Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)

doi:10.36487/ACG_repo/2645_12

Integrating multi-source data through a geomechanical digital twin: advancing risk management in cave mining

Juan Monsalve [a,*], Catalina Vanegas [a], Cesar Lemas-Pesqueira [a], Geoff Hilt [a], Scott Ferguson [a], Neil Shea [a]

[a] *Freeport-McMoRan, USA*

Abstract

Cave mining involves highly interdependent processes, making geomechanical risk management complex and dynamic. To address these challenges at Henderson mine, a geomechanical digital twin was developed to integrate production, cave development, geomechanical modelling, and monitoring data into a unified platform. A digital twin is a dynamic, virtual model that represents the state and behaviour of a physical system. In the context of caving, it is a near-real-time representation of the underground environment, continuously updated through the exchange of data between digital and physical domains. This system enhances the understanding of the caving process and strengthens communication across technical and operational teams. By leveraging real-time and historical datasets, the digital twin enables better informed decision-making and provides improved forecasting capabilities for early identification and prioritisation of geomechanical risks. This paper provides an update on the current state of the Henderson mine and discusses current cave management practices in this operation. The Henderson geomechanical digital twin is described with each of its components explained. Finally, a series of applications where this digital twin has supported the operation is discussed. This platform promotes collaboration between engineering and operations, supporting proactive planning and timely response strategies. This contributes to improved management of caving operations, increasing safety and operational efficiency.

Keywords: *digital twin, cave management, geomechanical risk, monitoring, numerical modelling, caving*

1 Introduction

Cave mining is a mass mining method widely used for extracting low-grade orebodies at depth, offering high production rates and cost efficiency. However, its complexity introduces significant geomechanical and operational risks that, if unmanaged, can lead to catastrophic outcomes. Water and mud inrushes, air blasts, ground collapses, and rock bursts are among the most critical hazards associated with this mining method. To mitigate these risks, operators have developed strategies and systems to monitor, predict, and control cave behaviour throughout the life of mine. These practices, collectively referred to as cave management, are formalised in cave management plans that integrate cave and mine design with monitoring protocols, operational controls, and trigger action response plans (TARPs) for unexpected conditions. Cave management also enables feedback loops to inform design updates and drive continuous improvement.

Recent work by Kamp et al. (2024) provides a state-of-the-art review of cave profile interpretation, detailing instrumentation and remote sensing technologies widely adopted in block cave operations. While this review offers valuable insights into monitoring practices, it does not extensively address how diverse datasets, spanning geomechanical monitoring, production metrics, and numerical modelling, are consolidated into a unified framework for decision-making. This lack of integration represents a critical challenge in cave management, where fragmented data streams often hinder timely risk assessment. These challenges highlight the need for advanced, integrated solutions, such as digital twins, to improve risk management and operational efficiency.

[*]Corresponding author. Email address: jmonsalv@fmi.com

The term digital twin was initially introduced by NASA in 1970 and has since evolved and been adapted to multiple industries such as aerospace, manufacturing, and building construction. Definitions and components of a digital twin have varied over time and across these multiple industries (Grievers 2017; Wang et al. 2025; Elmo & Stead 2020). van Eyk & Heyns (2025) proposed a definition and a framework for developing and implementing digital twins adapted to the mining industry. They defined a digital twin as "… a tool for driving optimisation across a physical entity. Comprising a digital model, physical counterpart, and connections between the two, it embodies a synchronised flow of data between the physical entity and the digital model, facilitating continual estimation of the entity's state…".

Based on the framework proposed by van Eyk & Heyns (2025), a geomechanical digital twin was developed to support cave management during the active extraction phase of the 7210 N-Panel. Its purpose is to provide an integrated, continuously updated representation of the cave system by consolidating production, development, geomechanical monitoring, and numerical modelling information within a unified platform. This environment enables engineers and operators to visualise cave behaviour, compare model forecasts with observed responses, and identify emerging risks as mining progresses. In the following sections, Section 2 provides an update of the Henderson mine operation, Section 3 summarises cave-management practices and key challenges, Section 4 describes the geomechanical digital twin implemented at the Henderson mine and details each of its components, and Section 5 demonstrates how the twin supported engineering, management, and operations during the 7210 N-Panel ramp-up. This geomechanical digital-twin platform promotes collaboration between engineering and operations, supporting proactive planning and timely response strategies, which contributes to improved management of caving operations, increased safety, and greater operational efficiency.

2 Henderson mine background

The Henderson mine, located west of Denver, Colorado, is a large-scale block-cave operation extracting a climax-type porphyry molybdenum deposit hosted in high-silica rhyolite intrusions. The orebody extends vertically and laterally over significant distances and has been defined through extensive drilling, supporting long-term planning and panel sequencing across multiple production levels, as shown in Figure 1. Henderson has operated as an underground caving mine since 1976 and currently produces approximately 20,865 tonnes of ore per day. Historic production is summarised in Table 1.

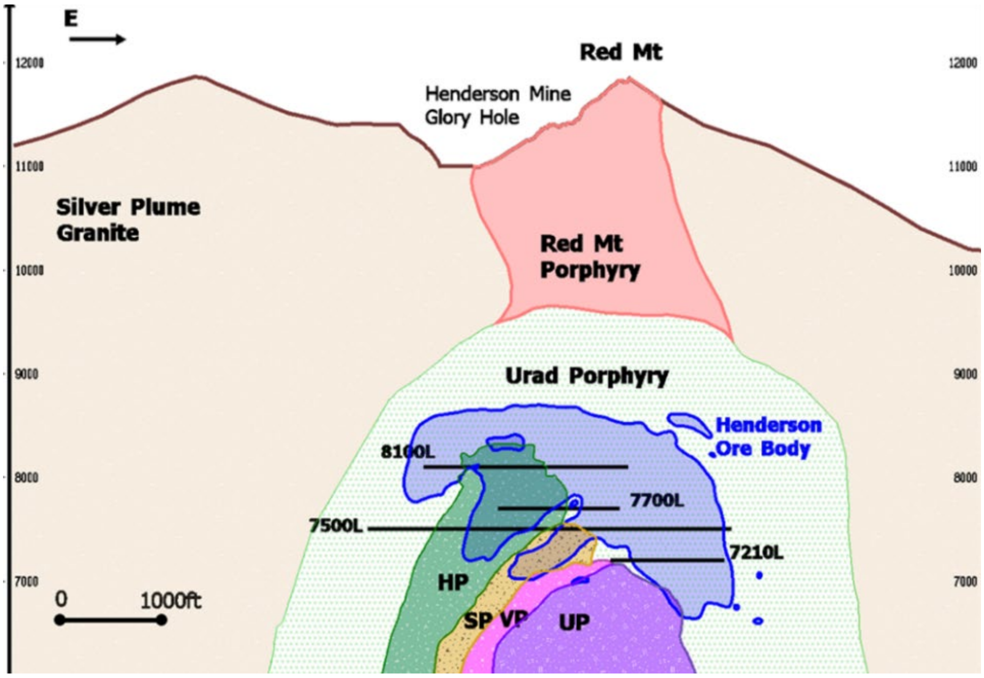

Figure 1 Henderson mine deposit geology

Table 1 Henderson panel cave historical production

No.	Panel caving location	Production year	Average capacity production	Status
1	8100 elevation, Main Panel Level	1976–1991	22–45k tonnes/day	Exhausted
2	7700 elevation, Main Panel Level	1992–2006	22–36k tonnes/day	Exhausted
3	7210 elevation, Main Panel Level	2005–2021	22–45k tonnes/day	Exhausted
4	7700 elevation, Southwest Panel	2014–2020	22–27k tonnes/day	Exhausted
5	7210 elevation, A-Loop Panel	2020–2028	18–27k tonnes/day	Operating
6	7210 elevation, North Panel	2023–2035	18–22k tonnes/day	Operating
7	7700 elevation, Northwest Panel	2028–2038	18–22k tonnes/day	Development/construction

