

Guidelines to improve geological confidence in geotechnical model definitions in Western Australian iron ore

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Abstract

Historically, the planning of drill programs to collect downhole data for resource modelling purposes has received limited review from a geotechnical perspective. As a result, geology models in the waste rock outside a defined resource were often produced at a low confidence level. The design acceptance criteria (DAC) for slope-design stability analysis have recently been updated to include an assessment of the geology model confidence. This has highlighted the scale of areas of low confidence in geology models for geotechnical purposes. The cost of the additional drilling required for increasing the geology model confidence can now be compared to the potential value when applying these DAC and the resultant optimised slope designs. The timing of an opportunity to increase this confidence is in the order of three to five years prior to detailed geotechnical design projects and such an opportunity had been missed prior to this improvement. This paper outlines the process of communicating the geotechnical requirements of the geology model confidence and the assessment of drill plans with regard to requirements for a high-confidence geotechnical model. An evaluation of the gaps highlighted in drill planning has been included to provide broad guidelines for assigning additional drill metres for various project types. A checklist has been compiled as a reference guide for assessing resource-planning data collection to ensure the resultant geology models will be fit for geotechnical design purposes.

Keywords: *data collection, model confidence, geotechnical model*

1 Introduction

The iron ore deposits of the Pilbara region of Western Australia are hosted in banded iron formation of the Hamersley Group. Open pit slope design within these deposits is strongly dominated by structural geology and the anisotropic nature of the persistent bands of sedimentary rock. The morphology of the anisotropy is defined by the bedding orientations of the top of individual stratigraphic units. Bedding orientations are measured directly within drillholes, using a downhole televiewer or outcrop mapping (for local scale), and modelled across the deposit as stratigraphic boundary wireframes as part of the resource modelling processes. Stability modelling, in both 2D and 3D, is undertaken for slope design, using these stratigraphic boundaries as analogous to the orientation of the bedding anisotropy throughout the unit. As such, the confidence in both the location and the orientation of the stratigraphic surfaces is a key input into overall geotechnical model confidence. Historically, the resource model extent has primarily focused on defining the resource limits, which often results in the stratigraphic surfaces extents behind planned pit slopes to be of low confidence. This paper provides guidelines adopted within BHP Western Australia Iron Ore (WAIO) for evaluating and improving data-collection design well ahead of mining, with the goal of achieving geology models of appropriate confidence in critical zones for geotechnical analysis.

2 Design acceptance criteria with model confidence

2.1 Development of design acceptance criteria

The WAIO geotechnical department delivers the slope-design recommendations of every deposit for detailed design to the mine-planning department. These recommendations include maximum inter-ramp angles, bench-face angles and minimum berm width.

Calculations of slope stability are subject to meeting the design acceptance criteria (DAC). Common practice in the mining industry is to satisfy the DAC, which can have either a deterministic or probabilistic approach to target Factor of Safety (FoS) and Probability of Failure (PoF) that satisfies slope stability using limit equilibrium (LE) or numerical models.

In WAIO, the optimal slope configuration is based on LE analysis with a deterministic approach, where both a central case FoS (FoS_{CC}) and a lower bound case (FoS_{LC}) must satisfy the DAC. The lower bound analyses are used as sensitivity checks against factors of higher uncertainty and are applied independently of one another. It must be mentioned that an equivalent PoF is calculated employing the FoS_{CC} and FoS_{LC} as inputs into a normally distributed density function.

The new DAC of WAIO accounts for two major inputs: the geotechnical model confidence and the failure consequence. This differs from previous DAC guidelines, which typically used only slope scale to delineate appropriate criteria and follows the work of Macciotta et al. (2020). Thus, the DAC becomes a matrix (a table of double entry), as depicted in Figure 1. Tables 1 and 2 provide expanded definitions of the consequence of failure and of model confidence, respectively. The failure consequence is reported as the potential disturbance on production; this assumes that adequate controls are put in place to address residual risks, independently of the DAC. The model confidence is evaluated against the level of study, with identification phase study (IPS), selection phase study (SPS) and definition phase study (DPS) confidence levels defined.

