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Integrated simulation and optimisation tools for production scheduling using finite element analysis caving geomechanics simulation coupled with 3D cellular automata

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Abstract

Key challenges integrating caving geomechanics simulation into mine planning processes start with the considerable effort to build realistic models and to map production schedules and cave back geometries into the simulation. Currently, calibrating parameters for the complex failure mechanisms that define the interface (cave back, possible airgap, muck pile) between solid and flow domain can be extremely time consuming. This also often requires a high level of expertise in modelling.

This work investigates the numerical efficiency of automated mesh and model building strategies and advantages of using high-performance computing on regular fine grids for non-linear finite element simulation. This allows direct mapping of cellular automaton results, and in return, predictions of rock mass failure without loss of accuracy at a higher frequency, maximising the use of information available from calibrated flow models for production scheduling. An important goal for such models must be the ability to simulate cave growth in complex geological settings and replicate realistic behaviour for relevant benchmark problems that reflect industry experience in block caving. These automated processes will not just accelerate the cave modelling processes and reduce manual processing time but also allow use of the full simulation cycle in case studies, sensitivity analysis and optimisation in an environment of uncertainty and constant changes to the available data.

Integrated simulation and optimisation tools significantly improve understanding of realistic geomechanics behaviour driven by the inherent characteristics of the rock mass and structural geological setting, by the extraction strategy and by other engineering decisions (interaction with underground infrastructure). This greater level of understanding reflects in key performance indicators related to safety, revenue maximisation (strategy on how best to exploit the mineral resource), and operation excellence (productivity).

Keywords: *caving geomechanics, cellular automata, finite element analysis, simulation, optimisation*

1 Introduction

A keynote paper (Dunstan 2016) at the 7th International Conference and Exhibition on Mass Mining (MassMin 2016) described one of the key challenges of mine planning for the Ridgeway gold mine, Newcrest Mining Limited, as:

> *"… however we're also fortunate that we had a mine-scale structure (North Fault) to assist us with cave propagation, and the cave propagated to surface in less than half the predicted time." (Dunstan 2016)*

The work presented in this paper aims to address aspects of uncertainty related to caving geomechanics that can be addressed by integrating geomechanics simulation directly into the mine planning process.

1.1 The integrated simulation challenge

1.1.1 Geomechanics modelling for block caving studies

Over the last decade or longer, a number of studies for block caving projects at pre-feasibility study and detailed feasibility study level incorporating significant efforts in advanced geomechanics modelling have been executed globally. In Australia, studies such as Perseverance Deeps BHP Nickel West (Arndt 2009, Beck et al. 2006), Argyle Diamonds Rio Tinto Group (Arndt et al. 2007), and Ridgeway Deeps Newcrest Mining Limited (Lachenicht 2011) equally relied on numerical modelling results using the software Abaqus (Dassault Systèmes 2018a) and caused the technology to provide three-dimensional geomechanics models to advance in problem size, performance and quality of calibration.

In these studies, the workflow was typically driven by the study level progression (stage gate approach) defining the scope, budget, timeframe and dataset (orebody knowledge) and the constraints arising from this approach will be addressed further below. In many cases, continuous involvement over many years allowed insight into the project beyond the written scope and enabled communication across disciplines, often supported by a culture of ongoing involvement of key external specialists or caving experts. Occasionally, competing consultancies would have been tasked with the same scope to compare alternative modelling methods, underlying assumptions and different software. Overall, this engagement model delivered significant results and proved successful for a number of flagship cave mining projects now operating, and many case studies have been published at the regular series of caving conferences.

1.1.2 The problem statement

Recurrent comments regarding improvements to the workflow for geomechanics modelling, based on the authors' experiences, can be summarised as:

- Limited understanding outside the group of expert users about the modelling process.
- Lack of transparency and confidence regarding model assumptions and limitations.
- Turnover time for modelling projects and time criticality of results for decision making.
- Lack of flexibility in response to deviation (new data, change of plan, production ramp-up).
- Integrating geotechnical constraints when optimising net present value (NPV).

The case for integrated simulation and optimisation tools should be reflected in contributing to business key performance indicators (KPIs) related to safety, reducing financial risk, revenue maximisation (strategy on how best to exploit the mineral resource), and operation excellence (productivity).

1.2 Workflow and the stage gate (or study level) process

1.2.1 From concept to detailed design

Early-stage modelling of a block cave will often assume that cave propagation is not an issue, provided a reasonable hydraulic radius is achieved. In these situations, modelling a simulated cave with vertical sides, which cave readily, is a relatively simple process within the software PCBC (Dassault Systèmes 2018b). However, several recent caving operations have demonstrated that cave back propagation is far from vertical with corresponding impacts on the material which can be mined, which in turn impacts on the mineable reserves and economic performance of the caves.

The need to be able to simulate a non-vertical, or complex, cave back propagation is evident. However, as a project progresses from concept to detailed design, hundreds or sometimes thousands of production schedules will be run to evaluate various project sensitivities such as mining rate, development rate, metal prices or footprint sizes, mining sequence, different flow assumptions and so on. However, nearly every different run will generate a different cave back. In this context, the traditional approach of having mine planning engineers run schedules and geomechanics experts run a few finite element analyses has severe limitations in that the cave back might not match the right schedule or the right schedule may be wrong because of incorrect assumptions about the cave back and cave propagation.