The Henderson mine has expanded through several levels over time. Currently, there are 3 active panels in 2 different levels, as shown in Figure 2. The A-Panel and the N-Panel in the 7210 Level, and the northwest panel in the 7700 Level. The A-Panel was undercut between 2019 and May 2022 and is currently under production. North Panel was initiated in October 2023, and the undercutting stage is expected to be finalised at the beginning of 2026. The 7700NW Panel is currently under development with cave initiation expected to begin in Q3-2027.

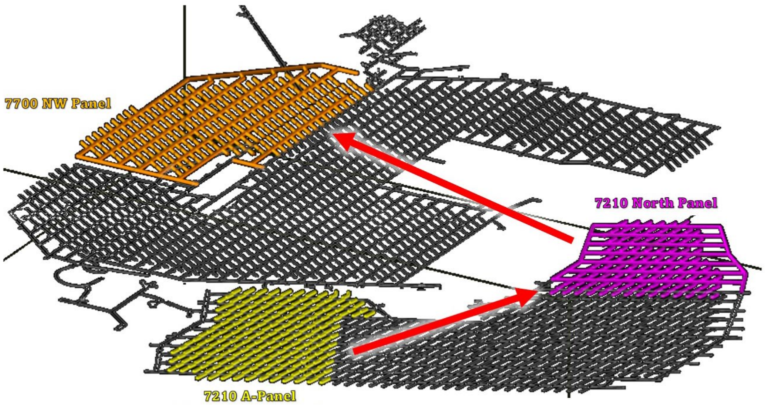

Figure 2 Henderson mine active panels layout and progression

Block caving is a mass mining method that allows extraction of large ore volumes at low operational costs once development, and production ramp-up have been achieved. In this method, a large block of ore is accessed from the bottom and blasted in sequence (undercutting). Blasted ore is extracted from pre-constructed drawpoints from an extraction level. As more area is undercut and ore is drawdown, a void space is created between the blasted ore and the cave back. When the area of the void is large enough, the rock mass on the back fails and falls onto the broken material below. As draw continues, cave propagates upward until reaching the surface or another pre-existing cave.

Cave mining is a complex mining method and presents a series of geomechanical and operational risks that if not managed appropriately can be catastrophic (Flores 2019). These risks include rock bursts driven by high in situ stress and stress redistribution during undercutting and cave propagation, air blasts associated with stalled cave growth and large air gaps, subsidence during cave breakthrough, and material inrushes such as wet muck, mud rushes, and water inflows during steady-state production.

Recent major incidents reinforce the hazards described by Flores (2019). In Chile, a seismicity-triggered fall-of-ground at El Teniente resulted in a catastrophic underground collapse that caused multiple fatalities and led to a full suspension of operations, highlighting the continued challenge of managing high-stress environments and dynamic ground failure in deep cave operations (Codelco 2025). Similarly, in Indonesia, a sudden rush of approximately 800,000 metric tons of wet material entered the Grasberg block mine from the former Grasberg open pit and travelled into underground workings, ultimately resulting in the loss of 7 workers and long-term production disruptions (Freeport-McMoRan 2025). These events closely mirror the inrush, rock burst, and stress-redistribution hazards described by Flores (2019) and underscore the critical importance of reinforcing the need for rigorous risk and cave management strategies.

3 Cave management and its challenges

Over the years, cave mining operations have developed a series of processes and strategies to help monitor, predict, and control cave behaviour throughout the life of mine. Cave management is a continuous process for identifying and understanding significant hazards and establishing the appropriate controls needed to minimise their potential consequences. The cave management process at the Henderson mine is comprised of 5 steps: cave design, mine design, cave control, response, and evaluation, as shown in Figure 3. Each of these steps feeds into the next sequentially, with many parts feeding back into the previous portion iteratively. This process establishes a set of guidelines and rules that are documented in the cave management plan (CMP). This document integrates cave and mine design with monitoring protocols, operational controls, and TARPs to manage unexpected conditions. CMPs are reviewed and updated regularly, particularly as new panels come online, supporting continuous improvement in cave management.