		Consequence of Failure			
		Low	Moderate	High	Very High
Model Confidence	Low	$FoS_{CC} \geq 1.3$ $FoS_{LC} \geq 1.0$ $PoF \leq 10\%$	$FoS_{CC} \geq 1.5$ $FoS_{LC} \geq 1.2$ $PoF \leq 5\%$	Not Acceptable	Not Acceptable
	Moderate	$FoS_{CC} \geq 1.2$ $FoS_{LC} \geq 1.0$ $PoF \leq 20\%$	$FoS_{CC} \geq 1.3$ $FoS_{LC} \geq 1.1$ $PoF \leq 5-10\%$	$FoS_{CC} \geq 1.5$ $FoS_{LC} \geq 1.2$ $PoF \leq 5\%$	Not Acceptable
	High	$FoS_{CC} \geq 1.1$ $FoS_{LC} = 1.0$ $PoF \leq 30\%$	$FoS_{CC} \geq 1.2$ $FoS_{LC} \geq 1.0$ $PoF \leq 20\%$	$FoS_{CC} \geq 1.3$ $FoS_{LC} \geq 1.1$ $PoF \leq 5-10\%$	$FoS_{CC} \geq 1.5$ $FoS_{LC} \geq 1.2$ $PoF \leq 5\%$

Figure 1 DAC matrix

Key items to call out with this new approach include the blue cells = ‘fully optimised’, the yellow cells = ‘balanced’, the orange cells = ‘robust’ and the grey cells = ‘slope design will not be produced’.

Table 1 Consequence of failure criteria

Consequence	Examples of consequence
Low	<p>Failure events are operationally manageable and limited to single-bench scale (12 m). Failure is not life-threatening, providing adequate ground control practices are deployed.</p> <p>Failure consequence is localised and operationally manageable with no, or minimal, effects to continuous operations (e.g. multi-batter failure with no impact on ramp access). Failure is not life-threatening, provided adequate ground control practices are deployed (low consequence).</p>
Moderate	Slope failure results in temporary loss of access to ore, causing delays in production schedule (e.g. ramp blockages or partial loss of ramp access resulting in temporary blockage of access to ore). This includes slope failure at the inter-ramp scale (typically slopes with height <150 m).
High	Failure can significantly impact the supply chain by limiting the access to ore for many months. This includes slope failures at the inter-ramp and the overall scale (typically slopes with a height between 150 and 500 m).
Very high	Failure can affect the life of the asset, impact on the lease boundary or affect a critical infrastructure or the environment. This includes slopes at inter-ramp and overall scale (typically slopes with a height between 150 and 500 m).

Table 2 Model confidence level against design study level

Description	IPS level (>5 years)	SPS level (3–5 years)	DPS level (0–2 years)
Geological model: the location of strat units could include an error of interpretation within 50 and 100 metres. There is not a geotechnical drilling investigation to inform rock mass properties (e.g. geological strength index [GSI]). The hydrogeological models are only based on pre-mining water level.	High	Moderate	Low
Geological model: the location of strat units could include an error of interpretation within 24 and 50 m. There is limited geotechnical drilling investigation to inform rock mass properties. Hydrogeological models have limited drilling data; water table could include 'most likely' and 'pessimistic' cases.	High	High	Moderate
Geological model: the location of strat units could include an error of interpretation within 12 and 24 m. There is sufficient geotechnical drilling investigation to provide information about spatial variability of rock mass properties (e.g. GSI, soil strength and fault character). Hydrogeological models include monitoring bore data sets to inform upper and lower bounds (seepage or pore pressure models). This is the level required for DPS level.	High	High	High

The implications of applying the new DAC in WAIO include the following with respect to the development of geology models:

- Easy to communicate to non-technical stakeholders, who are directly involved in taking business decisions regarding project investment.
- Model confidence matures with time, and stakeholders understand that early investment is required to reach confidence in the models. This enables commitment from the business before feasibility studies even start.
- Increasing drilling in time for pre-feasibility would result in more optimal pit designs by applying the DAC with a lower compliant FoS when a geotechnical model has high confidence, as opposed to applying the DAC with a higher compliant FoS when geology is poorly understood.

2.2 Model confidence

The geotechnical model confidence is the sum of uncertainties in three models: geological boundaries, material strength properties and groundwater models. However, the experience of the authors is that the uncertainty on the geological boundaries will typically dominate the other two model uncertainties, i.e. the overall model confidence is primarily based on the accuracy of structural geology.