This demonstrates that first, coupled modelling is very desirable and second, it needs to be efficient seeing as a large number of runs would typically be required to be completed.

1.2.2 The stage gate approach

In the conceptual phase, working with limited data and high uncertainty, initial parameters are set from financial analysis, geological modelling, and geotechnical input, among many other elements. Once the mining method selection is confirmed (gate), a more detailed analysis is performed. The full extent of this discussion is certainly outside the scope of this paper, but a number of key parameters iterated in the process give an indication of the complexity:

- Footprint and elevation.
- Drawpoint spacing, undercutting and drawpoint opening rate.
- Draw strategy, ramp-up and production schedule.
- Cave engineering and geotechnical risks.

Beyond the design phase and start of production, changing conditions, new data and external events can still require revision of adaptable parameters and provide new business KPIs. To draw analogies from other industries, the aerospace industry successfully transitioned from having regular 'design freeze' events, to ensure engineers would be working on the same model at a certain point (gate) in the development process, to having a 'digital twin', ensuring engineering efforts are all directed to the latest knowledge base.

1.2.3 Proposed workflow

The proposed workflow is to have an integrated coupled solution between a cellular automaton extraction and flow simulation with a finite element geomechanics simulation. PCBC's CA3D tool is used for the flow simulation and Abaqus is used for the finite element analysis. This should build on existing workflows defining a block model containing geological domains, their properties and a production schedule which defines the tonnage extraction from each drawpoint.

The aim for these automated processes is not just to accelerate the cave modelling processes and reduce manual processing time but also to allow use of the full simulation cycle in case studies, sensitivity analysis and optimisation in an environment of uncertainty and constant changes to the available data.

2 Modelling methodology

2.1 Caving geomechanics

2.1.1 The Duplancic model of caving

The conceptual model of caving (Duplancic 2001) is widely used in the mining industry to visualise the process of caving and the hand-drawn illustration has gained such recognition that reproduction here is not considered necessary. It defines five caving zones:

1. Caved zone.
2. Airgap.
3. Zone of loosening.
4. Seismogenic zone.
5. Pseudo-continuous domain.

In terms of a coupled model approach, the caved zone and airgap (1 and 2) are the domain of cellular automata, whereas the solid material (3–5) are the domain of finite element analysis.

This conceptual model suggests a continuous caving zone. Observations from recent experimental work on small-scale models for block caving operated in a centrifuge indicate that the cave propagation mechanisms might demonstrate more complex behaviours, such as fracture banding (Cumming-Potvin et al. 2016). This is an interesting aspect that relates to observations from the simulations presented in this paper, discussed in Section 4.

2.1.2 Modelling requirements

An important goal for geomechanical models for use in block caving operations must be the ability to simulate cave growth in complex geological settings and to replicate realistic behaviour for relevant benchmark problems that reflect industry experience in block caving. Key requirements suggested in this paper are:

- A three-dimensional representation of the problem geometry for the use in a numerical model. The level of discretisation is often measured in number of elements, or element size in the volume of interest, and linked to the number of degrees of freedom (DOF) directly relating to the computational effort.
- Mapping of geological and geotechnical data (block model) for property assignment such as Young's modulus and Poisson's ratio, density and available rock strength parameters (those for the constitutive model below and possible failure criteria to define material transitioning from the solid domain to the muck pile).
- In situ stress. Whilst the pre-mining stress is often considered as a uniform, linear, geostatic stress state defined by the weight of the overburden (lithostatic stress), a number of mechanisms can create more complex stress fields (Zoback 2007). Examples include the re-orientation of principal stresses along shear zones and areas of complex topography, such as mountain ranges. In these cases, an initial stress analysis is required to establish equilibrium.
- A constitutive model for non-linear analysis of rock materials that exhibits strain-softening behaviour and can quantify material failure to define the interface between solid and flow domain. This interface is the lower bound of the zone of loosening commonly described by the model after Duplancic (2001).
- A mapping algorithm to communicate the coupling of cellular automaton results from production scheduling to the geomechanics simulation, and in return predictions of rock mass failure according to above criteria to the flow domain. The coupling process is described further in Section 3.

2.1.3 Material movement in the caved zone

Modelling the flow inside the caved zone requires capturing different forms of material movement as illustrated in Figure 1.

Empirical mixing models in the PCBC software allow for vertical and horizontal mixing as well as fines migration down the draw column. The application of these simulation tools is directed at finding practical footprints within the constraints of mining costs and price forecasts. Production schedules are generated based on parameters such as total production rates, rate of commissioning of new drawpoints and cave drawdown scenarios.

