figure 8 Geological Strength Index (GSI) mapped in the field (upper) versus the GSI model used in the stability analysis (bottom) in iteration 1. Number one zone represents the upper inter-ramp slope area with an observed failure while number two zone represents the lower inter-ramp slope area with significant displacement and a partially stable slope

In addition to the updated GSI values, the reconciliation process also led to revisions of the clay content within the intact rock – an indicator of poor rock mass quality – and adjustments to the structural model. These updates further support the hypothesis that both geological features were contributing factors to the observed failure mechanism. Figure 9 shows an example of reconciliation coming from the drilling data. In this example, the clay content (left) and structures (right) were identified during an additional reconciliation campaign to gain certainty in these two critical parameters, as stated in Section 3.5. The information from drillcores shows evidence of a higher level of clay and an unforeseen structure dipping onto the slope. Both parameters played a significant role in the actual slope performance.



(a) (b)

Figure 9 **(a) Updates in the clay model and (b) the structural model during the geotechnical reconciliation process (courtesy of Escondida mine)**

3.7 Back-analysis and adjustment for the affected geotechnical domain

The information obtained through the reconciliation process informed the subsequent back-analysis, leading to a reduction in rock mass property values. This included adjustments to account for the influence of alteration zones and fault structures within the updated structural model. As a result, a second iteration (iteration 2) was initiated, during which the reliability assessment table was revised, and a new round of stability analysis was conducted.

In line with the decision point outlined in Figure 4 – Is actual slope performance lower than expected? (a CE versus ED decision) – the conditions observed in geotechnical domain 5 clearly indicate underperformance relative to expectations. Consequently, a back-analysis was carried out.

Table 6 presents the updated version (the first iteration after reconciliation) of Table 4 for geotechnical domain 5, incorporating the findings from the back-analysis. Highlighted entries indicate parameters that were revised during this iteration.

Table 6 **Updated qualitative reliability assessment by geotechnical parameters (example of geotechnical zone 5) – iteration 2**

		Reliability in relevant parameters (Rating)					**Relative weight**	
Item		**1**	**2**	**3**	**4**	**5**	**Weight**	**Value**
A	**Geology model**							
1a	Lithology							
2a	Alteration		●→		4		10%	0
3a	Mineral zones							
4a	Seismic coefficient							
5a	Stress state							
B	**Structural model**							
	Major structure							
1b	Bedding							
2b	Folding							
3b	Faults			●→	4		10%	0.3
	Minor structure							
4b	Minor faults		●→		4		20%	0.4
5b	Joints							
C	**Rock mass model**							

		Reliability in relevant parameters (Rating)					**Relative weight**	
Item		**1**	**2**	**3**	**4**	**5**	**Weight**	**Value**
1c	Intact rock strength							
2c	Strength Structures			3	*no changes		10%	0.3
3c	Rock mass classification							
4c	Rock mass strength		●⟶	⟶	4		40%	0.8
D	**Hydrogeological model**							
1d	Hydrogeological units							
2d	Hydrogeological Conductivities							
3d	Flow regimes							
4d	Phreatic surface							
5d	Pore pressure distribution		2	*no changes			10%	0.2
	Total						100%	2

It’s important to mention that the reconciliation assessment and back-analysis were carried out only in the areas where the mine execution in addition to the geotechnical characterisation campaign allow the creation of a significant update to the geotechnical model. In this example, only 6 of the 14 geotechnical zones were reassessed between Iterations 1 and 2.

The main outcomes from the back-analysis exercise were:

- The rock mass properties need to be changed. Considering the actual data from field, GSI values need to be decreased by 10 to 20 points in the area of interest.
- A high clay content (over 30%) in the geotechnical zone revealed a parameter with a significant impact on rock mass strength. Understanding spots with high clay content allow the Escondida team to create sub-domains to predict a better result in slope stability assessment.

Is hypothesis 1 (Table 3) for the mechanism of failure still valid? The mechanism is the same as the one considered in iteration 1, however, significant poorer rock mass is impacting the slope performance more than initially expected.

3.8 Iteration 2: uncertainties in geotechnical and hydrogeological parameters

As the final step in iteration 2, the geotechnical domains were updated in accordance with the flow chart methodology. This step is required for any domain where actual slope performance is found to be lower than expected.

In the Escondida case study, the primary drivers for updating the geotechnical domains were low reliability in the:

- rock mass strength parameters
- characterisation of major and minor structural features
- pore pressure model, in certain domains.

These updates ensure that the geotechnical model remains representative of actual field conditions and supports more accurate slope stability assessments in future iterations.

Figure 10 presents a summary matrix that plots geotechnical input ratings (as outlined in Table 4 and updated with the later iteration in Table 6) along the X-axis against the reliability of applying slope stability tools on the Y-axis, across the 14 geotechnical domains.

This case study highlights how the initial assumptions for geotechnical domain 5 evolved in response to actual slope performance. The geotechnical input rating increased from 2.2 to 3.7, validating the initial failure mechanism hypothesis and enabling refinement of the design parameters.