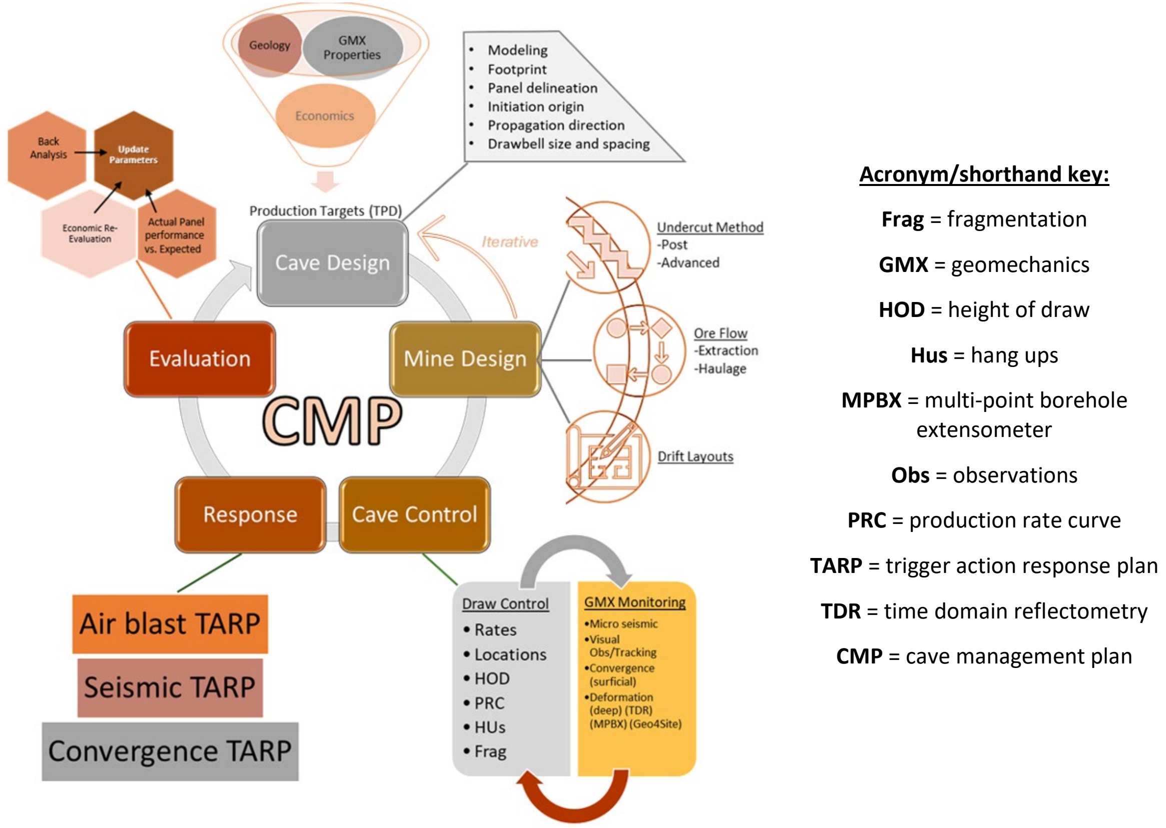

Figure 3 Cave management process at the Henderson mine

A fundamental challenge in cave management is that no single dataset provides a complete or consistent picture of cave behaviour. Monitoring systems operate at different scales, with varying resolutions, uncertainties, and update frequencies, and often respond to distinct physical processes (Kamp et al. 2024). Microseismic arrays delineate the seismogenic zone, time domain reflectometry (TDR) and smart marker systems detect localised deformation and cave back progression, convergence measurements describe drift response, and production data constrain cave back mass-balance estimates and cave geometry. Without an integrated approach, these fragmented data streams represent isolated observations of a much larger system, making interpretation vulnerable to incomplete or misleading conclusions. Figure 4 compares the classic elephant-and-blind-men analogy with a cave monitoring schematic. This underscores that understanding only one part of a complex system can lead to fundamentally incomplete or even misleading conclusions.

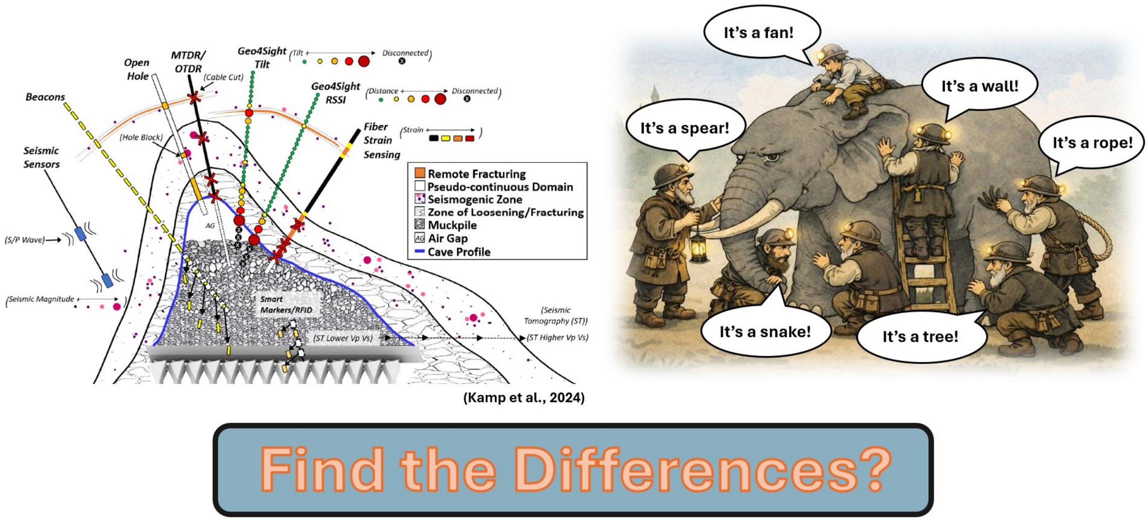

Figure 4 The 'find the differences?' comparison between a multi-sensor cave monitoring schematic and the blind-men-and-the-elephant metaphor, illustrating how fragmented observations can obscure the true behaviour of a cave system

One technology with the potential to address these integration gaps in cave management is the digital twin. Digital twins have been widely implemented in many industries such as aerospace, manufacturing and building construction allowing operations to reduce costs and time, increase productivity, and improve decision-making (Singh et al. 2022). Definitions and components of a digital twin have varied over time and across these multiple industries (Grievers 2017; Wang et al. 2025; Elmo & Stead 2020). van Eyk & Heyns (2025) proposed a definition and a framework for developing and implementing digital twins adapted to the mining industry. They defined a digital twin as an optimisation tool consisting of a physical asset, its corresponding digital model, and data flows that connect them. These connections support a continuous, synchronised flow of information, allowing the digital model to update and optimise the state of the physical entity in real time.

Figure 5 shows a simplified schematic indicating each of the 5 dimensions of the digital twin framework for the mining industry. The first dimension is the physical entity which is the real asset or system under observation. The second dimension is referred to as physical to digital updating (P2D), and it is comprised of all data captured from the physical entity which will be converted into the digital model's state. The third dimension is the digital model, a virtual representation of the physical entity that allows to estimate and forecast the state of the physical entity. The fourth dimension described as digital to physical updating (D2P) converts the outputs of the digital model into insights and corresponding actions that can be taken to alter and improve the conditions of the physical entity. At the core of this framework, there is a fifth optimisation dimension. Every dimension of the digital twin is prone to optimisation from improving physical data-acquisition workflows, to enhancing parameter and state estimation, to refining human interaction with the model. This paper introduces a geomechanical digital twin structured around this framework; the next section details each component and how these are implemented in the cave management process at the Henderson mine.

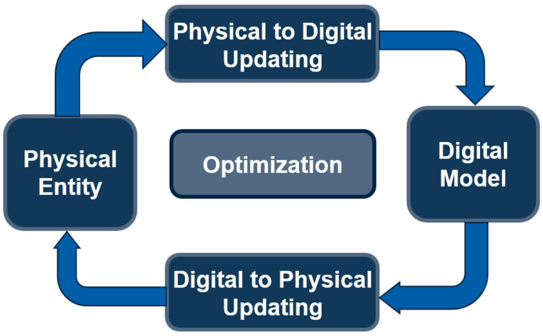

Figure 5 Simplified digital twin framework for the mining industry (after van Eyk & Heyns 2025)

4 Henderson mine geomechanical digital twin

The Henderson mine geomechanical digital twin is designed to support cave management during the active extraction phase of the 7210 N-Panel. Its primary goal is to create an integrated, continuously updated representation of the cave system by consolidating production, development, geomechanical monitoring, and numerical modelling data into a unified platform. This unified environment allows engineers and operators to visualise cave behaviour, compare model predictions against real-world responses, and identify emerging risks as mining advances.

This digital twin operates primarily during the ore extraction stage, more specifically during cave initiation, ramp-up, and production stages. This period provides the greatest geomechanical uncertainty and highest demand for timely decision-making. This digital twin model also provides valuable inputs during mine development and periodic design reviews. In practice, the twin serves 4 central functions at Henderson:

- integrating multi-source data streams into an accessible, time-enabled platform
- simulating and forecasting cave performance, including cave growth, stress redistribution, and rock mass response
- correlating monitoring data, numerical model outputs, and field observations to validate interpretation
- improving communication and coordination across engineering, operations, and management.

