Setting it up for success: considerations for caving projects

S Hanrahan *SRK Consulting, Australia*

Abstract

Established natural caving (i.e. block or panel caves) projects and operations have been underway for decades and are clearly visible. In recent years, a number of new caving projects have been under study. These projects are typically new discoveries or surface to underground transitions, with ownership outside of the existing mainstream cavers. The new projects do not typically have the benefit of deep in-house caving skills and rely on study teams that assemble a number of entities to investigate the various required study components. A key challenge for project owners is initially the quantum of finance that is required to source all the required orebody knowledge and carry out suitable investigations. In most cases, this is a serious challenge and drives the observed behaviours and outcomes. This paper focuses on the required workflow for natural caving projects from scoping study to about a pre-feasibility study level; in contrast to detailed design aspects that are discussed elsewhere in this conference.

Keywords: *new caving projects*

1   Introduction

The easy stuff is long gone.

Globally, the low-hanging fruit of yesteryear is gone for most existing operations and new projects. Deposits on surface and underground face increasing challenges to preserve and extend mine life. Examples of challenges that can now routinely be seen are:

Surface mining:

- Decreasing mine grades.
- Ever-deepening open pits with significant increased stripping ratios/volumes and associated haulage costs.
- Very high slope heights and associated geotechnical conditions.
- Mining below the watertable.
- Transition to refractory ore.
- Timelines to transition underground.

Underground mining:

- Increasing depth.
- Ventilation requirements for heat load and to meet stricter regulatory requirements.
- Mining-induced seismicity.
- Stress management.
- Raisebore stability.
- Materials handling limitations.
- Groundwater management.

Issues common to both mining methods:

- Mineral resource confidence: Ever increasing complexity of the geological setting, in particular a move to finding and exploring for 'undercover deposits' (Figure 1).

- Metallurgy: An increasing need for hydrometallurgical processes to recover mineralisation.

- Water supply: An ability to source and permit adequate supply.

- Social licence to operate: An all too public challenge that the industry faces.

- Tailings management: Bulk mining methods create larger tailings storage facilities. These create greater technical and social challenges.

- Increasing capital cost to extend mine life.

Each operation is unique, and mine operators have no choice but to work with these issues, to ensure mine life longevity.

Papier is geduldig[1]

Based on industry research, there is evidence that aspirant caving operators do not fully understand the implications of project study choices. The following examples illustrate this point.

- Exhibit A: A potential caving project study that generated a Joint Ore Reserves Committee (JORC) Ore Reserve statement, for which the supporting geotechnical data was inadequate to assess caveability, yet a 'competent person' saw fit to confirm the economic viability of this project.

- Exhibit B: A series of advanced study updates was done on a potential caving project, yet no in situ stress measurements informed those advanced studies. In situ stress measurements were inferred from a distant location in an open pit setting.

- Exhibit C: A project owner required a single sign-off JORC Ore Reserve statement informed by a pre-feasibility study. The study would rely on two geotechnical holes, that being all the project owner was willing to fund.

- Exhibit D: An existing open pit was investigating a transition to underground (Figure 2) with an expectation of a relatively fast transition to offset the need for further cut-backs. The potential caving inventory was predominantly inferred classification and there was very limited suitable orebody knowledge. Transition studies are ongoing and further cut-backs were required to extend production continuity after the reality of the required time frame was acknowledged.

These examples illustrate that potential caving projects under study are challenged by unrealistic owner aspirations and short cuts being taken across the technical investigations. The root cause is arguably a desire to increase the owner share price; but in tension with a lack of adequate finance to correctly evaluate the capability of the deposit to deliver as a cave production unit.

There are also indications of service providers falling under the spell of unrealistic owner aspirations and simply conducting the work as requested without any seeming consideration to their own professional obligations or application of suitable experience.

Caving settings:

In considering new caving projects, there are typically three observed scenarios; pure underground deposits, surface to underground transitions and, more recently, projects that commence with a sublevel cave (SLC) and then transition to a block cave (Figure 3).
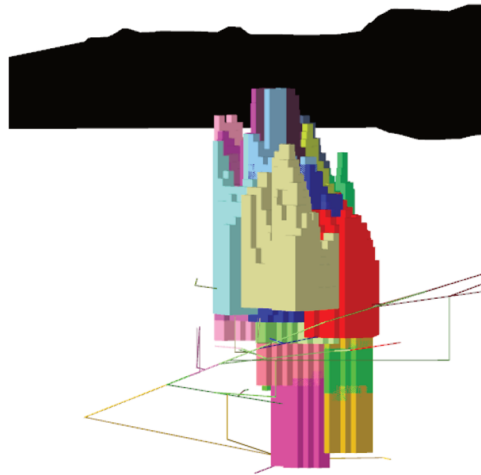
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[1] Paper is patient (Afrikaans)