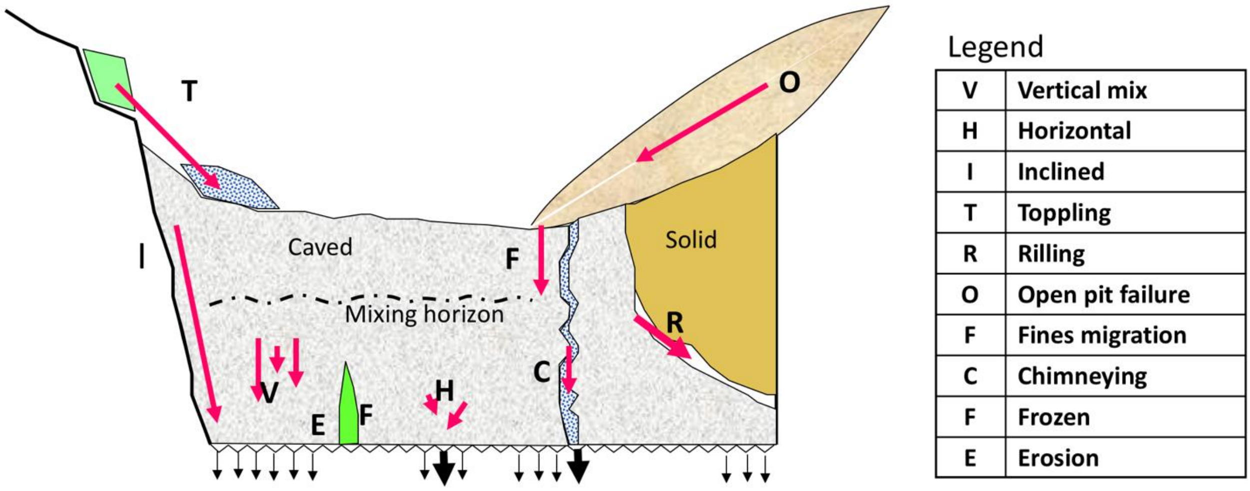


Figure 1 Different forms of material movement in a block cave scenario (Diering et al. 2010)

With most of the PCBC scheduling, the caved zone is modelled as a number of vertical columns above each drawpoint, referred to as a slice file. Material mixes between the slices as drawpoint extraction progresses. The most widely used mixing model in PCBC is referred to as template mixing (Diering 2007). The geometry of the slices in the slice file do not readily lend themselves to an interface to a finite element mesh. An alternative flow model within PCBC has been available for several years which uses a cellular automaton approach and a corresponding discretisation into cells or markers which corresponds directly with the geological block model and can accordingly be mapped effectively to the finite element mesh.

One of the limitations regarding the boundary conditions of this domain lies in the assumption that no forces are transferred onto the caving zone from the continuous domain and vice versa. Except for where rilling occurs on a free surface, vertical flow is defined by the mixing parameters.

2.2 Constitutive models

2.2.1 Mohr–Coulomb criterion

The work presented here takes advantage of the in-built Mohr–Coulomb constitutive model (and flow rule) in Abaqus. This provides a linear failure envelope in the meridional plane of the stress space, with an optional tension cutoff. Hardening and softening is provided as a function of cohesion over plastic strain.

2.2.2 Generalised Hoek–Brown criterion

The Hoek–Brown model provides a non-linear, empirical failure criterion and is widely used for underground excavations. Parameter estimation can be based on uniaxial compressive strength and rock mass classification to estimate parameters in the absence of triaxial testing. A number of proprietary implementations are coded with an extension to include an ubiquitous joint model. It is assumed that this approach would allow better calibration of realistic models and is planned for implementation at a later stage.

2.3 Computational efficiency

2.3.1 Model generation

The main motivation of this work is to allow for a fully automated, robust modelling process. This poses a number of challenges compared to the traditional workflow to generate a finite element analysis (FEA) model. The most efficient way to achieve such goal is to use a regular discretisation across the complete volume. The considerable advantage of a regular grid in a fully automated procedure is that the cost of model refinement is purely measured in its impact on computing resources, and these seem to be still becoming available at an exponential rate over the coming years.

2.3.2 Explicit integration scheme and choice of elements

In FEA, an explicit integration scheme is very efficient for problems with large numbers of DOF. The explicit solver performs a forward Euler integration using a central difference operator which is conditionally stable, based on the highest eigenvalue in the system. This can be conservatively estimated by the characteristic element dimension and effective, dilatational wave speed in the element.

Whereas tetrahedral meshing can lead to low element shape factors and high aspect ratios, significantly reducing the characteristic element length, cube-shaped elements provide the maximum possible time increment. A regular mesh of cube-shaped elements has the highest numerical efficiency for the resolution or discretisation of the mesh. The Abaqus element library provides three-dimensional brick elements with reduced integration of type C3D8R for use with the explicit integration scheme.

2.3.3 Mass scaling

The explicit integration scheme allows to accelerate solution processes by a technique called mass scaling. This increases the stable time increment by increasing the mass (density) of the element, therefore reducing the dilatational wave speed. This can be efficient in a mesh containing small numbers of very small elements as the overall mass change of the model can be neglected for time step increases up to several magnitudes though careful consideration of energy balances, and checks for inertia effects are required to ensure a quasi-static solution. Mass scaling is not required for the approach using a uniform size brick element mesh. The stable time increment will already be magnitudes larger and the critical element length is approximately constant throughout the mesh volume.

3 Coupling

3.1 Process automation

The approach to use a regular grid simplifies processing the PCBC model to provide the definition of the model domain significantly. A Python script performs the tasks in the following list and writes an analysis file.

1. A finite element mesh is created with properties and rock types taken from the block model.
2. Additional elements provide the volume allowing for far field deformation with parameters defining the size, number and bias.
3. Boundary conditions are defined for the outside faces of the model volume.
4. The analysis set-up is completed, defining the initial conditions for the stress.
5. The first analysis step is defined to check the equilibrium in the model.