By linking measurements from the physical mine with a continuously updating digital representation, the Henderson digital twin supports faster, more informed decisions related to draw control, sequencing, ground support, and TARP implementation. This section provides an overview of the Henderson geomechanical digital twin following the structure of the mining-adapted framework proposed by van Eyk & Heyns (2025). Subsequent subsections describe each of the 5 dimensions of the twin: the physical entity, P2D updating, digital model, D2P updating, and optimisation, and how these have been implemented within the cave management process at the Henderson mine.

4.1 Physical entity

The physical entity represented in this geomechanical digital twin is the 7210 North Panel, treated as a system-of-systems, in accordance with the digital twin framework proposed by van Eyk & Heyns (2025). This panel is not a single asset but an emergent system formed through the interaction of multiple interdependent subsystems whose combined behaviour governs cave initiation, propagation, stability and production performance. These subsystems includes, the geological system, the mining system, development and production systems, support systems, monitoring systems, and economic system. If one of these systems were not present, it would not be possible to develop or sustain the panel cave.

At the centre of this complex system lies the cave management process, which governs how design assumptions, sequencing, monitoring, operational controls, response actions, and evaluation activities are integrated throughout the life of the panel. Cave management continuously interacts with each of these subsystems, both receiving information (e.g. monitoring and production data), and issuing decisions (e.g. draw adjustments, access restrictions, repair requirements).

In this context, the physical entity of the digital twin is dynamic and evolving, with its state defined by time-dependent changes in stress redistribution, rock mass damage, cave initiation and propagation, excavation and drift deformation, undercutting progression, production draw, etc. The purpose of the digital twin is to continually estimate and update this evolving state across the development, undercutting, and production stages of the cave life cycle to ensure caving is being performed safely and economically. Figure 6 conceptually illustrates these interactions, showing how the subsystems and the cave management process integrate to form the physical entity modelled by the digital twin.

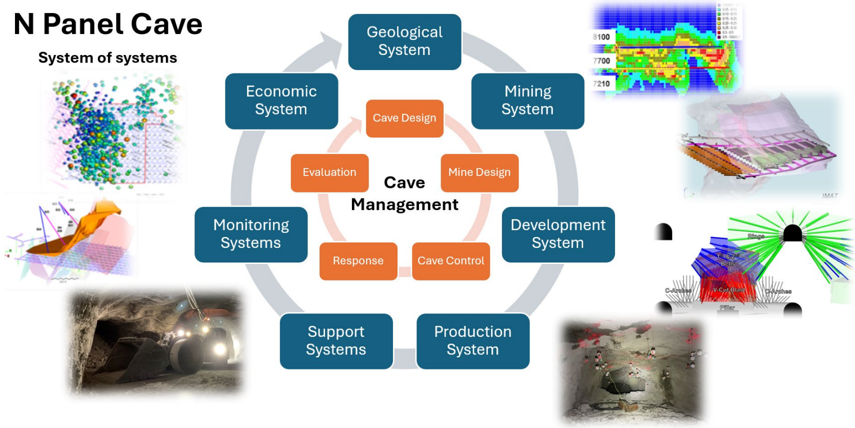

Figure 6 Conceptual representation of the 7210 N-Panel cave physical entity as a system-of-systems interacting and its interaction with the cave management process

4.2 Physical to digital updating

The P2D updating dimension converts observations from the physical mine into inputs that update the digital model. At Henderson, these inputs come from 2 primary sources: geomechanical monitoring systems, and design, operational, and production datasets that describe how the cave is developed and extracted. Figure 7 illustrates the special relationship between the 7210 N-Panel cave geometry and the primary monitoring and operational data sources feeding the Henderson geomechanical digital twin model. The following sections describe these data sources highlighting their updating, storage, and processing features.

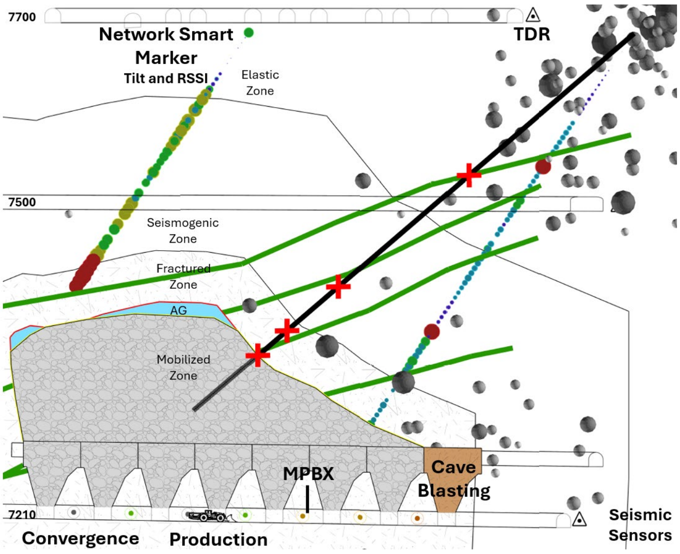

Figure 7 Cave profile interpretation using instrumentation and the cave conceptual model for the 7210 N-Panel at the Henderson mine

4.2.1 Physical to digital updating from monitoring systems

In block caving operations, the main purposes of monitoring systems are to verify cave initiation and propagation processes, assess excavation and infrastructure stability, and detect surface and subsurface subsidence associated with cave growth.

Henderson's geomechanical monitoring program is comprised of:

- a microseismic monitoring system to track mine-wide seismic activity
- TDR cables to monitor cave initiation and propagation
- connected smart markers to monitor cave initiation and propagation
- laser distance meters, LiDAR scanners and multi-point borehole extensometers (MPBXs) to monitor drift convergence.

These monitoring systems act as direct sensor-based P2D updating mechanisms, converting physical rock mass response into digital state variables that inform cave interpretation, hazard assessment, and management decisions. The following sections describe Henderson's monitoring components and the systems in place for data collection, storage, processing, analysis and updating of each of these systems.

4.2.1.1 Microseismic monitoring

The microseismic system consists of distributed triaxial and uniaxial sensors installed around the active panels. This system captures small-magnitude seismic events generated by stress redistribution, fracture growth, and cave-propagation processes. Events are recorded in near real time and continuously updated in the seismic provider's database, where routine reprocessing improves location accuracy and source characterisation. These data are reviewed in bi-weekly geomechanical (GMX) meetings, trigger automatic threshold notifications to operations when predefined levels are exceeded, and provide one of the primary inputs for updating the digital twin's representation of damage, abutment loading, and seismogenic zones.

4.2.1.2 Time domain reflectometry monitoring

TDR cables are grouted in boreholes above the cave footprint and measure depth-specific rock-mass damage by detecting changes in the reflected waveform of a voltage pulse. Measurements are collected every 12 hours and stored in the TDR system's platform, where engineers interpret waveform changes to identify clipping, breakage, or deformation that mark the position and vertical progression of the cave back. These interpretations are discussed during GMX monitoring meetings and incorporated into the digital twin to refine geometric constraints on cave growth.