Figure 1   Example of a pure underground/undercover project (SolGold Plc & Cornerstone Capital Resources Inc 2019)
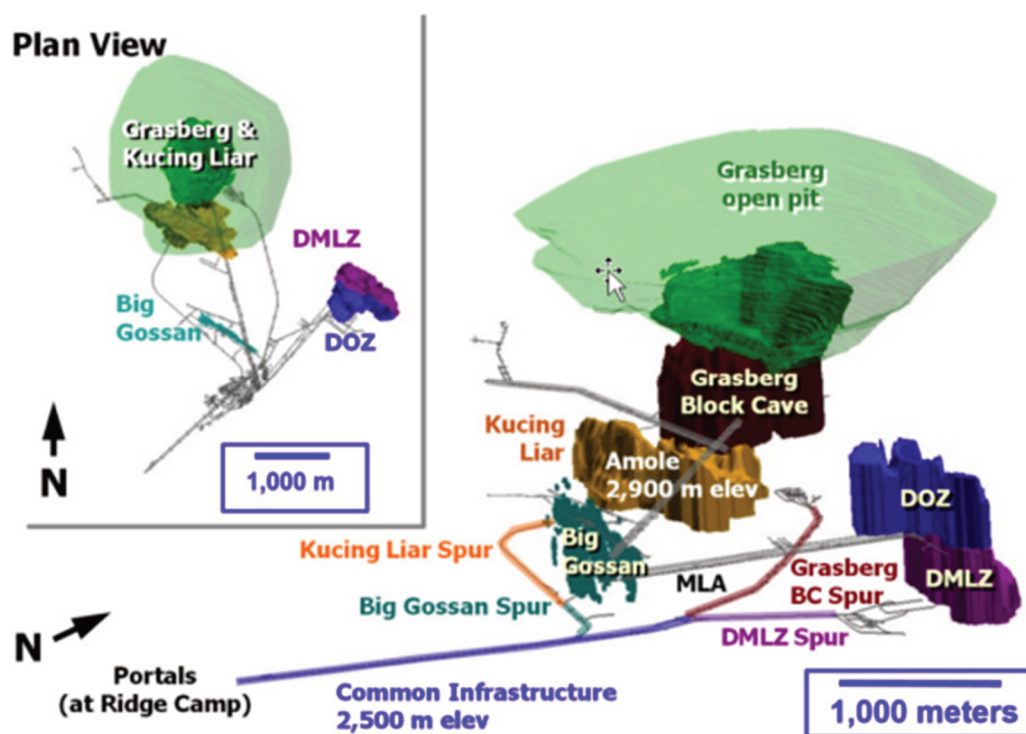

Figure 2   Example of surface to underground transition (Brannon et al. 2020)
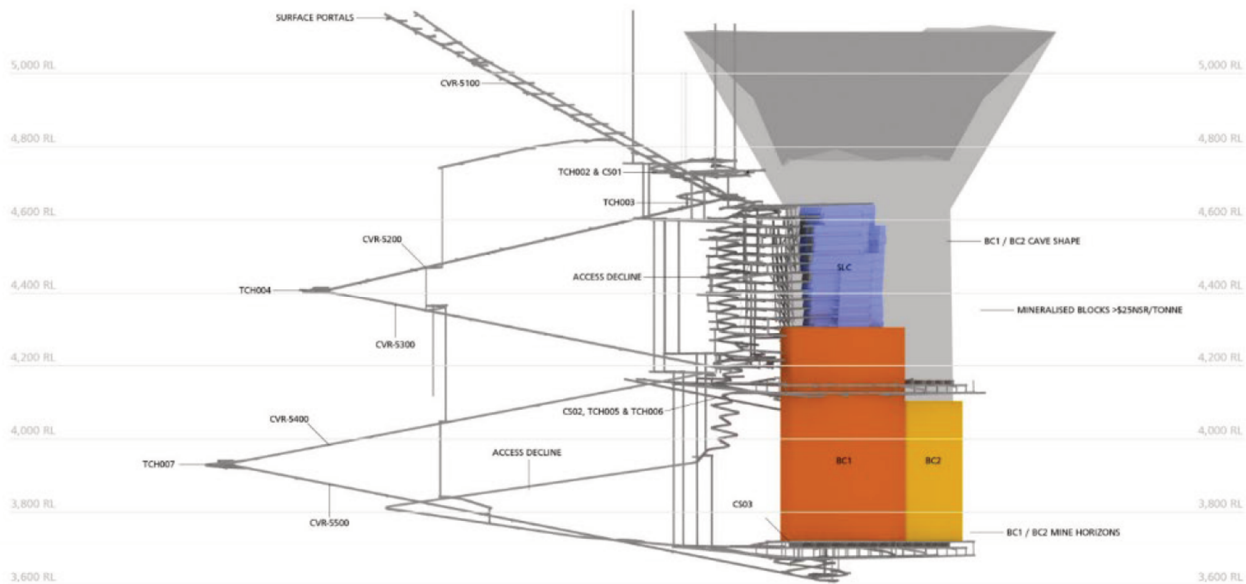
Figure 3   Example of SLC transition to a block cave (OZ Minerals 2021)

Without delving into the myriad of technical detail that is required to definitively investigate a caving project, the following technical areas are seen as critical to correct investigation, and owners should focus on these areas to ensure that their caving projects are set up for success and de-risked as much as possible to be able to attract investment and/or financing.

