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A sustaining pit-wide geotechnical stability model of Bingham Canyon Mine

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Abstract

The overall slope stability of Bingham Canyon Mine (BCM) has historically been assessed using multiple 3D wall-scale numerical models of the east, south and north walls of the pit, supplemented by 2D limit equilibrium analyses. The approach resulted in varied assumptions as each model was created during studies that spread across different years, versions of available data and objectives. As the orebody knowledge (OBK) at BCM is continually improving with new data collection, it is necessary that the engineering analyses reflect the most recent characterisation and field observations to support mine planning and long-term design decisions, reduce project uncertainty and eliminate OBK versioning differences between studies. A pit-wide (PW) stability model of BCM was developed to facilitate an improved approach and enhance the efficiency of OBK use in ongoing slope design. Full pit models were historically considered impractical due to computational and resolution limitations, but improved computing technology along with optimised workflows allow for development of a comprehensive PW numerical model that is regularly updated and maintained. The vision for the PW model is to provide a single, integrated representation of current OBK that can be used to inform both operational and mid- to long-term design changes, permitting a straightforward review of underlying assumptions and validation with available slope performance data. Equilibrium Mining and Rio Tinto Kennecott have collaborated to develop the first PW model of BCM, focused on efficient model construction and maintenance, and incorporating detailed back-analysis of the slope response over the past 25+ years. This paper outlines the methodology and key insights from this collaboration and presents an overview of back-analysis of the slope response in the south wall of the pit, demonstrating the value of a unified PW model.

Keywords: *slope stability, open pit, numerical modelling, back-analysis, slope movement*

1 Introduction

Located southwest of Salt Lake City in the Oquirrh Mountains of Utah, USA, and managed by Rio Tinto Kennecott (RTK), the Bingham Canyon Mine (BCM) is one of the largest open pit mining operations in the world. Since production began in 1903, BCM has yielded over 18 million tonnes of copper, along with significant quantities of molybdenum and gold. The mine's current dimensions – spanning more than 4,570 m in width and reaching depths of approximately 1,325 m (displayed in Figure 1) – present substantial geotechnical challenges due to both the scale and the complexity of the geological setting (Cambio et al. 2019).

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To manage geotechnical risks, the mine relies on an extensive suite of monitoring technologies including ground-based radars (real aperture and synthetic aperture radar), GPS, prisms, InSAR, thermal imaging, subsurface monitoring systems, Time Domain Reflectometry, inclinometers, Shape Accel Array and Vibrating Wire Piezometers. Frequent surface mapping complements these systems by identifying surface expressions such as tension cracks. The integration of these technologies supports both real-time hazard detection and long-term slope stability analysis (Ergun et al. 2023). In parallel, regional groundwater models, calibrated using extensive observational data and piezometer readings, along with comprehensive drilling programs to collect data are essential to manage slope stability at BCM. Continuous updates to the geotechnical database further contribute to data quality but also increase the complexity of managing and integrating large volumes of information.

Figure 1 Bingham Canyon Mine

Historically, slope stability has been addressed using separate 3D numerical models for the east, south and north walls (the west wall was included in both south and north wall extents), often supplemented with 2D section analyses and smaller targeted 3D models. However, these segmented models carry varying levels of confidence due to different characterisation and calibration across domains, introduced largely by the evolving orebody knowledge (OBK) from year to year. The 2021 Leo failure which developed in the southeast wall further exemplified a constraint in this approach as it was located at the limits of two separate domains/models, which introduced uncertainty in the interpretation of both analyses. A unified pit-wide (PW) model reduces uncertainty by ensuring consistent coverage, centralised updates, and alignment of input parameters across the entire pit with current OBK and site observations. This paper presents the development of the first version of a sustaining PW model using FLAC3D (ITASCA 2023), detailing the workflow, integration of large-scale datasets, calibration processes and the challenges encountered.

2 Methodology

The development of a unified PW geotechnical model for BCM was a complex, multi-phase effort spanning two years. This work involved not only managing the massive volume and diversity of input data including geological, geotechnical, hydrogeological and monitoring datasets – but also calibrating the model against a broad range of historical slope instabilities across different geotechnical domains. To achieve meaningful calibration and ensure computational efficiency, the PW model is systematically subdivided into smaller ‘window models’ focused on specific regions of the pit. These window models are used to test and refine input parameters against observed slope behaviour, and their learnings are incorporated and validated in the full model using a suite of automated workflows. While automation was essential for managing scale, the process demanded precise coordination as small QC issues in handling these large datasets could introduce downstream errors and undermine the entire process. This section describes the key stages of this project: the data review and integration process, the construction and refinement of model components, calibration strategy and optimisation schemes.

2.1 Data review and integration

Constructing a PW FLAC3D model for BCM necessitated a comprehensive review of both recent and historical geotechnical characterisation efforts. This undertaking presented both a significant opportunity, given the wealth of available data, and a considerable challenge in synthesising diverse datasets into a cohesive framework.

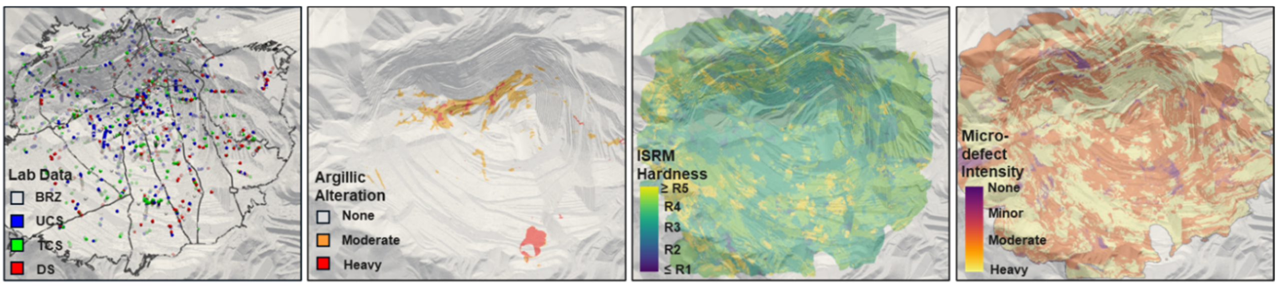
The review encompassed the latest geological and fault interpretations, structural data, extensive drillhole and laboratory testing strength databases, and various geotechnical block models. Past and current slope monitoring records, failure outlines and instability interpretations were reviewed to develop the calibration targets. Additionally, the review process involved a comparison of a series of legacy and recent reports to understand the evolution of characterisation methodology and geological interpretation over time, thus allowing for a more complete understanding of the strengths and limitations of available data. The primary goal was to consolidate these disparate sources into a consistent framework that could reliably inform the input parameters and underlying assumptions of the FLAC3D model.