The definition of model confidence has been examined by WAIO geoscience and geotechnical teams over the last couple of years and matured to the stage of a geological confidence matrix. It is also understood that the geology model confidence should increase as the maturity of the project (or new deposit) progresses with subsequent drilling campaigns, from the conceptual stage (IPS level) to the most detailed stage of investigation (DPS level, also known as the feasibility level).

The definition of model confidence is assessed with respect to the anticipated instability mechanism. Geotechnical engineers have identified three key mechanisms in the Pilbara environment, which are defined as follows:

- Circular failure of detrital slopes (and weak layers of West Angela unit).
- Rock mass failure (including composite failures) of Archean units.
- Structural failure with bedding-controlled slopes of Archean units.

The accuracy needed for the geology model's definition for each failure mode varies with the level of study, and this is depicted in Table 3. These definitions have now become the geotechnical requirements for geological models for use in slope stability assessments at WAIO. These definitions permit the appropriate assignation of DAC of stability models, and they help engineers to better communicate required improvements at each level of investigation, e.g. geological model may need verification of geological models at selection phase, thus more drilling is requested to create models for the detailed phase design. The responsibility for assessing the confidence levels and boundaries between varying levels of confidence within this system lies with the modelling geologist.

Table 3 Model accuracy requirement by stability control

Input 'spatial location' of stratigraphy boundaries	SPS level (moderate accuracy)	DPS level (high accuracy)	Execution phase
Detrital (BADA and WA2)	Detrital horizons with elevation error of 24–50 m	Detrital horizon with elevation error of 12–24 m	Location of detrital boundary is reconciled and is visible from batter faces (± 12 m error)
Rock mass controlled slopes	Wireframe location is within ± 24 –50 m	Wireframe location is within ± 24 m error	Wireframe location is within ± 12 m error, with operational reconciliation
Structurally controlled slopes	Wireframe location is within ± 24 –50 m. Dip of bedding $\pm 20^\circ$ Major structures can be modelled as thick units to account for spatial location uncertainty	Wireframe location is within ± 24 m. Dip of bedding $\pm 10^\circ$ Major structures can be modelled as thick units to account for spatial location uncertainty	Wireframe location is within ± 12 m. Dip of bedding ± 5 – 10° , with operational reconciliation

3 Developing model confidence within design schedule

The development of resource models, geology models and geotechnical designs often occurs concurrently and is historically completed without due input from one another and, at times, occurs on various timelines. As part of developing the relationship between models, defining the timelines that these models are built on was critical for the efficient combining of drilling programs and for ensuring final models would be suitable for all end users.

The relationship between the target level of data confidence and the study level is well understood within the geotechnical design, with the geological targets to be in the order of '80–90%' confidence for a detailed or 'for-construction' design (Wesseloo & Read 2009), which is interpreted within the WAIO setting as errors in location of stratigraphic wireframes are to be within 12–24 m (see Table 2). The drilling to support this level of confidence must be completed with sufficient time for geology interpretation and modelling to be completed prior to the geotechnical detailed-level design. It is also noted that efficiencies can often be found by timing the geotechnical diamond drilling programs required for geotechnical model confidence. Figure 2 shows the timeline required for the resource drilling and modelling, the geotechnical design and the mine-planning key tasks. This shows a timeline counting back from the planned commencement of mining and shows that the critical time frame for data-collection inputs into model confidence (both geological model and geotechnical strength models) is between three and five years before the planned start to mining. The key process that has been implemented for improving model confidence has been the assessment of gaps in the model confidence at and before five years out from the mining timeline.