4.2.1.3 Networked smart markers

Smart markers are wireless, multi-node deformation sensors installed along boreholes to measure tilt, rotation, and signal-strength changes as the cave develops. They update one to 2 times per day and transmit data to the vendor platform, providing near-real-time evidence of localised movement and early rock mass mobilisation. GMX engineers regularly review these streams and compare them with seismic, TDR, and production data to confirm cave initiation trends, especially during periods when other systems experience temporary connectivity interruptions. Their measurements are merged into the digital twin to strengthen the temporal interpretation of cave progression.

4.2.1.4 Convergence monitoring

Drift deformation is measured using MPBXs and handheld laser distance meters, and LiDAR scanning. MPBXs are located in strategic areas that may present stability issues in the future. These sensors are connected to a real-time monitoring system and collect 2 readings per day. MPBX data is processed and displayed in a web-based portal provided by the vendor where data can be downloaded and displayed in the digital model. Manual convergence stations are located on every pillar at each productive panel. These are measured bi-weekly using laser distance meters and recorded in tablets that store raw readings in Excel before archiving them in Acquire and visualising cumulative and incremental convergence trends in Power BI. LiDAR scans are collected in areas where convergence thresholds indicate active deformation to support three-dimensional change detection. All convergence data are summarised and discussed in bi-weekly GMX meetings and incorporated into the digital twin to assess excavation stability and support performance.

4.2.1.5 Drawpoint visual inspections

Visual inspections provide qualitative but essential P2D inputs, complementing instrumented data with observational context. The GMX team conducts periodic visual inspections within the cave footprint. During bi-weekly shutdowns, the entire panel is walked to collect convergence measurements and document ground conditions, including support performance, drawpoint water condition (classified as damp, wet, or oversaturated), and issues identified during workplace examinations. C-Arch conditions and fragmentation are additionally assessed on a quarterly basis. All observations are logged, discussed, and correlated with instrumented monitoring data during GMX monitoring meetings, strengthening the integrated interpretation of cave conditions used to support cave management decisions.

4.2.2 Physical to digital updating from design, operational and production data sources

In addition to geomechanical monitoring systems, P2D updating of the Henderson geomechanical digital twin relies on design, operational, and production data that describe how the cave is developed, undercut, and extracted over time. These data sources capture the operational forcing functions acting on the physical entity and provide essential context for interpreting the rock mass response observed through instrumentation. When integrated with monitoring data, design and operational information enables correlation between mining activities and geomechanical behaviour, supporting a more robust and continuously updated representation of the evolving cave state.

4.2.2.1 Production data

Production data defines the operational forcing functions acting on the physical entity and is essential for linking cave response to extraction behaviour. At Henderson mine, production planning starts with the life of mine schedule, created by the production engineering team using a production control long-range model. This model is used for simulating block model mixing and production forecasting. From that plan, engineers extract monthly tonnage rates for each drawpoint, known as the monthly target. These monthly numbers feed into the production control short-range model, which is used to build a detailed bi-weekly production plan on Henderson’s typical 7-day run cycle. This short-range plan includes drift schedules and expected drawpoint extraction rates.

The bi-weekly plan is loaded into the Henderson mine production SQL database, making it available to load– haul–dump (LHD) machine operators through the Enterprise Work System (EWS) app on their company-issued tablets. EWS gives operators their specific drift assignments and acts as the main tool for capturing shift level production data. During the shift, operators record everything from bucket counts and drawpoint conditions to equipment engine hours and downtime. At the end of the shift, they submit their digital draw card, which is automatically uploaded into the EWS Snowflake database.

All this information comes together in Power BI, where it’s visualised for engineers, supervisors, and managers. Every morning after a run day, the production engineers extract the raw data from a Power BI report to confirm drawcards have been submitted properly and no duplicate information exists. Once validated, this daily actual dataset is loaded back into the Henderson mine production SQL database, where it becomes available for engineering analysis, reconciliation, and short-term performance tracking. Validated production data are integrated with geomechanical monitoring information within the digital twin framework. Draw rates, spatial extraction patterns, and temporal variations in production provide key inputs for cave back estimation and evaluation of cave propagation rates. Production data are also analysed in conjunction with complementary datasets, including seismic activity and blasting records.

4.2.2.2 *Development data*

Development data describe the spatial and temporal progression of drawbell construction and undercut advance, which together control the geometry and early evolution of the cave. As each drawbell is opened and undercut rings advance, the excavation geometry and local stress distribution change in ways that strongly influence cave initiation and the onset of propagation. These data are captured through development and blasting records that document drawbell locations, timing of blasts, and undercut progress, and are stored in a semi-automated blasting database that is routinely updated as development advances. When aligned with seismicity, deformation, and production information, these records allow the digital twin to distinguish blast-induced effects from caving-related responses and to maintain an accurate representation of the evolving cave geometry during the transition from drawbell opening to sustained cave growth.

4.3 Digital model

The digital model used in the Henderson geomechanical digital twin is comprised of 2 complementary components: a geometric and data model, and a physics-based geomechanical model. Together, these components form a hybrid digital model, integrating both data-driven and physics-driven representations of the cave system, as shown in Figure 8. This hybrid structure enables the twin to organise multi-source information, maintain an evolving representation of the mine, and estimate the mechanical response of the rock mass as the cave develops.

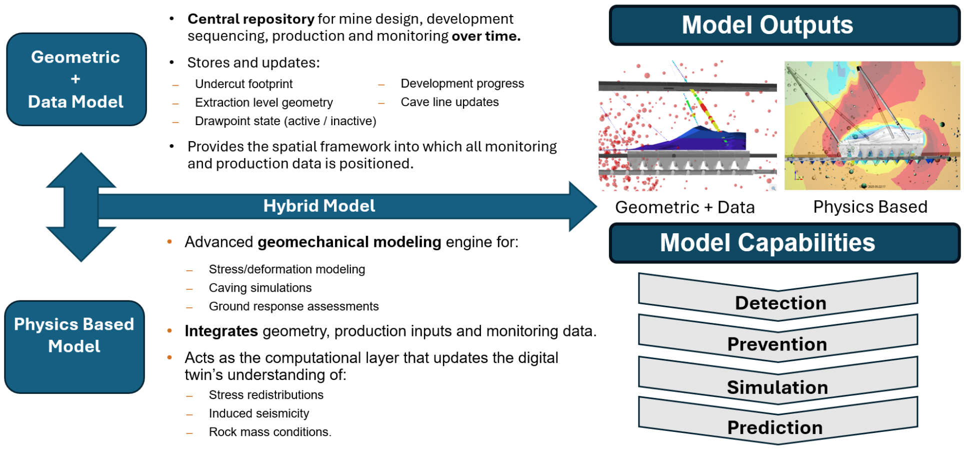

Figure 8 Hybrid digital model for the 7210 N-Panel combining a geometric+data repository with a physics-based geomechanical model to integrate, visualise, and simulate cave behaviour

The geometric and data model acts as the central repository for all spatial and temporal information associated with the 7210 North Panel. It stores, organises, and time-stamps geological and structural domains, geomechanical properties, mine-design elements, development progress, undercut sequencing, production data, and the full suite of monitoring inputs. Each dataset is attributed with a consistent spatial reference and a temporal update stamp, which allows the system to visualise and analyse the evolution of the cave in 4 dimensions. This model is continuously updated as the mine advances, incorporating changes such as undercut footprint growth, caving advance and progression, bell-blast completion, drawpoint status, and revised cave-line interpretations. By maintaining this information in a single, structured environment, the geometric and data model provides a spatial framework into which all monitoring and operational data are integrated, visualised, and communicated.