Synthesising and interpreting the large and diverse datasets demanded a strategic approach to balance the desire for detailed representation with the practicalities of representation in a model of this scale. Employing improved processes and leveraging automation tools, such as Python scripting, were crucial in efficiently managing and integrating these complex datasets. The subsequent sections outline the methodology used for data review and integration, and discusses the key insights and challenges encountered during this critical foundational phase of the process.

Three primary categories of inputs were derived from this data review: intact and rock mass strengths, major faults and fault strengths, and structural domains and discontinuity strengths.

2.1.1 Intact strength and geotechnical block model review

Geotechnical block models for alteration, micro-defect intensity and International Society for Rock Mechanics (ISRM) strength offered the potential to leverage BCM’s significant laboratory testing database to refine intact strength parameter assignments by further subdividing intact strength data (uniaxial compressive strength, triaxial compressive strength and Brazilian test laboratory results) based on the parameters within these block models (Figure 2).



(a) (b) (c) (d)

Figure 2 (a) Laboratory data; (b) Alteration; (c) International Society for Rock Mechanics strength; (d) Micro-defect intensity block models

To determine their appropriateness for refining intact strength parameters, the geotechnical block models first underwent rigorous validation against geotechnical logging data and core photographs. This step established confidence in their spatial representation of rock mass properties. Subsequently, these models were reviewed in the context of observed rock mass-controlled slope instabilities, both historical and ongoing, to determine if zones of known rock mass instability correlated spatially with areas characterised by unfavourable block model parameters, such as low ISRM strength, high micro-defect intensity, low geological strength index (GSI) or strong argillic alteration.

Next, the intact strength data itself was reviewed to identify the most impactful parameters for its subdivision within each geologic unit. Automated Python scripts were employed to efficiently explore various data subdivision scenarios based on alteration, micro-defect intensity and ISRM strength. A Bayesian analytical framework was then applied to develop Hoek–Brown intact strength curves for each subdivision (Figure 3). This was crucial for quantifying the resulting uncertainty and evaluating the improvement in model fit. Figure 3 presents 10,000 Hoek–Brown curves developed using Markov Chain Monte Carlo algorithms to sample from the posterior distribution of model parameters (σ_{ci}, m_i).

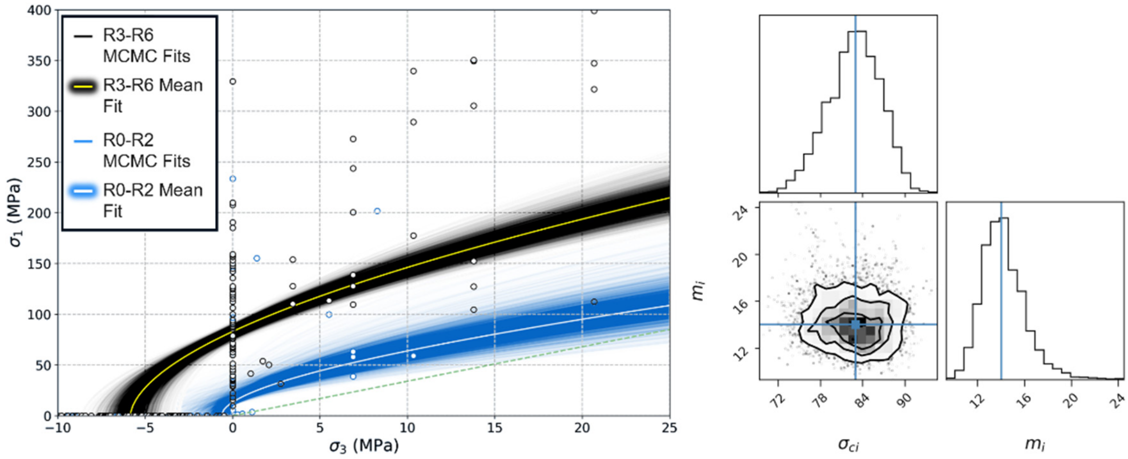


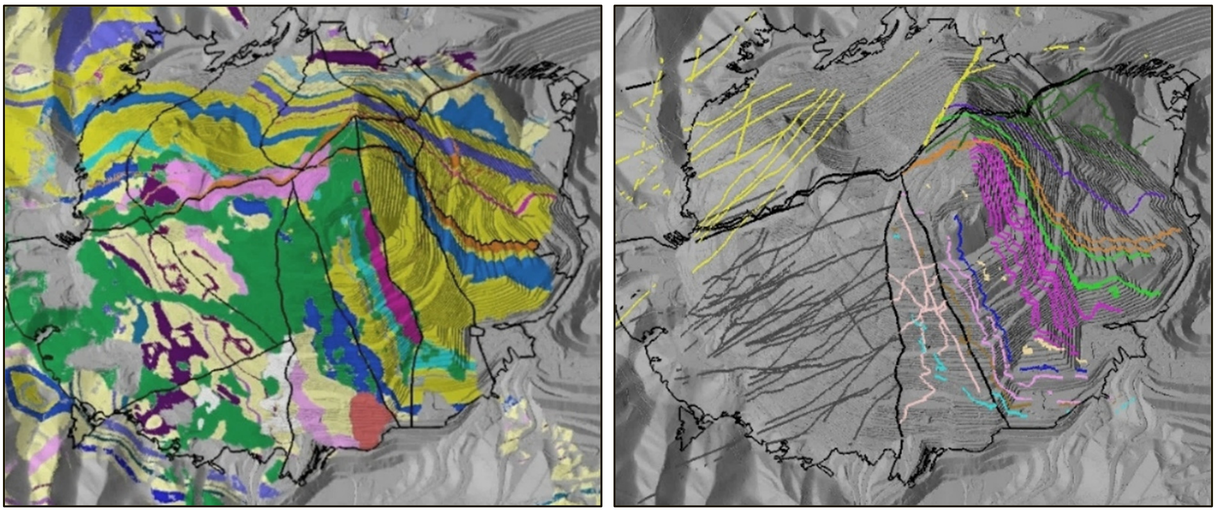
Figure 3 Example Hoek–Brown curve fits to laboratory data split by International Society for Rock Mechanics strength using the Bayesian method (based on Contreras et al. 2018)

The decision on which block model parameters to utilise for subdividing intact strength datasets within large geologic units exhibiting significant strength variability was based on two key factors: the correlation of the parameter with observed stability concerns in the pit and its correlation with the intact strength data itself. For smaller geologic units with limited data scatter, or where subdivision resulted in statistically unreliable datasets, the intact strength data was not subdivided.