An example of the finite element model for a test project, as described in the next section, is shown in Figure 2. The coloured layers relate to the rock types defined in the PCBC model, and standing out from the cut section is the ore volume. The drawpoints in the PCBC model are located at the bottom of this ore volume. Note that this small project has boundary conditions very close to the orebody to facilitate testing. A larger domain and a lower bias for the mesh gradient are usually recommended.

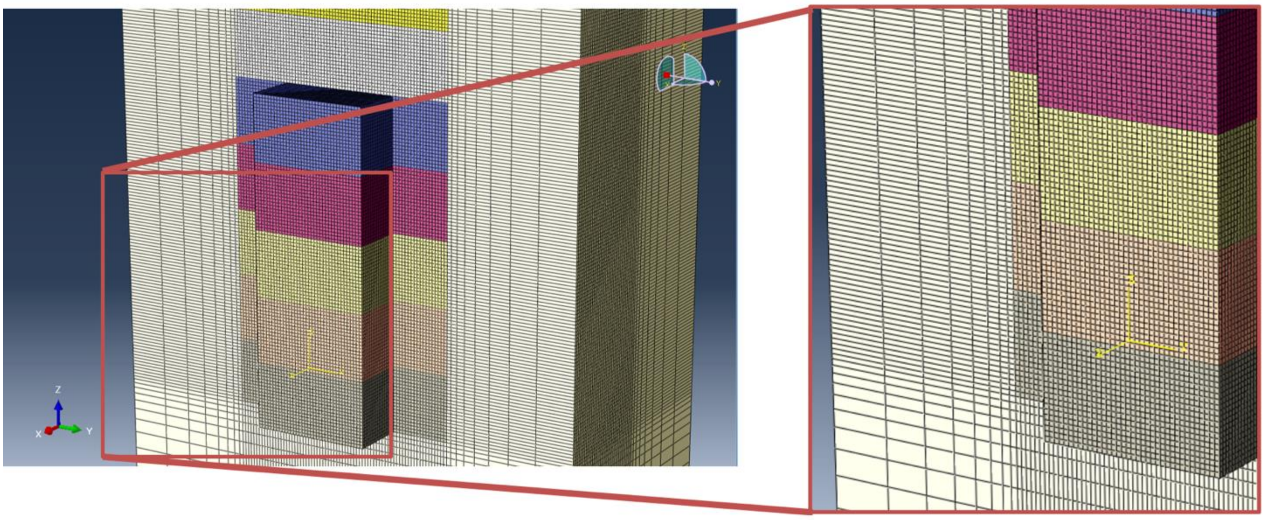


Figure 2 Finite element mesh for a test project with properties and rock types taken from the block model

3.2 Information exchange between codes

The use of identical regular fine grids both for the flow simulation (PCBC) and the non-linear finite element simulation (Abaqus) allows direct mapping both ways without any smoothing or loss of accuracy, making it suitable for coupling the two solvers at a high frequency, such as weekly intervals. This aims at maximising the quality of information available from the calibrated flow models for production scheduling and subsequent optimisation.

To demonstrate the logic of the process, one-way mapping from PCBC to Abaqus is shown in Figure 3. The caved zone is provided as a list of cells (column, row, level) from PCBC and the corresponding cells in Abaqus are set to have 'soft' properties for the caved zone (the weight of the muck pile still applies, leading to a hydrostatic stress distribution inside). Another list of cells representing the airgap are set to be stress-free in the simulation. In this small model with soft material, the damage zone that would be available for caving for this step is shown as the blue iso-surface. Therefore, cells outside this damage envelope should not be available to move in PCBC, or 'frozen'. These are shown purple in the stack of cells. As Figure 3 only shows one-way mapping, all cells can move in PCBC and no airgap can evolve in this example.

To close the coupling loop, the information about the damage envelope, which can be based on any number criteria to be defined, needs to feed back into the caving flow simulation. Both codes advance at the same time interval (weekly in this example) for each step.

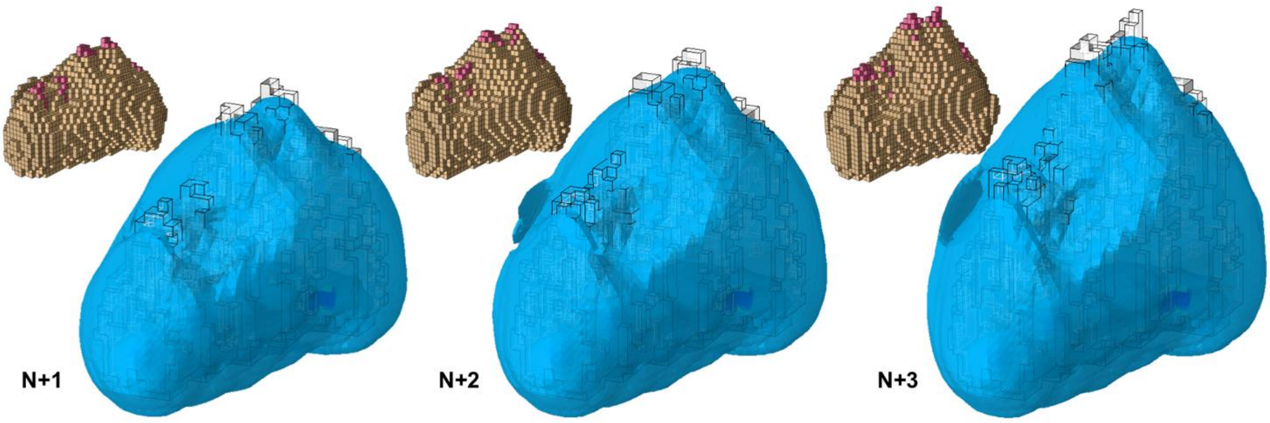


Figure 3 Mapping the PCBC cave zone into the Abaqus model (brown/white), and the damage envelope (blue) showing the required coupling effect for information flowing back into PCBC