In parallel, the physics-based model uses the information stored in the geometric and data model to construct a high-fidelity numerical representation of the cave's current state. This model is implemented using a finite-volume approach, allowing it to simulate stress redistribution, rock-mass yielding, deformation, and induced seismicity. The physics-based model is periodically updated to reflect the latest geometry, material properties, and operational changes, enabling it to estimate the rock mass response to the ongoing panel progression. By linking numerical predictions with real monitoring evidence, the physics-based model provides an evolving estimate of the cave's condition that can be compared directly with field observations.

Together, the geometric/data model and the physics-based model form a hybrid digital model that supports both descriptive and predictive capabilities, consistent with modern digital-twin frameworks. The geometric/data model synthesises and visualises the mine's current state, while the physics-based model estimates system behaviour and forecasts how the cave will respond to operational changes. This dual-model structure enhances interpretation, enables scenario evaluation, and supports the decision-making processes described in subsequent sections of the digital twin.

4.4 Digital to physical updating

D2P updating describes how insights generated by the digital model are translated into operational decisions and real-world actions. As shown in Figure 9, the D2P process has 3 core elements: the key indicators derived from the digital model, how those indicators inform cave management decisions, and the distribution of roles and responsibilities across strategic, tactical, and operational levels. These elements together close the loop between numerical predictions, monitoring evidence, and the actions required to maintain safe and efficient cave performance. This section describes how outputs from the digital model inform operational decisions.

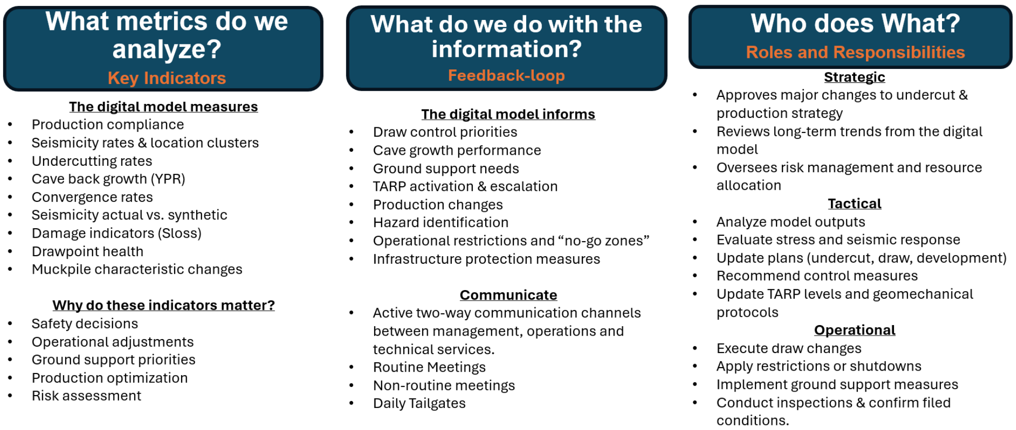

Figure 9 Digital to physical framework showing key indicators analysed by the digital model, how these indicators inform cave-management decisions, and the corresponding roles and responsibilities at strategic, tactical, and operational levels

The digital model produces a suite of indicators used to evaluate cave performance, identify potential hazards, and prioritise operational responses. These include production compliance, seismicity rates and event clustering, undercutting rates, cave back growth, convergence rates, synthetic versus observed seismicity, damage indicators, drawpoint health, and muckpile condition changes. These metrics matter because they guide safety decisions around ground support priorities, operational adjustments, and risk-management actions, ensuring that cave behaviour is interpreted consistently across technical and operational teams.

Outputs from the digital model are then translated into actionable insights that influence draw-control priorities, cave-growth assessments, ground-support needs, TARP activation/escalation, production adjustments, hazard identification, operational restrictions, and infrastructure-protection measures. This feedback loop relies on clear and timely communication, typically through periodic meetings, routine monitoring discussions, non-routine event reviews, and daily tailgates that ensure alignment between engineering, operations, and management.

Finally, the D2P updating process is structured around distinct levels of responsibility. Strategic roles approve major changes to undercut and production strategy, review long-term digital model trends for risk-management, and plan and allocate resources. Tactical roles analyse model outputs, evaluate stress and seismic responses, update undercut and draw plans, and recommend control measures, including TARP level adjustments. Operational roles execute draw changes, apply restrictions or shutdowns when required, implement ground support measures, and conduct inspections to confirm field conditions. This hierarchical structure ensures that model insights translate into timely, consistent, and well-coordinated physical actions.

For instance, uneven draw can induce excessive convergence in nearby production drifts, ultimately affecting drift stability. This condition can be monitored by tracking draw-compliance patterns together with convergence measurements in an area of concern. The digital model enables early detection of these trends, allowing engineers to evaluate its progression and anticipate potential ground-response issues before a convergence TARP is activated. To mitigate the condition, a change in the draw order is required to rebalance compliance and reduce localised loading from the cave. The engineering group raises the issue during routine meetings where operational responses are discussed, and management determines that a draw adjustment is the most appropriate action. The engineering group prepares an updated production plan, which the production team implements. The digital twin continues to be updated, reviewed, and discussed until the condition stabilises. The objective of the D2P dimension of the digital twin is to translate digital insights into real-world actions through structured roles, ultimately improving the safety and productivity of the operation.

4.5 Optimisation

Optimisation represents the final dimension of the digital twin framework and focuses on how insights generated from the physical, digital, and bidirectional updating processes are used to continually refine understanding, improve systems, and inform future planning. Optimisation at the Henderson mine operates across 3 complementary pathways: back-analysis, where historical models and monitoring records are integrated to evaluate past cave behaviour and improve geomechanical assumptions; systems improvement, where lessons learned from successive panels guide the adoption of enhanced monitoring technologies, modelling practices, and operational workflows; and forecasting, where the calibrated hybrid model is used to anticipate the performance of future panels and evaluate design alternatives. Figure 10 illustrates how optimisation is implemented at Henderson through back-analysis, systems improvement, and forecasting. Together, these optimisation activities ensure that the digital twin not only reflects the current state of the cave but also drives continuous improvement in safety, reliability, and planning effectiveness across the life-of-mine.