2   Risk

For companies outside the existing caving operators, financing single caving projects is challenging, made infinitely more so by lack of corporate capacity for execution, a long lead time between substantial investment and positive cash flow, significant technical risks that are slow to resolve, and low optionality (Winkelmann 2020). Lenders are risk averse and these aspects negatively influence financing evaluations.

Summers (2000) also highlights the aspect of risk; suggesting the need to have a clear understanding of what risk is, the risks relevant to the project under design, and the risk acceptance thresholds set by the owners of the project. Whilst these three requirements are easy to demand, they are far more difficult to implement in a real project.

Key hazards for caving projects, e.g. airblasts, mudrushes and potential large seismic events are very challenging to realistically assess, as there are no universal criteria. In contrast, assessing slope stability for open pits is typically based on industry accepted Factor of Safety and probability of failure analyses.

Risk can be managed, but cannot be eliminated – the key aspect is to understand the consequences of being wrong. The earlier examples of owner behaviour during studies do not assist in reducing risk, but rather magnify risk for all stakeholders, with owners seemingly oblivious to the downstream consequences.

A caving project typically has limited optionality (compared to more selective mining methods), e.g. no ability for a flexible cut-off grade policy, impossible to select a specific ore type, and not conducive to stop-start mining. Critically, once a cave is initiated, much optionality is lost with operational flexibility limited to adjusting draw rates. This decreased optionality increases the value of information prior to a construction/investment decision.

In reducing financing risk, one can add contingency (typically grossly underestimated) to assumptions, or reduce uncertainty. For caving projects, an important way to reduce uncertainty is characterisation of the rock mass. Characterisation is considered to be the combination of resource definition, field programs, test work, modelling and studies that combine to increase orebody knowledge and reduce project risk.

Figure 4 conceptually illustrates the relative spectrum of outcomes by relative expenditure on characterisation.
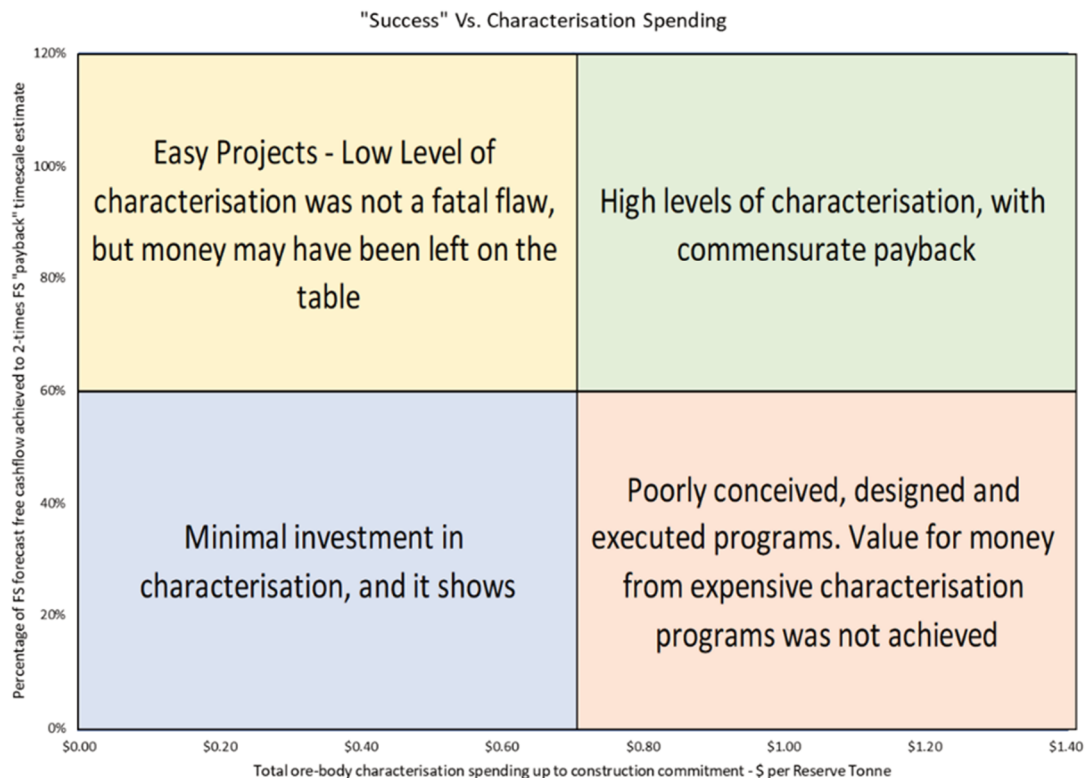

Figure 4   Success versus characterisation spending (Winkelmann 2020)