3.3 Prototype testing

3.3.1 Test project

For the development of this software integration, a small-scale test project was established. It was chosen to be relatively small for ease of set-up and to limit run times, but large enough to be realistic and comparable in size to some smaller block cave operations. The test project consisted of 144 drawpoints made up of six rows of drawbells in a herringbone style layout with 12 bells in each row. Key details are shown in Table 1.

Table 1 Properties of the test project

Feature	Value
Number of drawpoints	144
Drawpoint spacing	15 × 15 m
Production rate	10,000 tpd
Production tonnes	21,000,000 t
Block model dimensions	200 levels × 72 rows × 72 columns
Block size	5 × 5 × 5m
Scheduling periods	Weekly
Drawpoint opening rate	2 drawpoints/week
Abaqus C3D8R Elements	1,641,728

The simulated mining sequence and resulting heights of draw (HOD) from one of the test runs are shown in Figure 4.

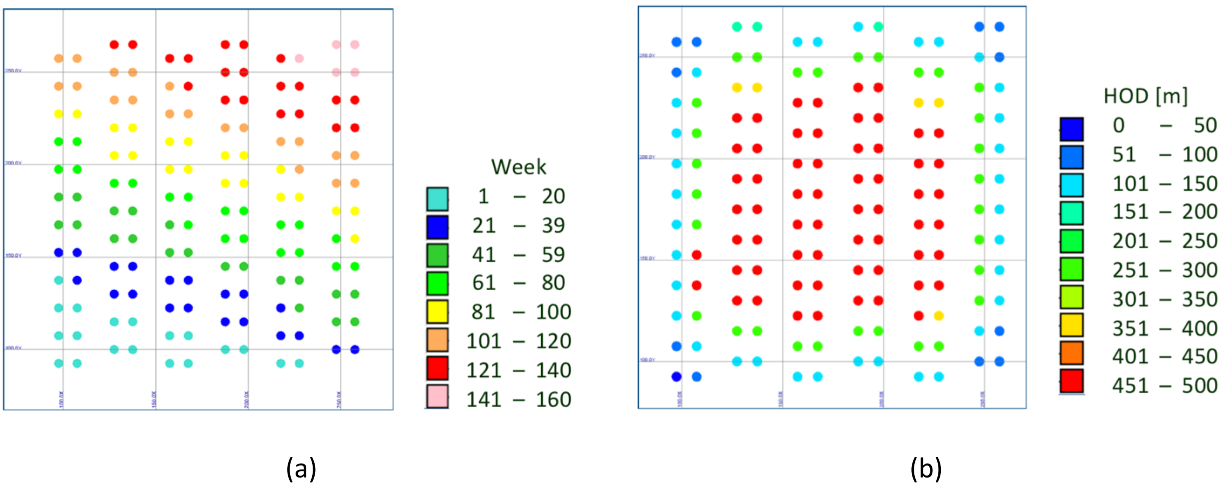


Figure 4 Footprint view of the drawpoint opening sequence; (a) Scheduled by week; and, (b) HOD, for the test problem

Despite the block model containing just above 1 M blocks, the requirement for the geomechanics analysis to allow for far field deformation results in 1.6 M elements in the Abaqus model. More than 90% of the analysis time is in the explicit solver, with wallclock time for the solver around 1 hr on a dual-Xeon workstation with 28 cores.

3.3.2 Benchmark cases

These cases were chosen so as to demonstrate the typical cave propagation or stall mechanisms which might be expected in a relatively small block cave layout. The six cases listed below are illustrated in Figure 5.

1. *Cave propagation.* The first benchmark aimed to simply demonstrate that the coupling mechanism was working and that, for appropriate rock strength parameters, a reasonable cave propagation would be observed.
2. *Inclined fault.* This option was chosen to demonstrate the impact of a geotechnical feature on the initial model, with fault strength aimed at contributing a small, but identifiable effect.
3. *Overhanging domain.* This case is similar to the fault option above, with the material above the inclined contact set to be more competent and less prone to caving (larger hydraulic radius). Continued drawdown should enable the cave to propagate across the interface eventually.
4. *Spill scenario.* This is a common and important problem in many caving situations and getting to be more common with the advent of macro block cave mines. It looks at how the cave might propagate up within a new mining block adjacent to a previously mined block and how material might spill from the older cave zone into the newer mining area.
5. *Multi-lift.* This is also a common situation. It looks at how mining a second lift might interact with a previously mined first lift, provided sufficient damage connects the underlying lift.
6. *Preconditioning.* This option starts to explore how preconditioning the rock mass can be used as a strategic or tactical measure to achieve production targets. One example is the extensive hydraulic fracturing (HF) campaign documented in Lett et al. (2016) and Lowther et al. (2016). For the specific challenges for the use of HF in mining, see also Preisig et al. (2015).