Ultimately, for the units determined appropriate to subdivide, the ISRM strength block model was selected for subdividing the intact strength data for the sediment units at BCM, aligning with the understanding that the various sediment beds are expected to have differences in ISRM strength. The argillic alteration block model was chosen for subdividing the intrusive units, aligning with the understanding that argillic changes to the rock matrix in intrusives have a weakening effect. Using this framework, each 7.5 × 7.5 m block in the PW model is assigned a unique rock mass strength based on its geologic unit, alteration or ISRM strength, and GSI.

2.1.2 Faults review

A key objective of this phase was to compile a comprehensive fault strength database for the PW model. This involved reviewing 3D fault wireframes in relation to as-built and life of mine (LOM) pit shells to understand their implications for calibration and predictive modelling. A total of 91 major faults were assessed using both historical and recent calibration studies. Fault strength values – sourced from laboratory testing and back-analyses – were consolidated into a unified database. These properties served as the initial input for the PW model and were further refined during the calibration stage. Figure 4 displays the geology and faults of BCM considered in the PW model.



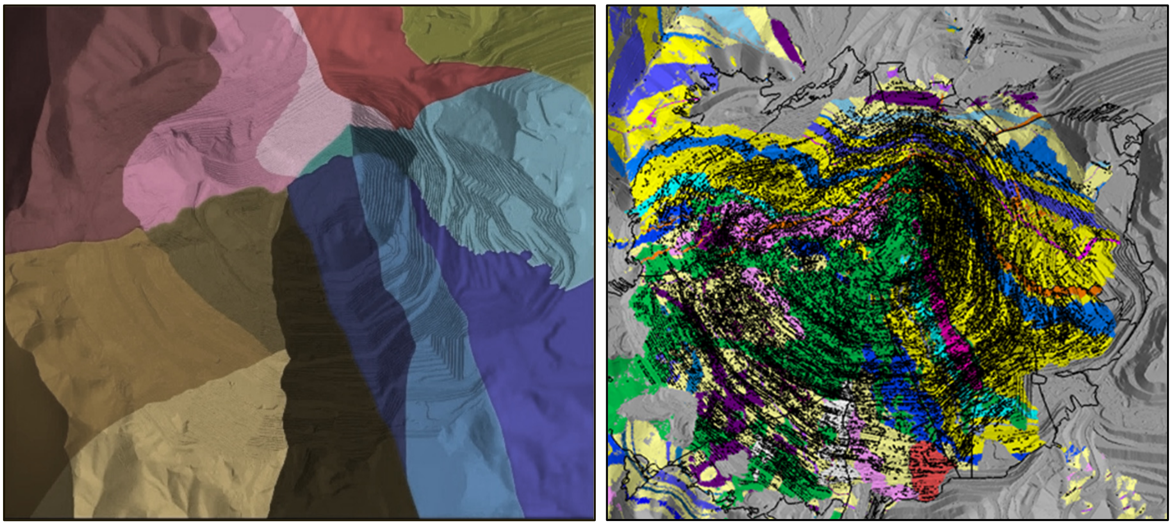
(a) (b)

Figure 4 Plan view mapped to March 2023 pit topography of (a) geology and (b) faults

2.1.3 Discontinuity review

The discontinuity review aimed to characterise anisotropy, based upon the latest structural domains, for input into the PW model. This involved processing the latest structural mapping and acoustic televiewer (ATV) datasets to flag their geological unit, structural domain, and distance to both as-built and LOM pit shells. Structural domains were subdivided into geotechnical units (GTUs), each representing a unique combination of lithology, stratigraphy and structural domain. For each GTU, stereonets were generated from both surface mapping and ATV data to analyse structural variability laterally and with depth. To efficiently manage this large dataset and enhance analytical capabilities, an automated workflow was specifically developed. This workflow streamlined the process of filtering relevant structures and generating stereonets, resulting in a significant improvement in data integration efficiency and reducing the potential for manual errors.

Within each GTU, dominant structural sets were identified based on slope orientation and relevance to historical instabilities. The relevant strength properties for dominant sets in each GTU were adopted from previous calibration studies, where available, and recent characterisation reports. Figure 5 displays the structural domains, and a spatial overview of the structural data reviewed and processed for this project.



(a) (b)

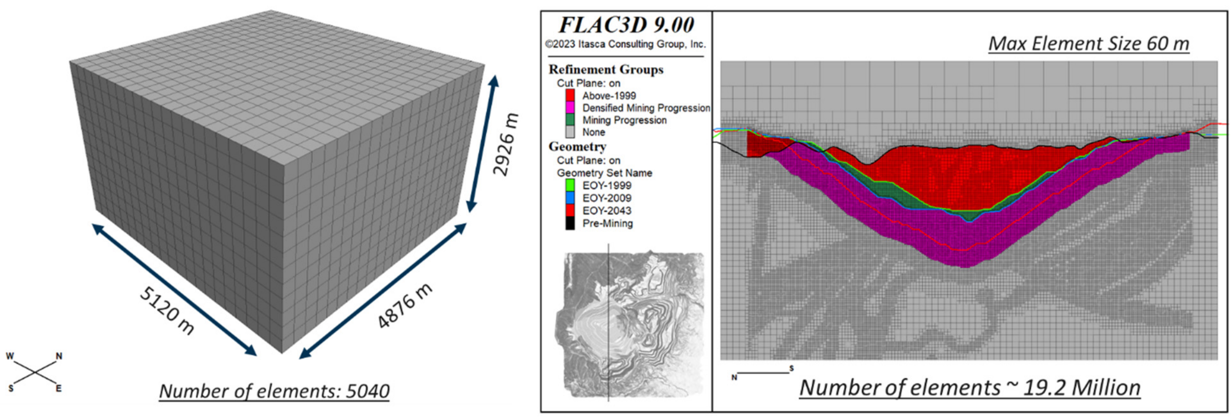
Figure 5 (a) Structural domains at Bingham Canyon Mine; (b) Overview of structural data reviewed