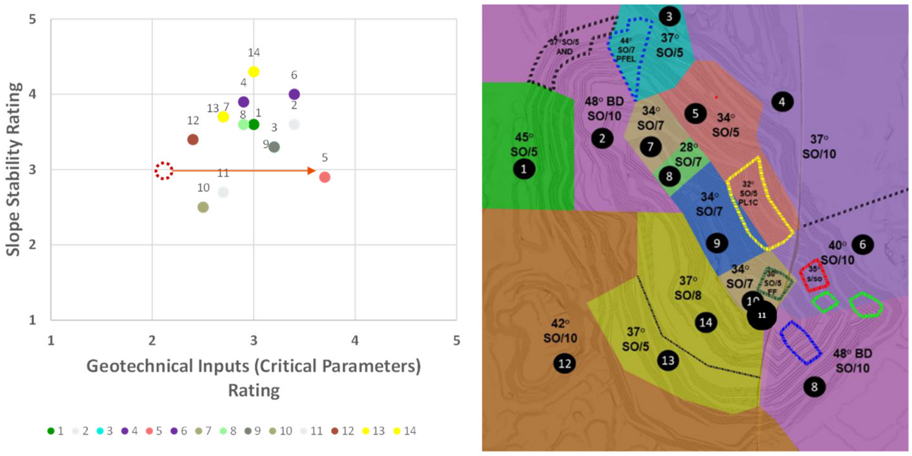


Figure 10 Summary matrix for the qualitative reliability rating by geotechnical domain

The OM played a key role in redefining the geotechnical domain, as illustrated in the right-hand image of Figure 10. Specifically, the inter-ramp angle was reduced from 37 to 34°, and in areas with elevated clay content, the angle was further reduced from 34 to 32°. Following these adjustments, slope performance improved, and numerical models were successfully calibrated to better represent the physical behaviour of the upper slope instability.

4 Conclusion

The Escondida pit case study demonstrates the effective application of the observational method (OM) in open pit slope design, following the principles outlined in the Slope Design Guidelines (Read & Stacey 2009) and supported by contemporary research in mining geomechanics. Central to this approach is the predict–monitor–reconciliation cycle, which ensures that slope designs are continuously refined based on observed performance.

In the case of geotechnical domain 5, the initial design was based on a set of assumptions regarding rock mass quality and structural conditions. However, through systematic monitoring and reconciliation, it became evident that actual slope performance deviated from expectations. This triggered a back-analysis and reclassification of geotechnical parameters, particularly a downward revision of the Geological Strength Index and the identification of high clay content as a critical factor.

The iterative application of the OM led to a more reliable geotechnical model and ultimately resulted in a reduction of the inter-ramp slope angle from 37 to 34°, and down to 32° in clay-rich zones. This adjustment improved slope stability and allowed for better calibration of numerical models, aligning predicted behaviour with observed performance.

This case reinforces the value of the OM as a dynamic and responsive framework for managing geotechnical risk in large-scale open pit operations, ensuring that slope designs remain both safe and economically viable throughout the life of mine.

The application of the OM in open pit slope design offers a structured and adaptive approach to managing geotechnical uncertainty throughout the mine's life. By integrating the core principles of predict–monitor–reconciliation, the method enables continuous refinement of slope designs based on actual ground behaviour rather than relying solely on initial assumptions.

Ultimately, the OM transforms slope design from a static to a dynamic process, improving safety, reducing operational risk and enabling more efficient resource use. Its systematic application in open pit mining represents the best practice for geotechnical risk management in complex and evolving geological environments.

Although the failure was not considered acceptable within the OM framework, the methodology facilitated a rapid and structured response, minimising operational disruptions and enabling the development of a revised mine plan with improved certainty in the geotechnical parameters. The economic implications, while confidential, included positive outcomes due to:

1. improved production performance through the mitigation of geotechnical events disrupting the operation
2. enhanced drill and blast practices tailored to updated and more reliable geotechnical domains
3. better spatial compliance, maintaining uninterrupted access to extraction areas as originally planned
4. increased mine plan reliability, particularly in preserving access through primary ramp infrastructure. By avoiding unexpected blockages or relocations of critical haul roads, cycle times for mine trucks were maintained at expected levels, preventing costly rerouting through alternative, less efficient access paths.

While the failure caused a localised impact, the OM approach enabled geotechnical and mine planning teams to proactively adjust slope designs and recover slope performance. By enabling real-time adaptation and model validation, the OM promotes risk-informed decision-making and long-term planning resilience. The shift from reactive monitoring to early-stage reconciliation strengthens both safety and operational efficiency.

Ultimately, the OM is a tool to reduce the frequency, magnitude and consequence of slope instabilities. If the slope performs significantly better than expected, the OM is also a tool to optimise slope angles. It provides a continuous improvement design philosophy that enhances operational certainty by systematically integrating updated field data and model verification into the design loop. The OM is thus validated not only as a responsive mechanism, but as a critical control for managing fall of ground risks and supporting safer, more efficient and more predictable mining operations.

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