3   Orebody knowledge

Expanding on the theme of characterisation, orebody knowledge can be considered to include, the mineral resource, geotechnical investigations, structural geology definition, hydrogeology, geometallurgy and for deposits at depth, knowledge of the geothermal gradient (vital to inform ventilation requirements) (Figure 5). Understanding all the components is critical to informing investment decisions. Information can be gathered by surface drilling, or an exploration decline or shaft. It is recognised there is significant tension in the perceived cost benefit of expending cost on some form of exploration access, but caving projects globally have reinforced the need for this work to be carried out.
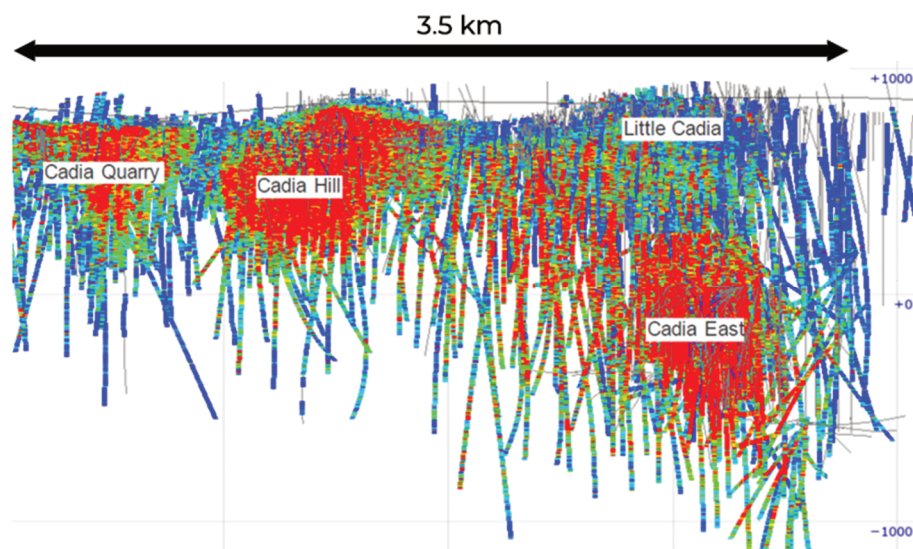

Figure 5   Example of expansive orebody knowledge gatherings (after Newcrest Mining Limited 2020)

A caving project is very dependent on understanding rock mass characterisation which includes:

- Collecting adequate and representative data.

- Preparing a geotechnical block model.

- Preparing a structural geology model.

- Domain definition.

- In situ stress definition.

- Modelling inputs quality.

- Fragmentation assessment.

- Potential preconditioning requirements.

- Hydrogeological setting.

Understanding the rock mass will typically take well in excess of the minimal holes that some current project owners deem sufficient. Project owners should avoid the temptation to collect only basic rock mass characterisation data from exploration drillholes thinking that will result in a quality and representative dataset. It should also be noted that exploration drilling has quite a different approach to quality compared to time consuming geotechnical drilling and logging.

Understanding the rock mass typically requires more drilling than is required to meet the minimum resource classification drilling, with higher levels of drilling required for infrastructure areas and the extraction level as well as drilling outside the mineralisation zone. Project owners who know they are looking at a caving operation can increase the quality of their dataset significantly by appropriately handling and analysing the core during the exploration phase, rather than having to come back to do specific geotechnical drilling after the opportunity has been lost.

Caving is a unique mining method where a rock mass often requires 'engineering' to encourage it to perform as needed. Understanding the rock mass characterisation is a foundational key to understanding just how much engineering will be required.

The most common form of cave engineering is preconditioning, a method of preferentially weaking the rock mass to assist in caveability, with secondary benefits of improving in situ fragmentation and reducing mining-induced seismic hazard.

Caving operations continue to demonstrate that you can never know enough about your unique rock mass, as in many instances, caves turn out to have a mind of their own and demonstrate that we just cannot understand everything.

Establishing a caving mine has relatively few excavations (e.g. undercut and extraction levels) where direct observations can be made of the rock mass. Hence, most of the knowledge of the rock mass is gained in the early stages of the project during core logging. This is not the case for mining methods such as sublevel open stoping or sublevel caving, where every level allows for drive mapping and increased knowledge of structural geology. Open pit mining, by contrast, has a highly visible rock mass, although deep-seated structures can be easily missed, as will be discussed later.

In assessing the rock mass, formal methods of analysis need to be used, but informal methods of assessment should not be overlooked. The author has experience of reviewing core, both the original intact core photos and the residual half cut core (Figure 6) trays.

What is noticeable between the original whole core that at face value exhibited a strong rock mass, was that the half core now has a number of additional defects visible. In this case, the only energy applied to induce new defect failure was a diamond saw. This energy input is infinitesimal compared to the energy involved in the internal cave mass once caving takes place. This anecdotal observation reinforces Denis Laubscher's age-old advice: "If in doubt, drop the core tray to see how the rock mass behaves." It should also be

recognised that core photos and logging should take place at the drill rig to allow the freshest, least disturbed, and most representative sample to be recorded, before any further disturbance or damage due to transport may result in misclassification.

Figure 6   **Example of residual half cut core (illustrating the generation of additional defects post-diamond saw cutting)**

4   Structural geology

The impact of understanding structural geology should not be underestimated. As in any underground mine, depending on the style and location of structural geology, this can impact the stability of major excavations, orientations of drives, cave initiation direction, cave propagation, and seismic propensity, once a significant volume of caving has been established.