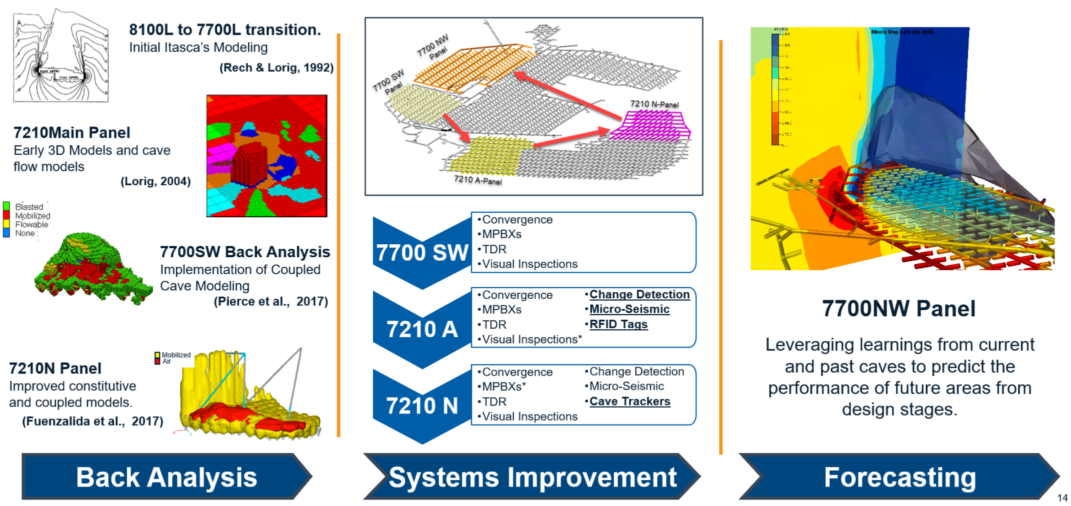

Figure 10 Optimisation dimension of the Henderson geomechanical digital twin showing how back-analysis, systems improvement, and forecasting evolve across panels

4.5.1 Back-analysis

The Henderson mine has been a pioneer in the implementation of geomechanical numerical modelling in cave mining operations. Early modelling work began in the early 1990s, prior to the transition from the 8100 level to the 7700 level. At the time, a two-dimensional finite-volume numerical model was used to forecast stress changes due to the development of the new cave and its interaction with the 8100 existing level (Rech & Lorig 1992). In 2004, an advanced three-dimensional numerical modelling solution was implemented to evaluate cave initiation, propagation, and abutment stress effects on the 7210 Main Panel. In addition, the first two-dimensional particle-flow simulations were performed to evaluate dilution potential in this level (Lorig 2004). In 2010, the first back-analysis efforts at Henderson took place in the 7210 Main Panel, where extensive convergence monitoring data was used to calibrate and validate numerical modelling assumptions (Sainsbury & Loring 2013). A hybrid three-dimensional continuous-and-particle-flow modelling approach was first implemented at Henderson in 2017 while back-analysing cave growth and extraction drift stability at the 7700 Southwest Panel (Pierce et al. 2017). Pre-cave and post-cave back-analysis simulations continue to be performed at Henderson. More recently, the 7210 A-Panel allowed integration of not only convergence data but also additional monitoring systems into the back-analysis workflow, including microseismic monitoring and TDR records (Fuenzalida 2023). In 2023, for the 7210 N-Panel, a strain-softening rock-mass model and an improved coupled continuum–cave-flow workflow were implemented, yielding more realistic cave-growth behaviour. With the geomechanical digital twin approach in place, complex models are now developed in-house, enabling back-analysis on the go, maximising the return on investment in instrumentation, and directing external consulting resources to specialised problems that exceed in-house capability.

4.5.2 Systems improvement

System improvements at Henderson have progressed panel by panel as monitoring technologies, connectivity, and data-management capabilities have expanded. Early panels relied primarily on visual inspections, manual convergence measurements, and manually read TDR cables. Subsequent panels incorporated networked instrumentation, enabling faster data transfer and automated threshold notifications that significantly improved response times for MPBX and TDR systems. The introduction of 3D LiDAR scanning further enhanced the ability to capture as-built drift geometry and perform change-detection analyses in areas of elevated deformation.

More recent panels, including 7210 A and 7210 N, integrated advanced microseismic monitoring systems, expanded LiDAR use, and deployed cave-tracker technologies such as RFID-based tags and networked smart markers to improve early detection of cave initiation and deformation. These enhancements increased the spatial and temporal resolution of monitoring data and strengthened the ability to correlate changes in cave behaviour with undercutting, development, and production activity.

Looking ahead to the 7700 Northwest Panel, planned improvements focus on building on lessons learned from recent operations. Higher-density seismic arrays are expected to improve event-location accuracy, with potential integration of optic fibre and distributed acoustic sensing to create virtual geophone coverage. Cave-tracker deployments will be optimised around initiation blasting to validate new drawbell-blast designs, and the geomechanics team will continue prioritising technologies that integrate cleanly into existing data architecture. This progressive enhancement of monitoring systems supports the optimisation dimension of the digital twin by improving data fidelity, strengthening model calibration, and enabling more robust interpretation of future panels.

4.5.3 Forecasting

Forecasting represents the forward-looking component of the digital twin, where the calibrated hybrid model is applied to anticipate cave performance under future mining conditions. Using parameters refined through back-analysis and informed by the monitoring improvements from recent panels, the digital model provides pre-caving estimates of cave initiation, propagation, stress redistribution, and potential deformation trends. These forecasts support evaluation of alternative undercut and draw strategies, inform ground support planning, and guide the location and density of monitoring systems for upcoming panels such as 7700 NW. By extending learning from previous operations into future designs, forecasting completes the optimisation loop and strengthens confidence in early-stage decision-making.

5 Geomechanical digital twin Implementation during North Panel cave ramp-up

This section summarises the 7210 N-Panel's progress from cave initiation in October 2023 through end-of-year 2025 and highlights how the geomechanical digital twin supported a safe and controlled ramp-up. Figure 11 summarises production, undercut blasts, and number of seismic events for this period and helps correlate undercut activity, production progress, and seismic response across key milestones. As shown, N-Panel achieved successful cave initiation and steady ramp-up despite a harder rock mass and a smaller footprint than prior panels, with model interpretations aligning well with underground observations and informing draw control, monitoring response, and ground support priorities. Where partial monitoring disruptions emerged, the digital twin enabled cross-checks against other monitoring systems, production, development, and geometry updates to maintain continuity during cave growth interpretation.

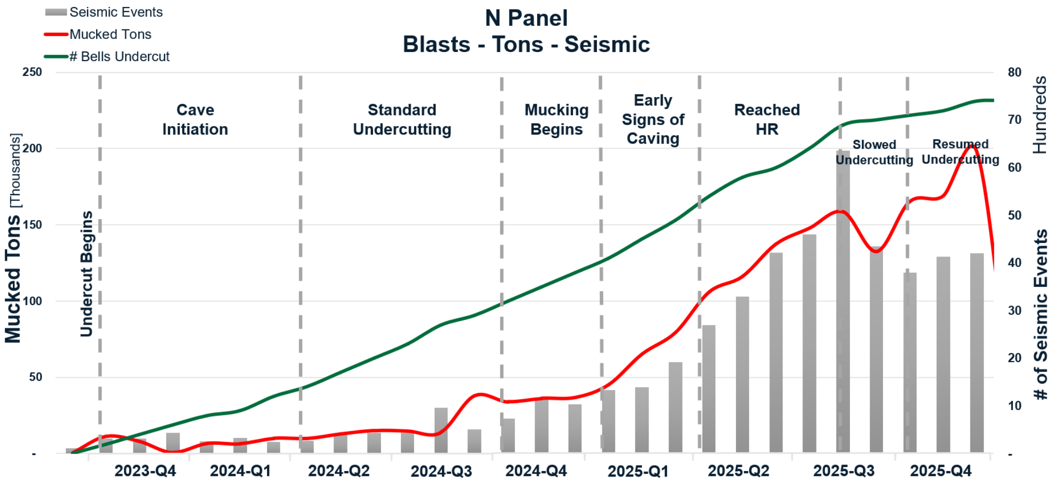

Figure 11 **Blast, tons, seismic graph for N-Panel cave development highlighting milestones during cave initiation and ramp-up**

Figure 11 highlights 3 major phases between October 2023 and December 2025: an initiation and early undercut phase with low production and low, stable seismicity mostly related to undercut blasting; a transition as production increased and the continued draw began to contribute broken rock, accompanied by a rise in seismic activity; and a post-hydraulic radius (HR) regime where seismic response correlated more strongly with undercut blasting intensity while production volumes continued to rise. This pattern supported tactical decisions to continue undercutting, adjust draw in localised areas, and maintain monitoring efforts in areas where the digital model forecasted elevated abutment loading, such as ventilation raises, fixed facilities and large intersections in the haulage level.