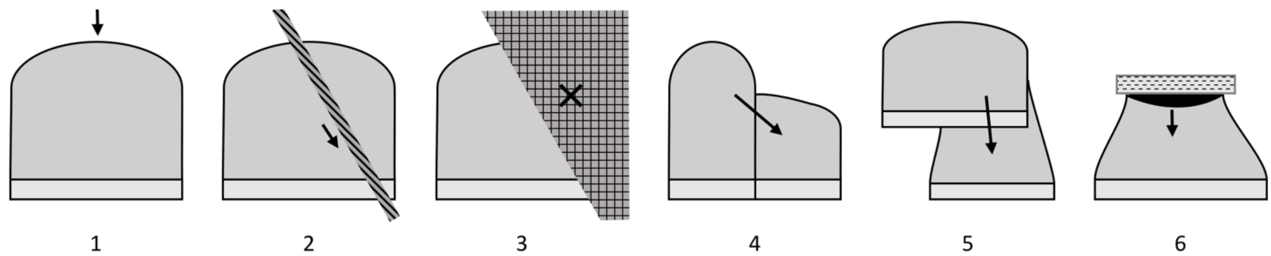


Figure 5 Benchmark cases evaluating key behaviours using the test project

4 Results

4.1 Overview

More than 50 fully coupled simulations were performed in the development phase of this project. Next to the choice of strength parameters, the combination of production rate and ramp-up together with the assumed swell factor was identified as a key parameter to design the benchmark cases.

4.2 Benchmark cases

4.2.1 Coupled cave propagation

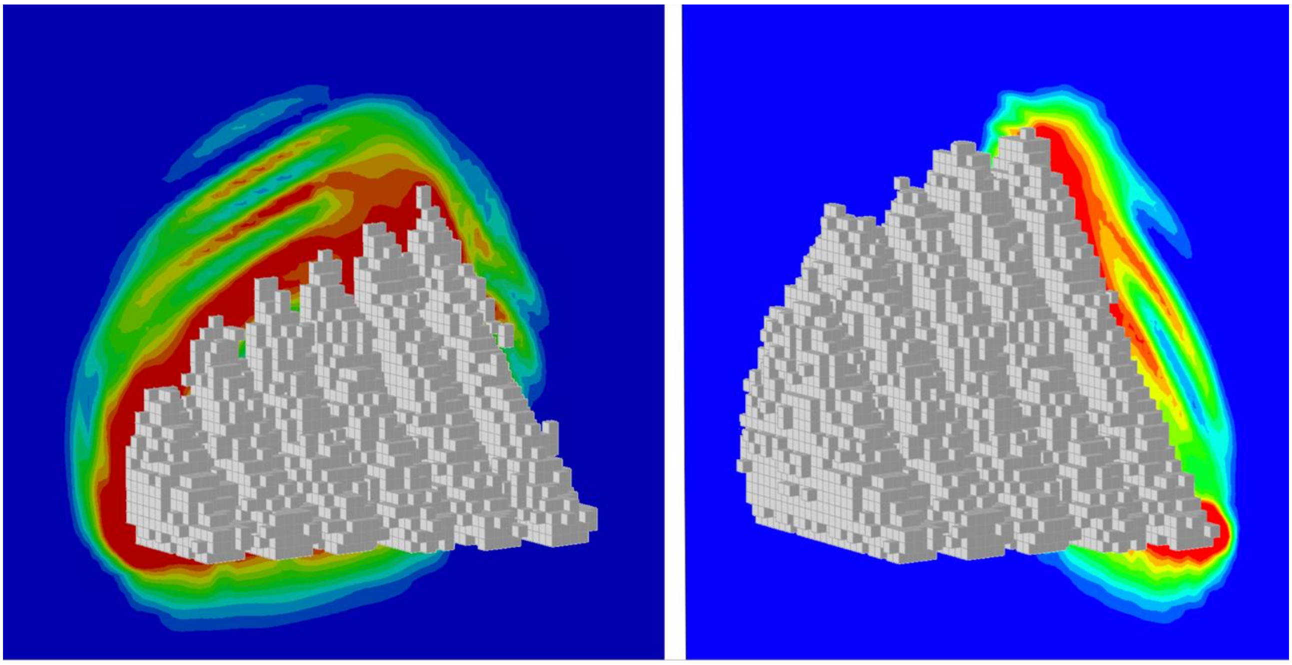
The base case of coupled cave propagation model was performed to ensure data exchange between PCBC and Abaqus could be verified.

An interesting observation from these models was the occurrence of shear zones, or ‘fracture banding’, where plastic strains are localising in advance of the caving zone. The underlying mechanisms appear to confirm observations in experiments performed on small-scale physical models in a centrifuge (Cumming-Potvin et al. 2016).

The authors assume that a combination of three model attributes allows the formation of these shear bands in the simulation:

1. The strain softening constitutive model with a brittle behaviour of the rock mass, where a 90% reduction of the cohesion in the Mohr–Coulomb parameters occurs over the first 2% plastic strain.
2. The discretisation using a very fine, regular mesh (5 m element edge length), providing the spatial resolution to allow shear bands to form and the propagation of these bands through the volume.
3. A homogenous material (single domain) throughout the test project volume defining this base case scenario combined with a geostatic stress field (linear with depth).