2.2 Model components

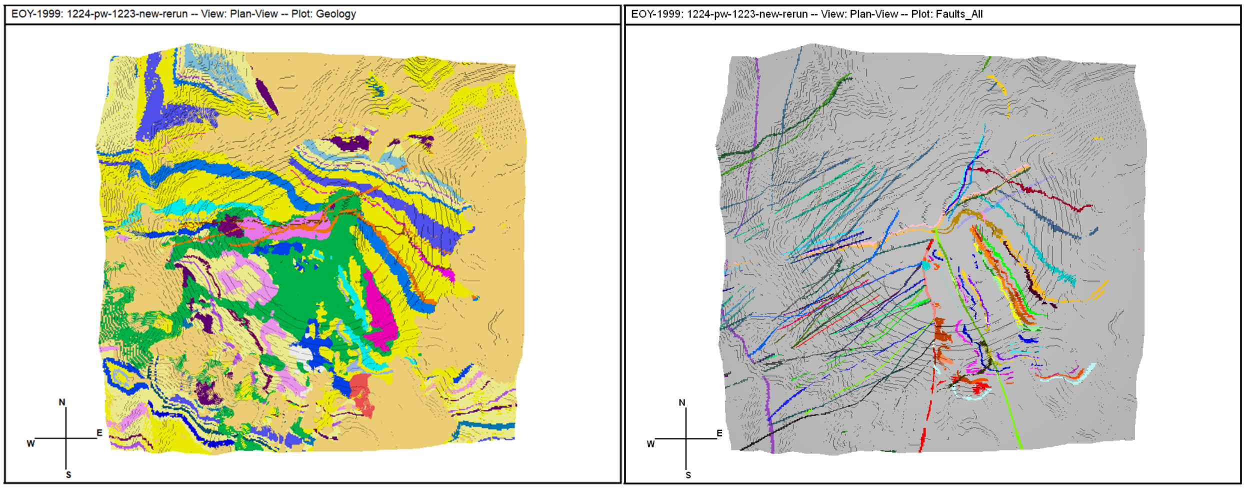
Constructing a PW FLAC3D model for BCM presented significant challenges due to the scale of the geometry and the complexity of the input data. Managing this level of detail required not only substantial computational resources, but also a streamlined and highly efficient modelling workflow. Early attempts at the mesh generation on standard workstations often led to computer memory and processing issues, highlighting the need for smarter, scalable approaches at every stage of the model build process. The following aspects were considered during the mesh generation stage:

- Mesh type: after evaluating various options, an octree mesh was selected as the most practical solution. This approach allowed for full automation of geometry integration, particularly for faults, geology, and as-built and design pit topographies, without requiring intermediate pre-processing through CAD-based tools, which would have prevented streamlining the update process in future versions of the model. While each meshing method has its advantages and limitations in terms of accuracy, automation and flexibility, octree was chosen for its balance of resolution and flexibility in a dynamic modelling environment. The PW FLAC3D mesh development process is completely automated, providing for efficient updates with evolving OBK.
- Mesh resolution: a uniform 7.62 m (half a single bench) was adopted in the active, historic and future mining areas. This permits the evaluation of any as-built topography post-2009 to approximately 150 m below LOM without additional refinement. In addition, smaller-scale faults mapped as mining progresses can be included without additional remeshing and refinement. This strategy was selected to ensure adequate resolution to capture large-scale and inter-ramp scale instabilities while maintaining a manageable model size and performance.

The mesh generation phase necessitated the building of efficient workflows that not only support the high computational demand but can also accommodate frequent updates to geology, faults and intermediate topographies, and pit design revisions. The lessons learned from this process were essential in ensuring that the model remained scalable, and adaptable over time. Figure 6 illustrates the mesh refinement strategy applied around key mine features, along with plan views of the geology and fault models. The final PW model consisted of over 19 million zones, reflecting the complexity and resolution required to capture the scale of the pit and the geological features.



(a) (b)



(c) (d)

Figure 6 (a) Model dimensions; (b) Refined mesh with 7.62 m resolution in the mining progression region; (c) Geology model; (d) Faults model (both presented on end of year 1999 as-built topography)

After completing mesh development, the next phase focused on defining in situ stress conditions, selecting and implementing the appropriate constitutive model, and determining how key geological features – particularly faults and anisotropy – would be represented. A custom constitutive model was used, extending the ubiquitous joint model to allow for up to three unique anisotropies. This was considered critical to capturing the structural fabric variability observed across multiple geotechnical domains. Major faults were modelled using the densified zone approach which was selected over discrete interfaces to permit efficient updates in future versions of the PW model (for additional details on fault modelling approaches see Azarfar et al. 2018; Pierce & Garza-Cruz 2018; Peik et al. 2023). Table 1 summarises the key input assumptions and approaches.

Table 1 Model components and adopted input assumptions and approaches

Model component	Input/approach
In situ stresses	The intermediate stress (major horizontal) is rotated 32° counterclockwise from mine north with a ratio of 0.5:0.8:1.0 (h:H:V)
Major fault representation	Densified zone approach
Rock mass strength	Failure envelope is represented using the Hoek–Brown strength criteria
Intact strength	Delineated by International Society for Rock Mechanics Index and alteration intensity with unit weight assigned per geology
Fault strength	Mohr–Coulomb failure criteria
Anisotropy	Up to three unique anisotropies, per geotechnical units, based on available mapping and downhole data
Pore pressures	3D groundwater grid from calibrated pit-wide hydrogeological model

Comprehensive QA/QC protocols have been developed and implemented during the model build phase to ensure the input parameters, geologies, faults, structural domains and block models are represented accurately in the model.

2.3 Back-analysis approach

The calibration process was divided into two phases, with Phase 1 focusing on east, south and southwest wall instabilities, and Phase 2 covering the north wall instabilities. Phase 1 has been completed and is the focus of this paper. Historical instabilities (post-2009) in these regions of the pit were reviewed with specific mining stages and calibration targets developed in collaboration with RTK's site teams. A total of 12 historical instabilities spanning 15 years were considered as part of the Phase 1 calibration campaign.