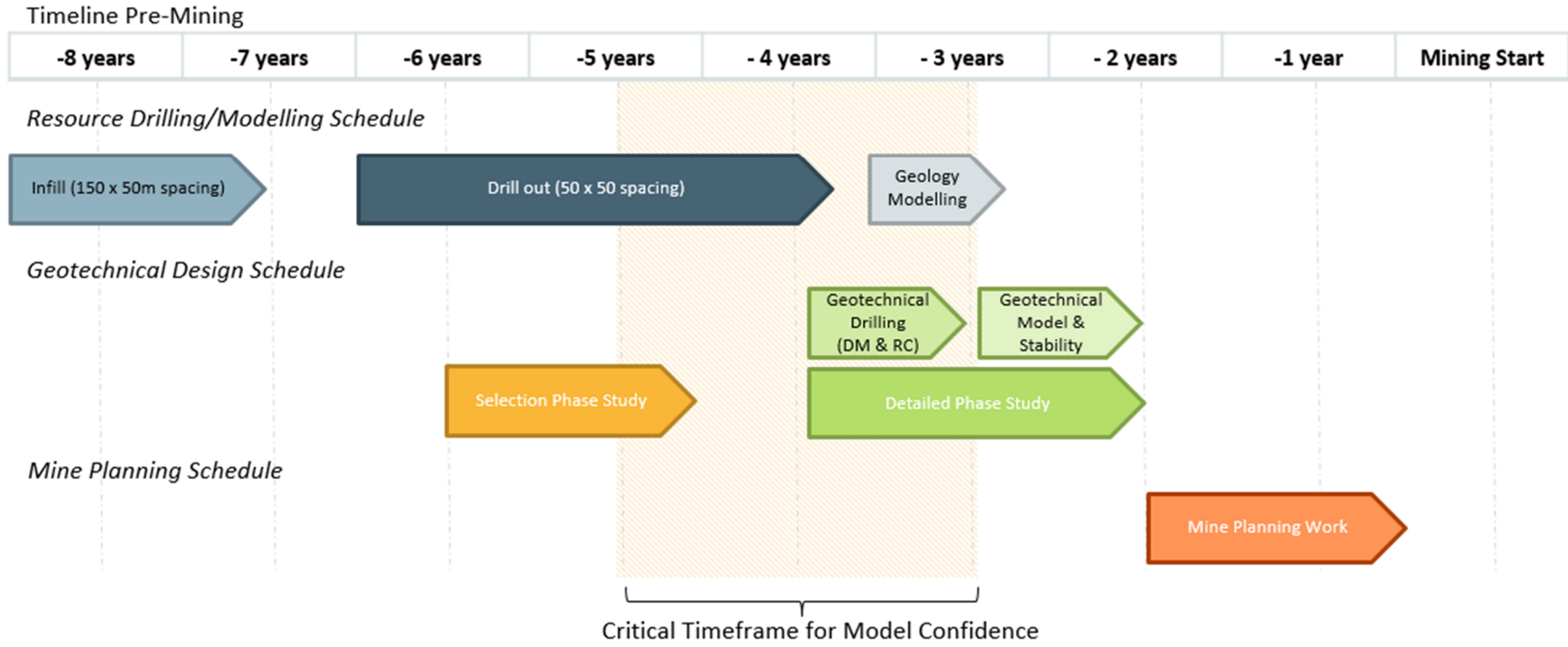


Figure 2 Timeline of data collection for 'on-time' high-confidence models

4 Evaluation of resource level datasets

4.1 Existing data checks

A series of checks have been developed for geotechnical design engineers to evaluate geology model coverage when there is still an opportunity to fill in any gaps in confidence and coverage of areas that will fall within the geotechnical zone of influence, defined as the zone in which instability surfaces are anticipated behind pit walls.

The timing of these checks is critical to allow sufficient time for additional drilling and to inform any geology model updates prior to the geotechnical design. This means that the data checks and geotechnical input into resource drilling needs to occur at least four years before mining is scheduled. This also allows sufficient lead time to undertake simultaneous checks on geotechnical and hydrogeological models to improve the input data to achieve the model confidence levels required by the DAC outlined in Section 2. These checks are included in the checklist provided in Table 4.

Table 4 Checklist for evaluation of models at drillout phase

Model	Criteria	Test
Geology	Drillhole coverage – lateral extent	Conduct a visual check against planned pit crest, and evaluate against zone of influence (i.e. distance behind crest). Include any potential pit expansions, and increase offset where unknowns exist. Use polygons to communicate the extent of gaps identified in check.
	Drillhole coverage – depth	Conduct a visual check ‘porcupine test’, and evaluate against planned pit. Highlight gaps using digitised polygons; see Figure 3.
	Constraints to coverage – terrain	Conduct a visual check against areas of steep terrain; define gaps using digitised polygons. See Figure 4.
Geotechnical	Laboratory samples – by domain	Number of valid samples against target for high confidence.
	Logging coverage	Number of holes and length of core logged against target for high confidence.
Hydrogeological	Anticipated water table interaction with slope stability	Pre-mining water table >20 m above base of pit.
	Coverage of hydro installations (i.e. VWPs)	Conduct a visual check (plan view).