The appearance of fracture banding is shown in Figure 6.



(a) (b)

Figure 6 (a) Long section; and, (b) Short section perspective views of fracture banding for a selected frame in a coupled caving simulation (contour plot of plastic strain on a scale 0–5%)

4.2.2 Fault

A fault overhanging the approaching cave will lead to activation of the fault (shear deformation, slip) and the stress changes will affect the damage evolution in advance of the cave, whilst shielding the material above for a period of time. Once the cave has propagated far enough, deformation breaks through the fault and propagation behaviour shows similarity to the model without a fault (Figure 7).

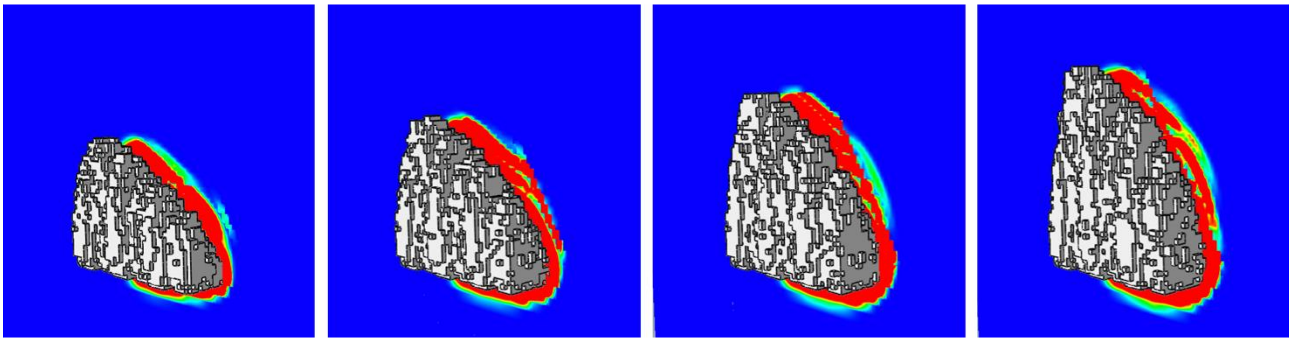


Figure 7 Four steps showing interaction between cave and fault (contour plot of plastic strain on a scale 0–2.5%)

4.2.3 Overhanging domain

The high rate of production and low swell factor leading to fast cave propagation in soft material is probably not a realistic scenario, although observations of cave zones and airgaps following inclined contacts have been mentioned in the industry. In this model, the cave zone and airgap initially follow the contact confined to the weaker domain. Eventually the damage in the overhanging stronger rock develops and cave growth becomes vertical. A late stage of the model is compared to the base case (propagation scenario) for the same draw strategy (Figure 8).

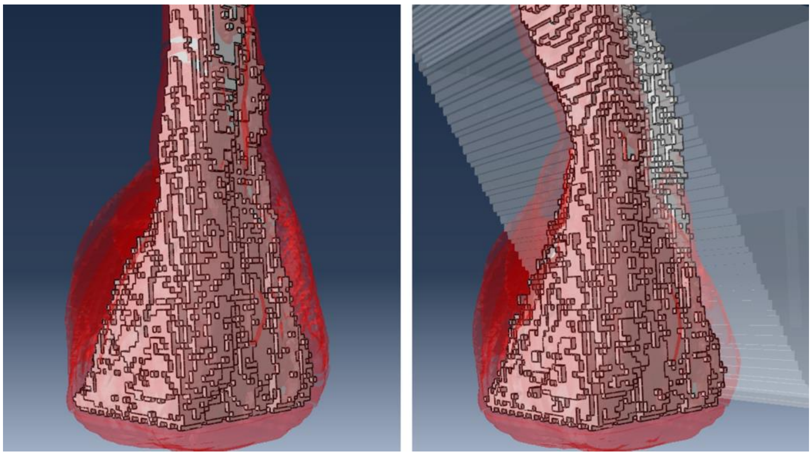


Figure 8 Comparison of base case (propagation) and overhanging domain, with the grey cells showing the cave zone from PCBC and the red iso-surface representing the damage criterion in Abaqus (plastic strain)

4.2.4 Spill scenario

The test project was successfully run for this scenario. It became apparent in testing whilst investigating horizontal movement from a first mining block to an adjacent second block that only minor horizontal mixing between columns occurred. The consideration of spill from the older cave zone into the newer mining area might require an airgap and rilling to be more prominent. Further study of this scenario is planned.

4.2.5 Multi-lift

After establishment of a small footprint block cave (half the footprint of the test project was used) a second lift (second half of the footprint, translated below and re-sequenced) starts production. The damage zones, based on the coupling information from Abaqus and visible in Figure 9 by the material colour code replacing the light blue domain of 'frozen' CA3D cells, connect between both lifts, and lift one material (green) flows into the cave column below. Again, fracture banding can be observed in this model.