Calibration directly into the full PW model would be computationally intensive with a model of this scale, requiring up to 24 hours of execution time per stage (27 stages in total in the current PW model) and possibly hundreds of calibration scenarios. Instead, a sub-model or window modelling approach was adopted where eight smaller window models (see Figure 7) were extracted from the PW model (after mining-induced stresses have developed) for use in the back-analyses. These smaller models allowed for focused calibration in key regions of the pit, critical for each back-analysis, and were iteratively updated through more than 1,200 scenarios, incorporating continuous feedback from field observations and operational teams. Using the learnings and revisions developed as part of the window model iterations, the larger PW model was updated and all back-analyses replicated – validating that the window model approach can be used to interrogate multi-bench to inter-ramp scale instabilities, with impact between different regions then assessed in the PW model. The window model set-up process is completely automated, so any area of the PW model can be extracted to investigate potential areas of concern that may develop as mining progresses.

The following criteria were used to confirm that the window model and PW model produced consistent back-analysis results with the field observations:

- consistency with radar data (deformation pattern/mechanism extent/failure mechanism)
- matching prism/GPS direction and magnitude (if available)
- capturing the stability trend before and after the targeted instability
- alignment of the predicted failure mechanism with subsurface/TDR data.

While the PW model was effective in capturing larger-scale inter-ramp mechanisms, its mesh resolution (7.5 m) was too coarse for accurately replicating shallow instabilities observed at depths of 15–20 m. The mesh resolution is not considered adequate at this scale to accurately resolve stresses and delineate a yield/failure surface. Initial back-analyses demonstrated that the shallow failures could technically be replicated within the PW model, but non-defensible strengths were required. With realistic strengths, and grid refinement in the area (to increase accuracy of stress resolution), however, the observed slope response would be replicated. This was an important learning which led to a secondary automated window modelling approach for smaller (1–2 bench scale) and/or shallow mechanisms, which included successive adjustments to increase mesh refinement and accuracy of the stress resolution near the surface. Stresses from the PW model are stored and interpolated to the refined window models. After assigning the interpolated stress fields and re-equilibrating, strength assumptions consistent with mapping and testing data could be applied to successfully replicate small-scale failures. Once calibrated, these refined properties were carried forward in the PW model. Results from the PW model provide indications of a potential mechanism at the smaller scale (i.e. increased deformation, strain, etc.) but do not predict failure (strength reduction factor [SRF] < 1.0). Therefore, in forward-analysis, results need to be interrogated to assess if smaller, refined window models are necessary to identify shallower mechanisms. Note the original objective of the PW model was to inform larger-scale areas of concern. This refined window model approach was a necessary addition to capturing shallower mechanisms, which are still a significant operational concern as they may be shallow but extend 6–8 benches high.

3 Results

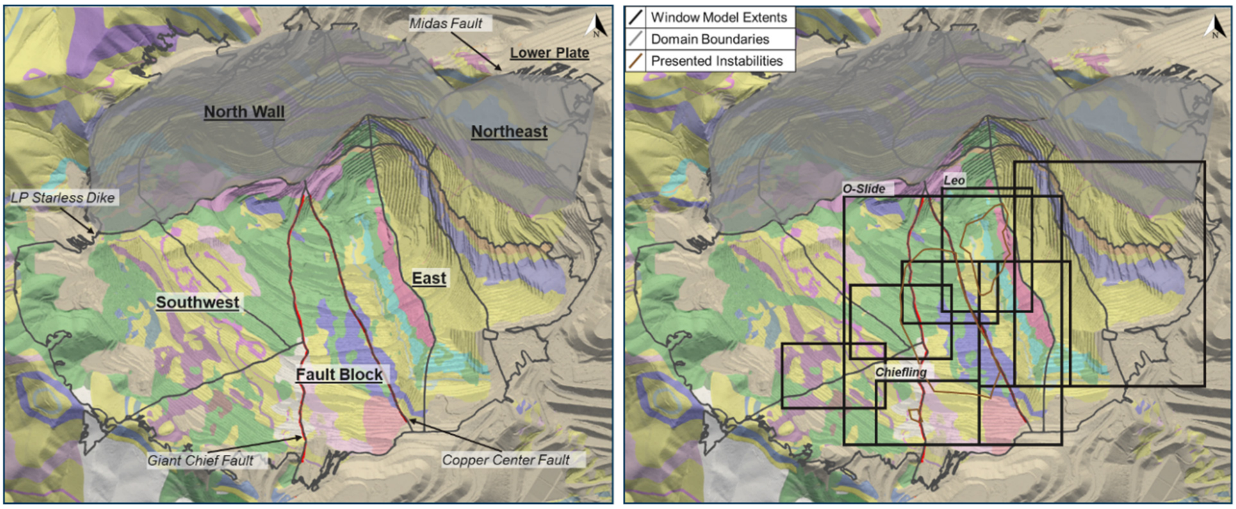
The Phase 1 calibration effort considered a wide range of historical slope response across BCM, many of which were complex and interacting, and occurred under evolving geological and operational conditions.

Several mechanisms influenced adjacent slope behaviour or were triggered in sequences, making back-analysis particularly challenging. This paper presents three of the 12 calibration areas that reflect the scale and broader spectrum of results achieved in the PW model. These are:

- Large-scale movement: the O-Slide mechanism as documented by Cambio et al. (2019). A deep-seated, long-term instability on the south wall, characterised by gradual deformation over several years before acceleration, this O-Slide mechanism, approximately 600 m high, is considered a complex mechanism with major structure, pore pressure and rock mass controls.
- Historical failure: the Leo failure mechanism – a 19-Mt collapse on the southeast wall in May 2021, notable for its complex mechanism and the effectiveness of integrated monitoring systems in predicting the event (Ergun et al. 2023).
- Multi-bench scale failure: the Chiefling failure, a localised, multi-bench scale instability exemplifying the challenges of modelling smaller-scale failures within the broader PW model framework (Abrahams 2023).

Figure 7 presents a plan view of the BCM highlighting the domains of the BCM pit (with north and northeast regions, excluded from the Phase 1 study), window model extents and instabilities considered in the back-analysis presented in this paper. The domains are defined as follows:

- north wall, north of the LP Starless dyke
- southwest, west of the Giant Chief Fault and bound by the LP Starless dyke
- fault block, bound by the Giant Chief Fault to the west and the Copper Center Fault to the east
- east wall, east of the Copper Center Fault and bound by the LP Starless dyke
- lower plate, below the Midas Fault.