The tests listed in Table 4 are demonstrated in the following figures. Figure 3 shows a ‘porcupine’ test, which involves conducting a visual check of an inverted pit shell and existing drillhole traces to show where gaps exist in the drilling at depth, behind pit walls. Figure 4 shows both the drillhole coverage in lateral extent – with a check of collar locations in plan view allowing for areas of low drilling coverage to be highlighted – and the potential constraints that may have led to the coverage gaps, such as steep terrain. In Figure 4, steep terrain created by gullies in topography is shown in red. Inclusion of the potentially mitigating factors in our gap analysis has significantly reduced the variation between geotechnical gap analysis and geoscience planning and has streamlined the drill planning design.

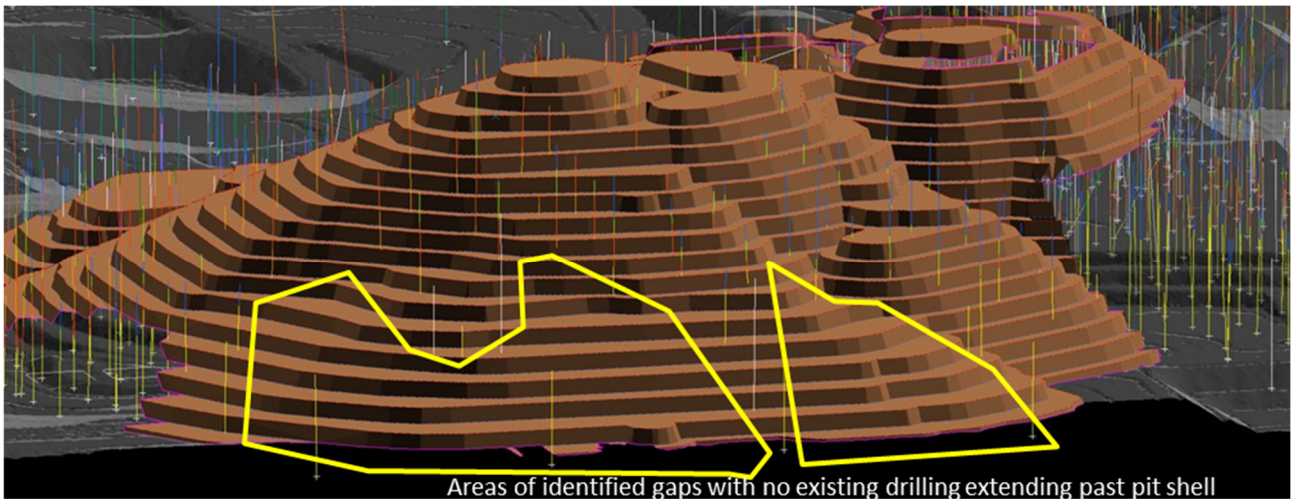


Figure 3 Drillhole coverage: depth, using inverted pit shell 'porcupine' test

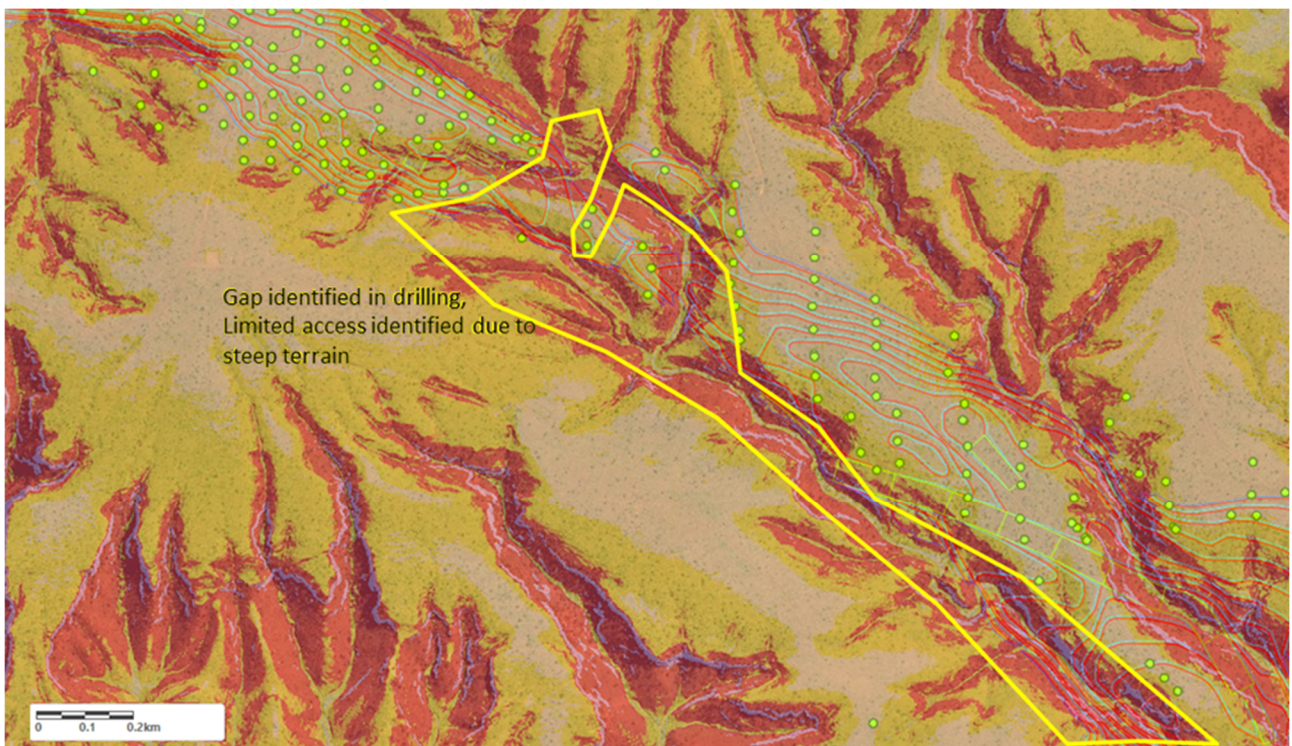


Figure 4 Drillhole coverage: lateral extents with terrain constraints

4.2 Communication of data gaps

The data gaps in the infill drilling for geology model confidence identified by following the checklist in Table 4 must then be quantified in terms of drilling required to meet the coverage criteria. This has been achieved using broad calculations of the number of drillholes required to meet an infill-level drilling coverage, assuming a 50 m grid, multiplied by the average depth of the pit to obtain the drill metres required.

The communication deliverables of the data gaps are a presentation of each deposit with the visual check, as per Table 4 and Figures 2 and 3, along with a tabulated form of drillhole count and metres. Where significant access limitations are present, these are noted and removed from achievable drilling to reduce gaps. These gaps are not possible to be closed due to access and will result in a lower geology model confidence. As such, stability assessments in these areas will be assessed against a lower confidence part of