Understanding structural geology is a journey, and the team needs to be aware from an early stage to collect data from all core logging so that the structural setting can be pieced together to inform mine design, production sequencing, and numerical and flow modelling. This has been graphically illustrated at Oyu Tolgoi where the understanding and impacts of structural geology have evolved over a number of years (Figure 7).
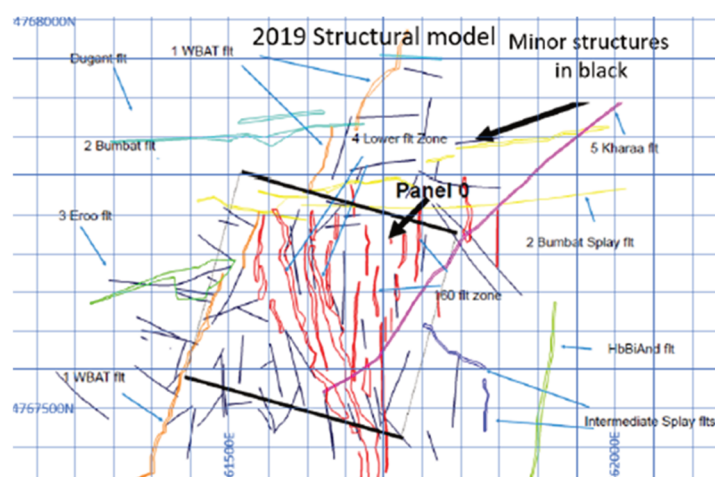

Figure 7   **Example of caving structural setting (AMC Consultants 2020)**

As with both surface and underground mining methods, the focus of drilling is always on the ore definition, and often it is only recognised later in the study sequence that there is inadequate knowledge of the surrounding rock mass/waste. When this is identified by smaller operators, then the inevitable tension is:

"Do we need to spend this money outside of the orebody?" In establishing a mass mining method such as a block cave, the cave volume can impact the external rock mass, creating changes that can trigger strike-slip events in adjacent structures. These types of structural features can become active at very inconvenient times during the production phase, so advance drilling and seismic monitoring once in production need to be used to inform an advanced understanding of the structural setting.

5   Raisebore holes

All underground mines require raisebore holes for ventilation, in particular. Given the large mining area, ventilation requirements for caving projects are substantial and hence a large number of raise bores are typically required.

The establishment of the required raise bores is becoming increasingly challenging due to weaker ground conditions and the required diameter and depth of holes. It is critical that a geotechnical hole is bored in reasonable proximity to the proposed alignment of the raisebore, so that adequate data can be obtained to conduct a stability assessment.

Figure 8 illustrates an example of a post-mortem analysis after a raisebore failure. The raise was pulled at a 5 m diameter and failed in the lower section. A subsequent 'blind' analysis demonstrated that the stability analysis had overestimated stability and had been a key contributing factor to the hole failure.
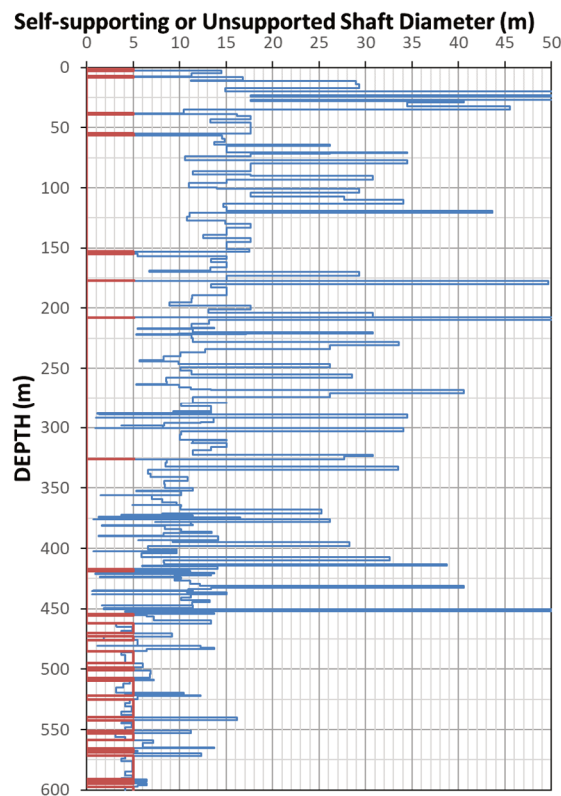

Figure 8   Example of a raisebore stability assessment (SRK Consulting 2019)

6   Feast or famine – water

Water management for many existing operations and new projects is becoming increasingly challenging. Water supply in some jurisdictions is becoming scarcer due to regulator restrictions, driven in part by negative social impacts or just poor local supply. On the flip side is an excess of water that some operations and projects must deal with, whether excess groundwater or high rainfall events. Climate change is creating another layer of complexity around this aspect and making it more challenging to provide defensible rainfall estimates.

Projects that generate a positive water balance often then have a water discharge challenge, an area that is increasingly under regulatory scrutiny for both quantity and quality of discharge.

In assessing potential underground caving projects, understanding the hydrological and hydrogeological setting is critical. This understanding will inform the required pumping capacity, water management strategy and draw/inrush management, particularly if the new mine is in a high rainfall area.