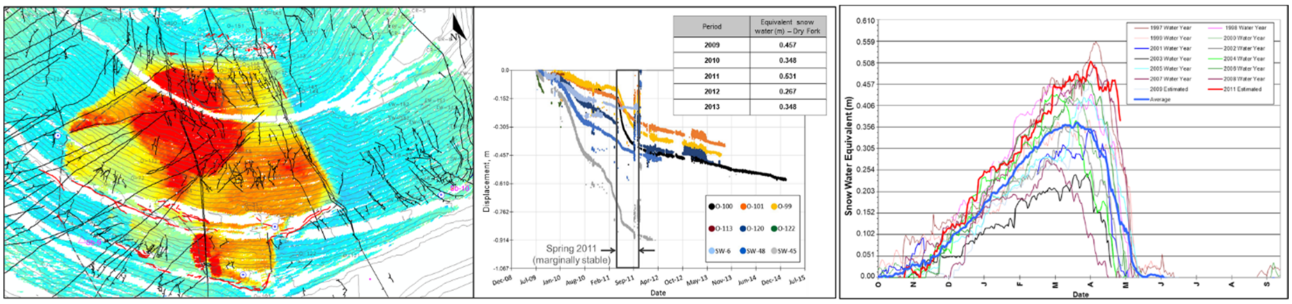


(a) (b)

Figure 7 Plan view of March 2023 pit topography at Bingham Canyon Mine, highlighting (a) different regions of the pit and (b) window model extents and instabilities presented in this paper

3.1 Large-scale movement

The O-Slide mechanism refers to a significant slope movement event that occurred in the south wall and fault block regions at BCM in 2011. Deformation rates in the area increased substantially between March 2011 and August 2011, despite minimal mining activity during that period. This region exhibited precursory movement in the years leading up to 2011, but the 2011 episode marked a distinct acceleration phase. Previous studies (Cambio et al. 2019) have attributed this deformation to elevated pore pressures following a period of high snow water accumulation during the spring of 2011. Figure 8 displays the movement area and accumulated snow water in 2011, highlighting that the acceleration is coincident with increased pore pressure in the south wall. The back-analysis aimed to replicate the acceleration in August 2011 due to high pore pressure, with a stability margin near SRF = 1.00, based upon local site experience with similar deformation levels.

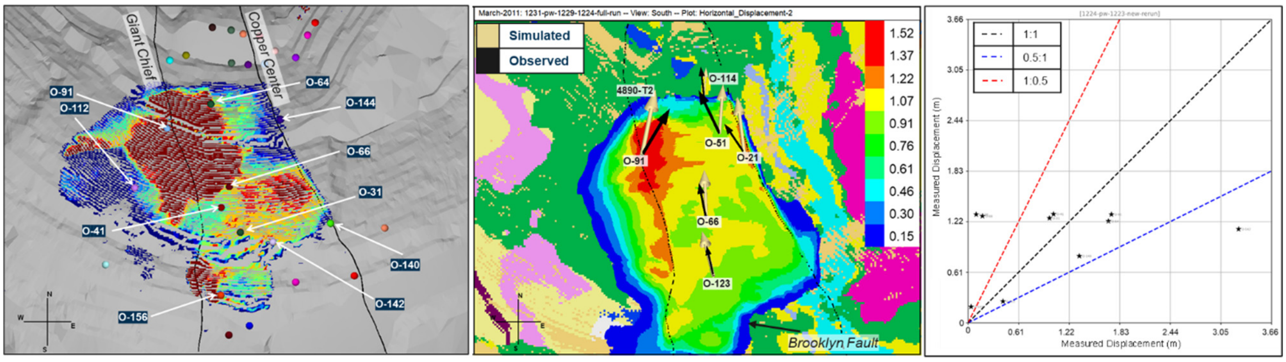


(a) (b) (c)

Figure 8 (a) Image by interferometric survey deformation 22 July to 9 August 2011; (b) Cumulative displacement from the O-Slide prisms from 2009 to 2013; (c) Snow water equivalent showing higher than average snowpack in 2011

The back-analysis results are summarised in Figure 9 with the following observations:

- Radar deformation comparison: deformation from radar and simulated horizontal displacement contours from the August 2011 PW model are shown in Figure 9a and b, with simulated and observed displacement vectors overlaid in Figure 9b. The simulated deformation is generally in agreement with the observed deformation pattern, with higher displacements along the Giant Chief Fault and extending west. Note that the model is unstable (SRF < 1.00) as per the calibration target, with the mechanism constrained largely to the fault block and extending west across the Giant Chief Fault
- Movement direction: simulated displacement vectors (Figure 9b) show excellent agreement with directions from prisms. The deformation is predominantly north-dipping mid-slope, transitioning to northeast-dipping in the lower slope near the Giant Chief Fault, matching observed field trends
- Deformation magnitudes: Figure 9c presents a comparison between observed and simulated deformation magnitudes at key prism locations. Overall, the model achieves good agreement with field data, consistent with prior south wall back-analyses presented in Cambio et al. (2019)
- Critical controls: increased pore pressure near the Giant Chief Fault along with damage/shear zones in the fault block area are the primary drivers of the mechanism. The Brooklyn Fault (base of limestone, upper extent of the displacement contours in Figure 9b) contributes to the mechanism by mobilising the upper slope, while anisotropy in the lower slope contributes to the movement direction
- Stability trend: consistent with field observations the model was stable in March 2011 (prior to the increase of pore pressure) with lower deformation observed. The reduced stability in August 2021 is a result of the localised high pore pressure
- Future improvement: deformation along upper eastern extent (Copper Center Fault) can be improved upon as there may be local geological controls.



(a) (b) (c)

Figure 9 (a) Image by interferometric survey deformation 22 July to 9 August 2011; (b) Simulated horizontal displacements (m); (c) Displacement magnitude comparison