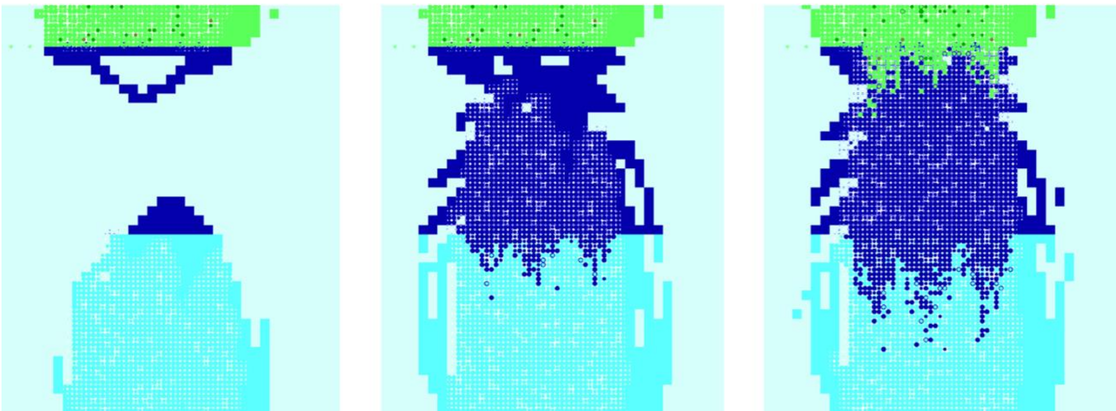


Figure 9 Three steps in the interaction between the 1st and 2nd lift from coupling as observed in the PCBC model

4.2.6 Preconditioning

In this scenario, the cave propagates towards an overlying horizontal layer of very high strength (such as an intrusive) with a height of 50 m resulting in the cave stalling and forming a prominent airgap. An assumed HF campaign is damaging this layer bottom-up, a single cell height (5 m) in each step. 30 m or six layers into the process, enough damage evolves for the remaining layers to fail, in an analogue to voussoir beam theory (Oliveira & Pells 2014), and the damage immediately extends to the volume above with material moving down into the airgap below as demonstrated in the sequence in Figure 10. In this figure, the CA3D domain shows 'frozen' cells in light blue and an airgap forming (empty cells) above the blue domain drawing down until material from above (green) is released due to failure of the sill. The bottom row shows the Abaqus domain; grey volume are cells mapped from CA3D muck pile and contours show plastic strain (failure criterion reached when red).

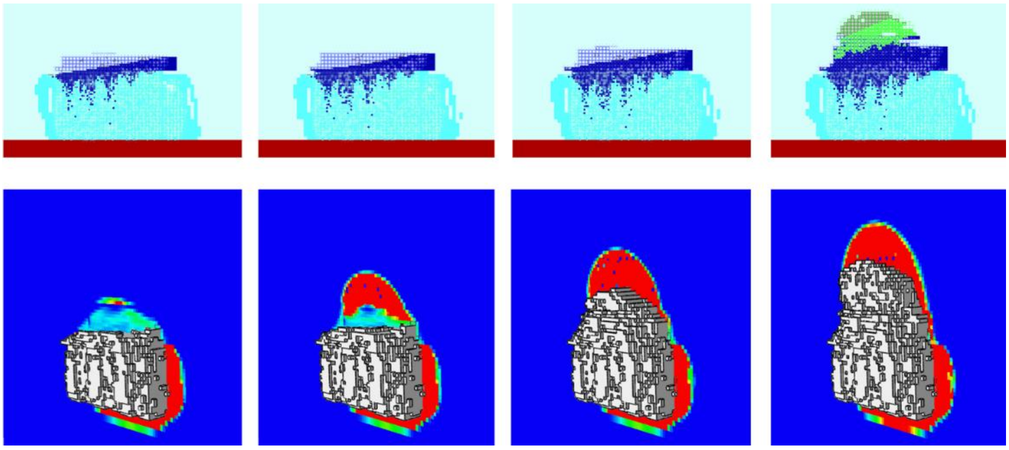


Figure 10 Four steps from the preconditioning benchmark (advancing left to right). The top row shows the CA3D domain, the bottom row shows the Abaqus results (plastic strain) in a section through the cave. The sequence shows an airgap forming until material from above is released due to failure of the sill

5 Conclusion

The work reported in this paper describes the coupling of PCBC (cellular automaton) with Abaqus (FEA). It has clearly demonstrated that a coupled solution is not only possible, but also realistic in terms of the ability to model real-world block cave operations within a reasonable time frame. Key achievements to date include:

1. The basic workflow will be compatible with well-established production scheduling and geotechnical modelling frameworks already established within the industry.
2. Industry-proven technologies (PCBC and Abaqus) are used as the key building blocks for the new coupled system.
3. The working environment makes use of high-powered computing technologies to improve turnaround times.
4. Several of the basic cave propagation mechanisms can be effectively modelled with this new approach.
5. The effective coupling algorithm should allow for higher spatial resolution as well as in the time domain element (step sizes).

As always, there is still further work to be done and the next steps in the process will focus on these areas:

- Further calibration of the model to actual mining operations as available.
- Improvements in performance.
- Improvements in the non-linear failure mechanisms to better model fractured rock masses.
- Application and forecasting of real mining projects.

The coupled PCBC/Abaqus system is well-positioned to become a mainstream tool for use by site-based mining and geotechnical engineers which will result in wider use of the technologies and improved mining designs. It is believed that the trend to be followed will be similar to the evolution process for geostatistical reserves modelling which used to be the domain of geostatistics experts or gurus but has now become a mainstream procedure used by mining and exploration companies.

The potential improvements to project valuations and reductions to mining risks for large block cave projects make this an excellent area for further study and research.

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