Gathering adequate hydrological and hydrogeological data can be time consuming, and can be the longest lead time for projects as measurements need to be undertaken, often over years, to establish the baseline setting. These baseline settings are required to inform studies and to allow for inputs for permitting applications within project timelines. Hydrogeological data and understanding often seems to be neglected, but is a very important requirement. Some underground projects have only been discovering their true hydrogeological settings to their detriment during development.

7   Modelling

As in a number of aspects of mining these days, modelling is used to better understand operational dynamics. Caving is no different; numerical modelling is used to critically investigate cave propagation, cave flow and excavation stability. Simulation modelling is also used for investigating a range of production planning scenarios involving mobile fleet requirements and production interruption issues.

George Box (Box 1979) famously stated that: "All models are wrong but some are useful," reinforced by an earlier statement (Box 1976) "Since all models are wrong the scientist must be alert to what is importantly wrong. It is inappropriate to be concerned about mice when there are tigers abroad."

As an example, and as illustrated in Figure 9, the flow dynamics in a caving rock mass are multiple and when overlaid with cave propagation dynamics, there are multiple modelling variables at play.
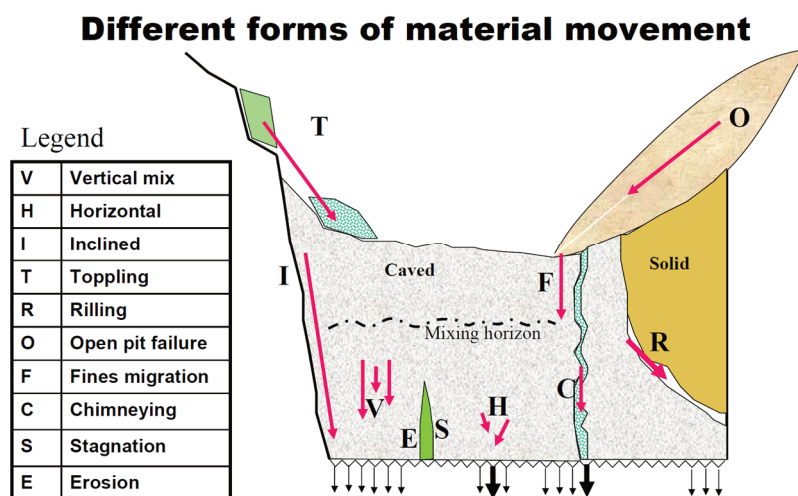

Figure 9   Cave mass flow systems (Diering 2007)

The accuracy of all predictions made using numerical modelling for rock mass is strictly limited by the natural variability of the geological materials coupled with considerable natural variability in the in situ pre-mining stress and rock lithology (Wiles 2005). It is not just a case of plugging in data and hitting 'run' (Cundall 2020). Modelling outcomes can give the impression of precision, particularly when impressive graphics are used. However, users are cautioned in inferring confidence of modelling outcomes for early-stage projects. The information needed to create a model is usually hard to obtain and a significant amount of time may be required to source an ideal set of adequate and suitable data (Cordova et al. 2020). Given the typical lack of adequate data in early-stage evaluations, modelling is best used for comparisons between various strategies. A relative understanding can then be provided on potential best options. It must be understood at an early stage that the quality of modelling outputs is only as good as the quality of inputs.

Predictions using a numerical model are limited to the natural variability of the rock mass and the poor understanding of the constitutive models that represent the rock mass behaviour. Complex material models require simplifying assumptions to be made about one or more parameters. Models must deal with geological materials that are non-uniform, heterogeneous and isotropic, resulting in stress, strength and other characteristics varying from point to point (Wiles 2005). Cundall highlights that it is crucial to understand mechanisms, and if the model is too complicated, mechanisms may be obscured.

Pretorius (Pretorius & Ngidi 2008) highlighted that modelling for Palabora was inaccurate and this led to an unanticipated failure in the north wall. This again reinforces the need for quality inputs to generate a reliable outcome.

Calibration of models ultimately helps – but – one needs actual data to do meaningful calibrations and that takes a number of years to generate. Only then can that data be used to perform calibration runs and develop a more reliable model. It should be noted that data for caving operations is often scarce, and typically absent, when it is realised it is needed. Investment in draw markers during the project phase of a cave is vital to enable access to high quality data during the caving and ore draw phases.

Wiles (Wiles 2005) highlights that back-analysis cannot guarantee unique solutions, but prediction reliability can be established by comparing results based on back-analysis of multiple predictions. Agreement in a few isolated cases, is at best anecdotal.

8   Open pit–underground transitions

With some surface mines reaching their economic limits, where the orebody is suitable, caving methods are being considered to continue economic extraction at depth. The lead time is a critical issue in most transitions. New caving project owners are particularly susceptible to grossly underestimating the time required to carry out a successful transition. The time required to source sufficient orebody knowledge, conduct adequate studies and develop an underground mine is typically at least a decade.

Intertwined with this is the ability of the open pit to deliver to the planned end of life. It is observed that underground development always takes longer than planned and hence an open pit will be required to keep operating beyond original expectations. This introduces the dilemma of just how much recoverable ore is there now at the bottom of the pit, and the ability to mine concurrently between surface and underground, particularly after a cave has been initiated. Contingency planning needs to be done to identify alternative ore sources, e.g scavenging higher up in the open pit or stockpiles that can provide a buffer of production continuity if underground initiation is late.