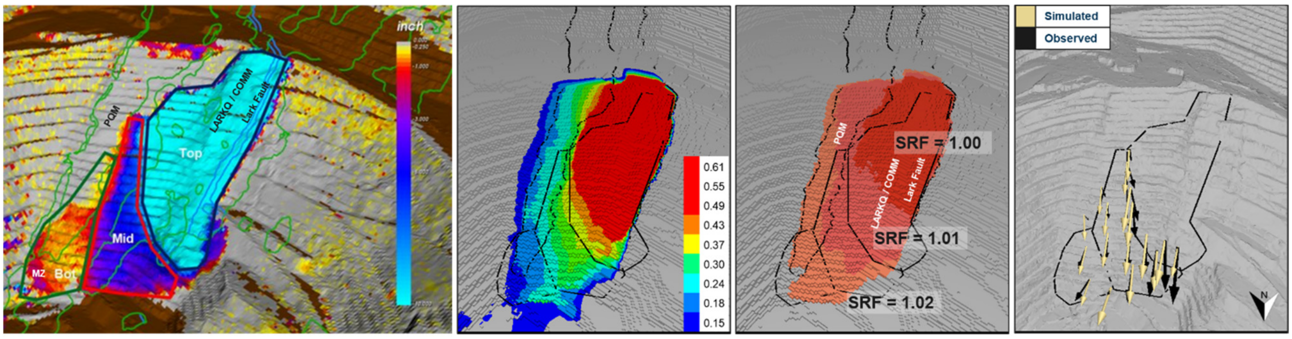
3.2 Historical failure

In May 2021, BCM experienced a 19-Mt slope failure referred to as the Leo failure. Early detection of the initial slope movement and prediction of the collapse by BCM's integrated monitoring systems allowed for safe evacuation of the mine staff and equipment.

Figure 10a displays the radar deformation prior to the Leo failure, where three distinct areas of movement were identified: Block 1 – top, Block 2 – mid, Block 3 – bottom. Block 1 was identified as the primary driver of the mechanism (Ergun et al. 2023) with Blocks 2 and 3 considered secondary or progressive aspects of the failure. The Leo back-analysis in this paper aims to replicate the Leo mechanism with Block 1 unstable (SRF ≤ 1.00) and the mid/lower blocks more stable (SRF = 1.00–1.05), consistent with previous studies (Ergun et al. 2023).

The back-analysis results are summarised in Figure 10 with the following observations:

- Radar deformation comparison: observed deformation (Figure 10a) and simulated line of sight (LOS) displacement (Figure 10b), SRF = 1.02, display the deformation pattern and interpreted mechanism for the Leo (Blocks 1 to 3) failure, with the highest deformation observed in the Block 1 area gradually decreasing across Blocks 2 and 3, and providing an excellent agreement
- Stability trend: the calibration target of SRF = 1.00 in Block 1 has been achieved as indicated by the stability margin heatmap in Figure 10c, with the gradual increase of the SRF across Block 2 (SRF = 1.01) and Block 3 (SRF = 1.02) boundaries. Excellent agreement is observed in the shape of the mechanism (Block 1 to 3 transition)
- Movement direction: the simulated displacement and prism vectors are compared in Figure 10d, illustrating an excellent agreement with the observed movement direction, including the toe heave observed at the base of the Leo mechanism
- Critical controls: consistent with previous studies (Ergun et al. 2023), Lark Fault was identified as the primary driver of the mechanism along its western extent, with anisotropy in the sediments, LARK Quartzite (LARKQ) and Commercial (COMM) units, forming the eastern release of Block 1. With increased load in Block 1, failure in the toe extended through intrusives, Porphyry quartz monzonite (PQM) and monzonite (MZ), exploiting anisotropy (Figure 10).
- Future improvement in understanding the stability trend in the months prior to the failure.



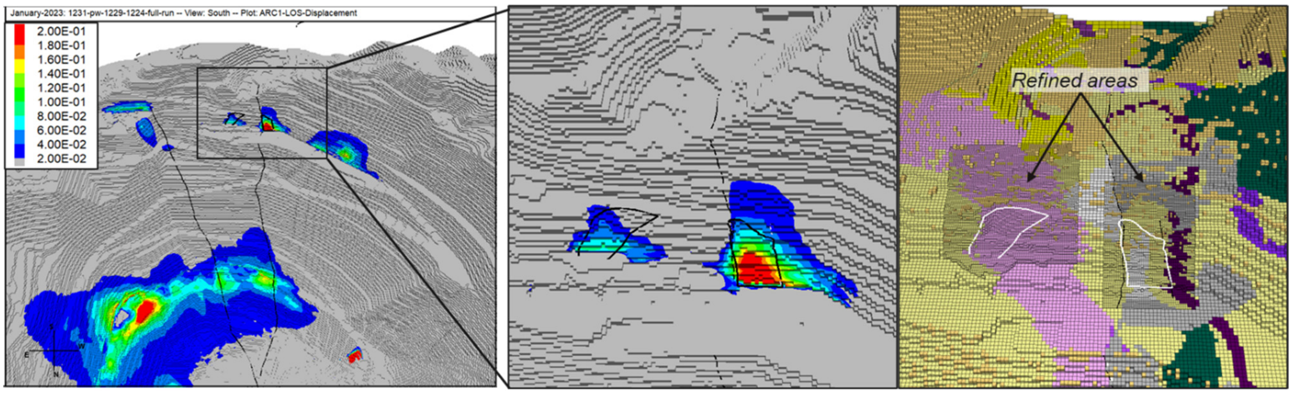
(a) (b) (c) (d)

Figure 10 (a) Radar ARC 3 Live displacements: 30 days, 1 May (12.00) to 31 May (09.00), 2021; (b) Model displacement contours (Radar ARC 3 line of sight displacements, m); (c) Strength reduction factor stability margin heatmap; (d) Movement direction comparison

3.3 Multi-bench scale failure

The Chiefling failure, displayed in Figure 12b, is approximately five benches tall (75 m) and 90 m wide, and occurred on 24 January 2023. The failure mass involved 300–400k tonnes of material with a failure depth approximated as 15 m based on back scarp measurements. The Giant Chief Fault and MZ dyke (Figure 12b) provide the east and west side releases with weak rock mass and shallow dipping bedding sets mapped in the field at the base of the mechanism. The back-analysis aimed to capture the Chiefling failure in the January 2023 stage. Note that the alternative window modelling approach was used to achieve calibration for the Chiefling mechanism due to the shallow depth.

The simulated LOS displacement contours for the PW model (January 2023) are displayed in Figures 11a and b, highlighting relatively high isolated deformation near the Giant Chief Fault – providing an indication of the Chiefling instability (but SRF > 1.00 in the larger PW model). Figure 11c displays localised refinement of a window model which was extracted from the larger PW model for further interrogation. The secondary refinement area is a separate calibration target, not discussed in detail in the current paper but referred to as the Zulu failure (Abrahams 2023).