As cave growth progressed, the digital twin was routinely calibrated against the evolving state, reinforcing confidence in undercut advance rates and draw sequencing. The D2P workflow formalised communications among engineering, operations, and management, shortening the loop from detection to action. Key lessons included the importance of multi-layered, overlapping monitoring systems, which proved essential when instrumentation connectivity was interrupted and individual sensors temporarily dropped offline. The digital twin also enabled integration of monitoring, modelling, production, design, and operational datasets in a single platform, significantly strengthening cave-condition interpretation across all levels of the organisation. Continuous communication between management, engineering, and operations further ensured operational buy-in, increasing the likelihood that unexpected conditions were reported promptly and that work was paused when additional geomechanical investigation was required. The ability to view all relevant information in one time-enabled environment greatly improved data availability and transparency, expediting decision-making during ramp-up. Overall, the 7210 N ramp-up showed that an integrated geomechanical digital-twin approach can maintain high-quality interpretation and effective decision support even when monitoring coverage is uneven or individual data streams are temporarily degraded.

6 Conclusion

This paper presented a practical implementation of a geomechanical digital twin for cave mining and its application at Henderson mine. The twin integrates multi-source operational and monitoring data with a hybrid digital model that maintains an evolving representation of the cave while estimating geomechanical response to operational changes. The implementation of this digital twin enabled several conclusions, which are summarised below.

- This work demonstrates that challenges associated with cave management can be addressed through the implementation of a geomechanical digital twin that consolidates multi-source data and provides a continuously updated representation of cave behaviour.
- The framework proposed by van Eyk & Heyns (2025) enabled the integration and alignment of all practices and processes within the cave-management program, structuring a complex system into a coherent and practical digital twin model that supports engineering, operational, and management teams.
- The optimisation dimension allows the digital twin to become an integral element of the cave-management process by fostering a continuous-improvement mindset. This is achieved through back-analysis, parameter calibration informed by accumulating evidence, and the integration of new monitoring and analytical technologies that enable the system to evolve without disrupting established workflows.
- The D2P dimension represents the most critical component of the digital twin, as it is the stage where many implementations fail. It is in this dimension that model insights are translated into real operational actions, and where measurable benefits to safety, efficiency, and overall cave performance are realised. By operationalising insights through clearly defined roles, responsibilities, and communication channels, the D2P dimension ensures that strategic groups provide direction and resources, tactical groups provide technical support and define control strategies, and operational teams implement changes.
- Overall, the Henderson geomechanical digital twin demonstrated that integrating data, modelling, and decision workflows into a single system can materially improve proactive risk management and operational performance. As monitoring systems expand and models continue to be calibrated, this approach is positioned to deliver growing value and support planning for future caving panels.

References

Codelco 2025, *Codelco lamenta accidente en proyecto Andesita de la División El Teniente (Codelco regrets an accident at the Andesita project of the El Teniente Division)*, viewed 31 July 2025, https://www.codelco.com/codelco-lamenta-accidente-en-proyecto-andesita-de-la-division-el-teniente

Elmo, D & Stead, D 2020, 'Disrupting rock engineering concepts: is there such a thing as a rock mass digital twin and are machines capable of learning rock mechanics?', in PM Dight (ed.), *Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 565–576, https://doi.org/10.36487/ACG_repo/2025_34

Flores-Gonzalez, G 2019, 'Major hazards associated with cave mining: are they manageable?', in J Wesseloo (ed.), *MGR 2019: Proceedings of the First International Conference on Mining Geomechanical Risk*, Australian Centre for Geomechanics, Perth, pp. 31–46, https://doi.org/10.36487/ACG_rep/1905_0.3_Flores-Gonzalez

Freeport-McMoRan 2025, *News Releases Details*, viewed 24 September 2025, https://investors.fcx.com/investors/news-releases/news-release-details/2025/Freeport-Provides-Update-on-PT-Freeport-Indonesia-Operations-df08fc3a7/default.aspx

Fuenzalida, M 2023, *Back Analysis of Cave Propagation and Footprint Stability at 7210 A Panel - Henderson Mine*, ITASCA, Minneapolis.

Grievers, M & Vickers, J 2017, 'Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems', *Transdisciplinary Perspectives on Complex Systems*, pp. 85–113.

Kamp, C, Cumming-Potvin, D, Lett, J, Poulter, M, Shea, N, Jalink, B & Vanegas-Palacio, C 2024, 'Cave profile interpretation using instrumentation and the cave conceptual model', in D Johansson & H Schunnesson (eds), *MassMin 2024: Proceedings of the*

International Conference & Exhibition on Mass Mining, Luleå University of Technology, Luleå, pp. 318–349, https://doi.org/10.36487/ACG_repo/2435_C-02

Lorig, L 2004, *Numerical Modeling Assessment of Rock Mechanics Issues Associated with Caving on the 7210 Production Level at Henderson Mine*, ITASCA, Minneapolis.

Pierce, M, Fuenzalida, M & Katsaga, T 2017, *Analysis of Cave Propagation and Drift Closure in 7700SW Panel*, ITASCA, Minneapolis.

Rech, W & Lorig, L 1992, 'Predictive numerical stress analysis of panel caving at the Henderson Mine', Proceedings of Massmin 1992, Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 55–62.

Sainsbury, DP & Loring, DM 2013, 'Analysis of extraction level performance at the Henderson Mine', in Y Potvin & B Brady (eds), *Ground Support 2013: Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction*, Australian Centre for Geomechanics, Perth, pp. 539–550, https://doi.org/10.36487/ACG_rep/1304_37_Sainsbury

Singh, M, Srivastava, R, Fuenmayor, E, Kuts, V, Qiao, Y, Murray, N & Devine, D 2022, 'Applications of digital twin across industries: a review', *Applied Sciences*, vol. 12, no. 5727.

van Eyk, L & Heyns, P 2025, 'A framework to define, design and construct digital twins in the mining industry', *Computers & Industrial Engineering*, vol. 200, no. 110805.

Wang, Y, Rezaei, A & Hicks, S 2025, 'Digital twin applications in geotechnical engineering: a systematic review', *Machine Learning and Data Science in Geotechnics*, pp. 77–91.