the DAC matrix. The recommendations of drilling required to facilitate adequate geology model confidence is also delivered as a summary table that is accessible to all stakeholders with links to the data gaps presentations. This allows for robust design of drill plans over a number of years in advance of detailed geotechnical projects, along or ahead of the ideal timelines shown in Figure 2.

5 Conclusion

The DAC matrix allows for sectors within the same deposit to be assessed against different criteria where the geological model confidence differs. The key driver for change to improve confidence in geotechnical models has been linking confidence levels with the DAC used in geotechnical design. This has allowed the cost of additional data collection, e.g. drilling, to be linked to increased compliant slope angles.

The implementation of the gap analysis checks as part of geotechnical drill planning, conducted well in advance of the detailed design project, has allowed for significant year-on-year reductions in the gaps identified for planned pits. This is attributed to the increased understanding of the requirements for geotechnical model confidence prior to the critical detailed-level study. Over time, as gaps in drilling are closed earlier in the overall project timeline, it is expected that high-confidence geology models will be routinely provided across the full area of stability controls, also known as the geotechnical zone of influence.

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References

- Macciotta, R, Creighton, A & Martin, CD 2020, 'Design acceptance criteria for operating open-pit slopes: an update', *CIM Journal*, vol. 11, no. 4, pp. 248–265.
- Wesseloo, J & Read, J 2009, 'Acceptance criteria', in J Read & P Stacey (eds), *Guidelines for Open Pit Slope Design*, CSIRO Publishing, Melbourne.