An observed key challenge is the orebody definition at depth, e.g. the mineral resource classification. In a number of instances, the quantity of acceptable classification (i.e. indicated category and above) has been challenging. This is not surprising given the historical focus on surface mining, but also demonstrates the lack of foresight at a high level of what it takes to plan ahead for mine life longevity.

If there is a meaningful orebody extension at depth, then advance planning needs to be done to source orebody knowledge from within existing open pit workings and scheduling to accommodate this.

A structural geology understanding is critical for surface-underground transitions where structurally induced mass failures can introduce large proportions of finer fragmented dilution into a cave. Mass failures in Palabora (Figure 10) and Bingham Canyon (Figure 11) clearly demonstrate that major structures went unidentified for many years, and in Palabora's instance, directly impacted an operating cave.

Figure 10   North wall failure (130 Mt), Palabora (Pretorius & Ngidi 2008)

Figure 11   Bingham Canyon open pit failure (Romero & Adams 2013)

An increasing number of existing (Grasberg, Palabora, Venetia and Argyle) and new open pit – underground transitions are located in regions of seasonally high rainfall. This introduces a particular risk of flooding of the underground workings during high rainfall events when connectivity has been made to surface. Caving connectivity to a large open pit is analogous to a 'bath without a plug' and creates a very large funnel leading to the cave volume. A careful assessment is required of climatic conditions, surface topography and the hydrogeology setting to inform how the water management risk will be addressed. Key design considerations are the flow management of the water underground, surge storage capacity, installed pumping capacity and water discharge specifications. Ginting et al. (2020) provide an excellent design evaluation and summary of how significant rainfall and groundwater and groundwater ingress is handled for a large-scale operation.

A transition to underground involves very different skill sets. These skill sets need to be developed, often for surface workers transitioning to the underground workforce, and also secured for specialist technical roles. The time frame to plan and achieve the required skills build-up should not be underestimated in terms of appropriate leadership for the process and developing and enacting a successful methodology.

9   Undercover deposits

A recent observation is that 'undercover' deposits are now being established, e.g. Carrapateena (OZ Minerals) and Ridgeway (Newcrest). Mineralisation is some 500 m below surface and the sedimentary sequence must first be mined through to establish access to the orebody at depth. These styles of deposit

are likely to become more frequent as exploration studies unfold, with a number of companies actively exploring for this style.

This style of deposit creates two key challenges; the need to do significant waste development to reach the top of the orebody, and careful design is required to be able to manage propagation through to surface and dilution when in production.

Sedimentary sequences can vary in quality and aquifers may also be present. This can impact ground support requirements and water intersection management. Both these issues will impact advance rates and the cost of development.

Project owners need to mitigate these risks by adequately characterising these sedimentary sequences so that access and propagation are not compromised during project implementation.

10   Development and production ramp-up

Development is the initial key in the door to create a future production platform. This key aspect reinforces the need to gather adequate orebody knowledge to confirm an ultimate production schedule. Development in any underground mine can be challenging at the best of times, but given the quantity of development required to establish a caving operation, this can involve a long gestation period.

Development delays are typically a result of poorer than expected ground conditions and unexpected water intersections, excluding the multitude of 'other' management related delays. A secondary issue can be created by inadequate labour skills and underestimating ramp-up times. Ideally, some form of development should be done as part of the exploration program to establish existing ground conditions. Feedback from this can then inform required ground support and consequent planned advance rates.

If there was one common denominator observed across all aspirant cavers' management, it is the expectation to bring new caving mines into production in seemingly very short time periods. In some aspirant projects, this is most evidenced by production ramp-up rates.

Cuello and Newcombe (Cuello & Newcombe 2018) present recommended maximum extraction rates applicable during cave propagation for preconditioned volumes. These rates are typical industry norms and have been demonstrated to work in established caves. These are therefore a good industry guideline for new caving projects to reference.

Figure 12 illustrates actual ramp-up rates and one outlier aspirant caver with a rate that materially exceeds the ranges of well-established caving rates. Potential investors and lenders will pay particular attention to this benchmark when looking at new projects, and the obvious question will be how such an extreme rate is possible compared to actual rates achieved by experienced caving operations.
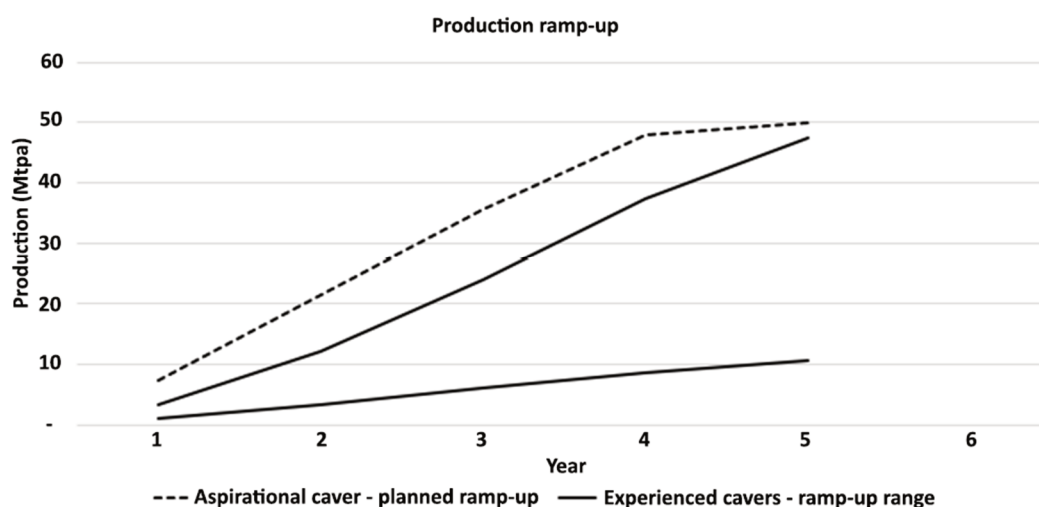