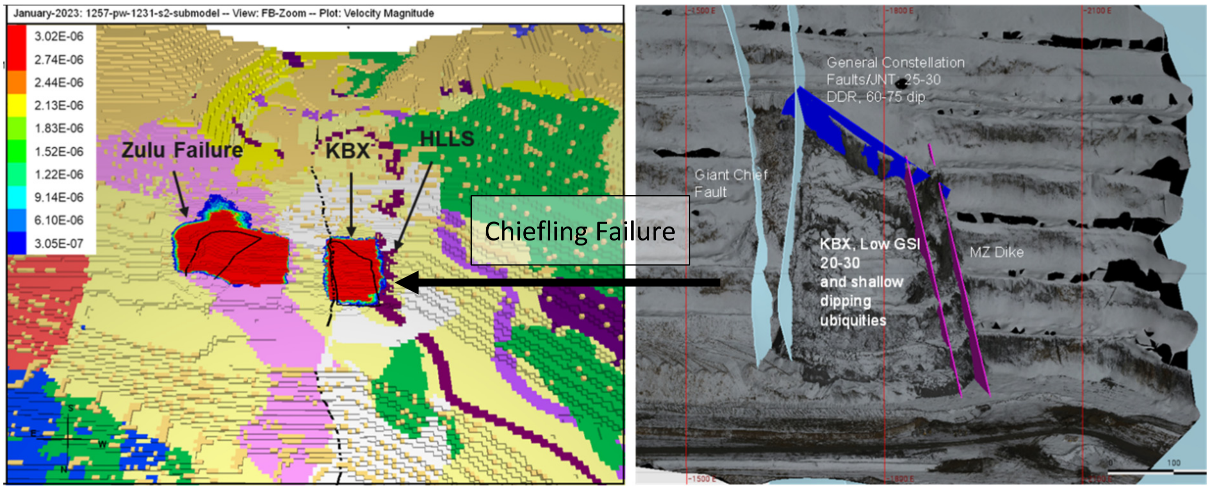


(a) (b) (c)

Figure 11 (a) Simulated ARC 1 line of sight displacements (m); (b) Zoomed in view; (c) Refined window model

Figure 12 presents the results of the refined window (same strength parameters as the PW model but with increased mesh resolution) with the following observations:

- Radar deformation:
  - the velocity contours (predicted failure mechanism) for the January 2023 stage refined sub-models are presented in Figure 12a, highlighting that the Chiefling (and Zulu) mechanism is achieved with increased mesh resolution. The Chiefling failure is displayed in Figure 12b.
- Critical controls:
  - the mechanism primarily exploits the KBX and HLLS units along with the Giant Chief Fault and MZ dyke as side releases of the mechanism. The weaker rock mass in this area is a critical contributor to this mechanism.
- Future improvement:
  - smaller MZ dykes and localised areas of poor rock mass are not considered as part of the more general geotechnical model, though they are mapped when exposed. More direct integration of these local conditions into the PW model will improve confidence in model results.



(a) (b)

Figure 12 (a) Simulated failure mechanism for both Zulu and Chiefling in the window model, shown using velocity magnitude contours (m/step); (b) Chiefling failure – 24 January 2023

4 Conclusion

The primary objective of developing the PW FLAC3D model for the BCM was to create a unified, robust and scalable geotechnical framework capable of capturing complex slope behaviour across the full pit. As OBK evolves and mining progresses, the PW model is intended to serve as a dynamic decision-support tool, enabling efficient calibration, predictive analysis and scenario testing across different regions of the pit, which is updated frequently by the most recent available data.

BCM is one of the largest open pit operations in the world. Modelling such a vast and geologically complex system required the integration of an enormous volume of data, spanning decades of geotechnical characterisation, drilling, laboratory testing, structural mapping, hydrogeological modelling and monitoring records. The scale and heterogeneity of the data introduced significant challenges in terms of data management, model set-up and computational performance, requiring a carefully structured approach to ensure fidelity, efficiency and scalability.

The benefits of a single, integrated model are significant. It eliminates the limitations of isolated local or even quarter or half pit-scale models, improves consistency in input parameters across domains and allows for the assessment of slope performance at the full pit scale (including the impact of mitigation efforts on adjacent areas). The model provides a platform for evaluating design changes and informing long-range planning. The use of automated window modelling and refinement workflows further enables the resolution needed for smaller-scale instabilities without sacrificing overall model manageability or requiring separate studies with local models.

Collating the data and developing/calibrating a model of this scale did not come without challenges. This included managing the volume and complexity of data, spanning 94 faults, 60 geologic units and 575 geotechnical units, as well as maintaining computational efficiency across more than 1,200 model scenarios in a model that is approximately four to five times the size of what would historically be considered a large open pit model. Simulation compute time ranged from one hour (for smaller window models) to over three weeks, with over 6,000 hours of total simulation time recorded and approximately 60 terabytes of output generated. This scale of effort required a significant advancement in modelling structure, workflow efficiency and QA/QC strategies.

An enhanced modelling framework that emphasised automation, repeatability and transparency for all stakeholders across multiple disciplines was implemented. Model construction, meshing, pre-processing and post-processing, and window model extraction were fully automated. Version control and custom QA/QC routines were developed to track parameter consistency, identify key differences between scenarios and validate model behaviour against inputs assumptions. These processes developed as part of this work ensure that the PW model can be confidently and efficiently maintained into the future iterations.

Key to the success of the PW modelling effort was the strong collaboration within the team. The scale and complexity of the model necessitated frequent, structured engagement across disciplines (i.e. geotechnical, geological, hydrogeological and operational teams, as well as multiple external consultants). Weekly working sessions, open feedback and shared knowledge allowed for continuous refinement of assumptions, calibration and interpretation of results. The collaborative environment directly enabled the robustness of the QA/QC processes, efficiency in the use of the model and practical insights in operational decision-making.

The PW model provides a scalable, technically defensible platform for ongoing geotechnical analysis at BCM that is capable of handling both present-day operational demands and future optimisation with confidence.

5 Future work

While the current PW model represents a significant advancement in geotechnical modelling at BCM, it is inherently a work in progress. The calibration effort to date, while extensive, remains iterative, and further refinements are both expected and necessary as more data becomes available and mining progresses. Material properties implemented in the model, though supported by available data and calibrated back-analysis, will continuously be improved to better reflect field conditions and slope performance. Additionally, the model resolution limits its ability to fully resolve shallow or highly localised mechanisms without refinement. Additional efforts to develop criteria for overcoming these limitations are in progress. As this is the first iteration of a live evolving tool, ongoing calibration and validation, and continuous improvements, are integral to maintaining its reliability and value for future use.

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