Figure 12   Global caving ramp-up rates

11 Construction quality

Developing and constructing a cave mine requires a 'civil standard' of quality which can be a paradigm shift from typical underground development and construction, particularly the logistics of achieving this. Underground construction of this nature requires multiple components, all in a confined space, and very careful analysis to set the construction plan up for success. Given the cost pressures, this civil standard aspect is often challenged by new caving project owners; "Do we really need to spend this much?" The answer can be framed around the functional intent of an extraction level – to set the project up as a 'rock factory'. Appropriate ground support and civil standard QAQC are required to enable the uninterrupted high cash flow ore production scenarios typically envisaged in the feasibility studies that justify investment in the project.

Firstly, adequate orebody knowledge is required to inform the level of ground support required. This reinforces the need to gather adequate orebody knowledge so that advance rates and ground support can be defensibly determined.

Industry experience demonstrates that where ground support is skimped on, it becomes an issue of 'short-term gain, for long-term pain'. The caving environment is dynamic, and particularly so with weaker rock masses where mining-induced stresses can start to unravel tunnels. This can then generate extensive rehabilitation requirements resulting in increased costs and significant production interruption.

12 Caving is rules-based

In comparison to many other mining methods, caving is very much a rules-based method. This commences with design and escalates through to operations. Examples through the value chain are:

- Design philosophies: Good cave operators lay out a hierarchy of design philosophies, i.e. the sequence in which design aspects are addressed and which take precedence over other aspects.

- Design hierarchies: This can be extremely challenging to achieve in the ideal fashion to meet all the required success factors. A classic example is how to deal with structures, e.g. dykes and faults. The ideal drive and undercut orientation may be perpendicular to these features, but this may not align with the ideal sequencing to maximise project value.

- Development compliance to plan: Development activities are a critical part of the journey to production and need to be completed in the required sequence leading up to cave initiation. The sequence will have been designed to align with the draw strategy which in turn will underpin cave propagation. Hence it is critical that compliance to plan is managed from the outset.

- Cave initiation: Cave development inevitably runs late, which leads to ramp-up challenges, as previously discussed. In the haste to generate revenue, there is a risk that well thought out strategies can be put aside, and short cuts may be condoned, for cave initiation and ongoing propagation, which while potentially giving immediate benefit, may cause serious challenges later in the cave life.

- Cave operation: The industry term of 'rock factory' implies a consistent operation, and this is what good cave operators strive for. To achieve consistency requires a well thought out draw strategy; one that while maximising revenue, also works with the rock mass such that ongoing sustainable caving can be achieved.

13 The enemy within

As evidenced at the outset of this paper, project owners are at risk of being their own worst enemies. It is recognised that there can be enormous tension between funding availability and a desire to increase the share price. This can play out in directing teams to produce over-adventurous estimates across the spectrum of development advance rates, production ramp-up and costs.

One of the enormous benefits of the caving industry is that there is now a wealth of information from existing caving operators sharing their experience. This is of benefit to the industry, and new caving projects can leverage this information to help set their projects up for success.

Flyvbjerg (2021) identifies a number of project management biases that can impact project development. Industry observations confirm a number of these biases are applicable to caving projects, namely:

- Strategic misrepresentation: Distorting or mis-stating information for strategic purposes, e.g. stating an Ore Reserve with inadequate geotechnical information.

- Optimism bias: Over-optimism about planned actions; overestimation of the frequency and size of positive events and under-estimation of the frequency and size of negative ones, e.g. forecasting an overly aggressive production ramp-up.

- Planning fallacy: The tendency to underestimate costs, schedule and risk, and overestimate benefits and opportunities.

During project development, a balance needs to be maintained across all study aspects to strive for a defensible outcome, that is within benchmarking expectations of actual achievements.

14   Conclusion

Cave mining is arguably the most complex mining method available to extract mineralisation, and experience to date continues to illustrate this. New discoveries need to be treated with respect when investigating caving methods, and an adequate sequence and content of workflow needs to be executed. The focus should be on building a defensible foundation that will support an adequate detailed design. If the focus is going to be solely on maximising share price at the expense of effectively and progressively de-risking a new project, then significant unintended consequences can take place.

Acknowledgement

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