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Geological and historically based numerical assessment of seismic hazard in an evolving block cave mine

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Abstract

We developed a workflow to calibrate and forecast seismic hazard and its evolution, generated by seismic activity in known geological structures located next to an evolving block cave mine and corresponding mine-induced stresses. This approach is particularly relevant in caving mines with several mining sectors, where learnings from rock mass behaviour and the associated seismic response of the earlier blocks are used to characterise, back-analyse and forecast future blocks' seismic hazard, and can also be applicable to other types of underground mines. The methodology considers the geological/geotechnical characterisation of the geological structures such as continuity, planarity, roughness and other associated properties as observed in drillcore and mapping data. Together with observed seismicity, it allows for the ranking of structures by their potential to generate large seismic events. The methodology relies heavily on numerical modelling to track the changes of the stress field due to the cave evolution and its effects on the identified geological structures. The structures are modelled explicitly using interfaces to assess the slip potential and estimate the associated seismic source parameters. The geomechanical model is calibrated using the observed seismicity during previous cave development and then used to forecast (forward analysis) the maximum slip potential of currently seismically inactive structures due to stress evolution (and resulting unclamping) once future block caves are developed. Based on the estimated time-evolving maximum slip potential and associated seismic source parameters, site-specific ground motion prediction equations are used to forecast peak ground motion for critical infrastructure and other sites of interest, allowing an early assessment of seismic hazard based on the geological/geotechnical characteristics of the existing geological structures. The seismic hazard assessment is developed during the study/design stages, allowing for testing multiple scenarios and aiding in minimising the seismic hazard in areas of interest.

Keywords: *seismic hazard, numerical modelling, ranking of seismic structures, block caving*

1 Introduction

Assessment of mining-induced seismic hazard in underground hard rock mines is paramount for safety management and operational assurance. In block caving mines, seismic events with the potential to cause damage can be grouped into two families: events that are located near the footprint and excavations; and events that are located away from the cave and excavations, usually within waste rock. The first family has traditionally received more attention, and numerical modelling approaches are standardly used to minimise the generation of these events and mitigate seismic hazards by evaluating the most effective mining method and sequence (Carter et al. 2015). This paper focuses on the second family of seismic events and the associated seismic hazard, which are becoming more prominent in deep and large block cave mines (Carter et al. 2015). These events occur by sudden slip failure on existing geological features in the flanks of the cave at a distance from excavations (typically 50 to 350 m distance range), which are mobilised by the redistribution and rotation stress resultant from block cave mining. In our approach we use numerical modelling to estimate the slip potential of identified geological features, and geological and seismic data to calibrate and validate the numerical model. The calibrated model is then used to forecast the slip potential

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of the geological features during the study/design stages of new cave panels, permitting the testing of multiple scenarios. This multidisciplinary approach allows the integration of detailed knowledge from several fields to refine numerical models and constrain uncertainty in the seismic hazard forecast. In this paper we present a workflow we developed for the methodology and present results on how it is applied to an evolving block panel mine during the study/design stages of a new block.

2 Seismic hazard assessment workflow

We developed a workflow for seismic hazard assessment in a collaborative and multidisciplinary approach to integrate knowledge from geological, seismic and geotechnical fields, and bring physical-based considerations into the numerical modelling of seismic hazard. The workflow is separated into an initial model calibration and back-analysis phase, followed by a forward prediction phase. This approach is applied to the study of a new block cave panel at Cadia East mine in New South Wales, Australia. A diagram illustrating the workflow is shown in Figure 1. It relies on initial computationally intensive calculations of the stress field surrounding a block cave as it evolves and grows over time. The latest structural and rock mass models for Cadia East were used for the numerical modelling of the stress field. These models have been refined and well-calibrated using the historical interaction of the rock mass with cave growth and the development of two previous block cave panels. In the next step the evolution of the estimated stress field is used to assess the slip potential on geological structures over time, and to estimate the maximum magnitude and other seismic parameters of potential seismic events. The observed seismicity on the geological features is used to back-analyse and calibrate the model. The physical properties and dimensions of geological structures are integrated into the seismic hazard assessment by ranking the known geological structures in terms of capacity to generate damaging seismic events. Seismic data is used to confirm the geological considerations and calibrate the numerical model that corresponds to observed seismicity and measured cumulative parameters. The integration of seismological and geological data allows for the ranking and categorisation of types of geological structures in terms of seismic hazard. The integration and calibration of the numerical modelling data provides confidence in using the final model to forecast seismicity on identified hazardous geological features and determine maximum slip potential.

Once the model is calibrated it is used to forecast seismic and ground motion hazard for future block cave panels. Slip potential is modelled on the surface of high-ranking hazardous mapped geological structures. We selected the structures that have similar geological characteristics to the ones that ranked high on the back-analysis step, which are the ones that showed the capacity to generate large seismic events. This approach allows us to target the modelling to the important structures, eliminating structures that are not ranked as able to be seismically active, and saving computational time while eliminating fallacious seismic hazards.

From the forecasted slip potential of the geological structures over time, synthetic seismic catalogues are generated. These catalogues are used to track the evolution over time of the estimated probabilistic maximum magnitude event for each structure, and the corresponding estimated probabilistic peak ground motions at critical infrastructures and overall workings, which will inform/confirm ground support inputs and considerations. The peak ground motions are calculated from ground motion prediction equations (GMPE) specifically developed for Cadia East from recorded seismic data. Estimated peak ground motion and seismic hazard impact the mine design and the placement of important infrastructure. It will also lead to proactive measures in seismic hazard reduction, such as hydraulic preconditioning of modelled highly hazardous geological structures.

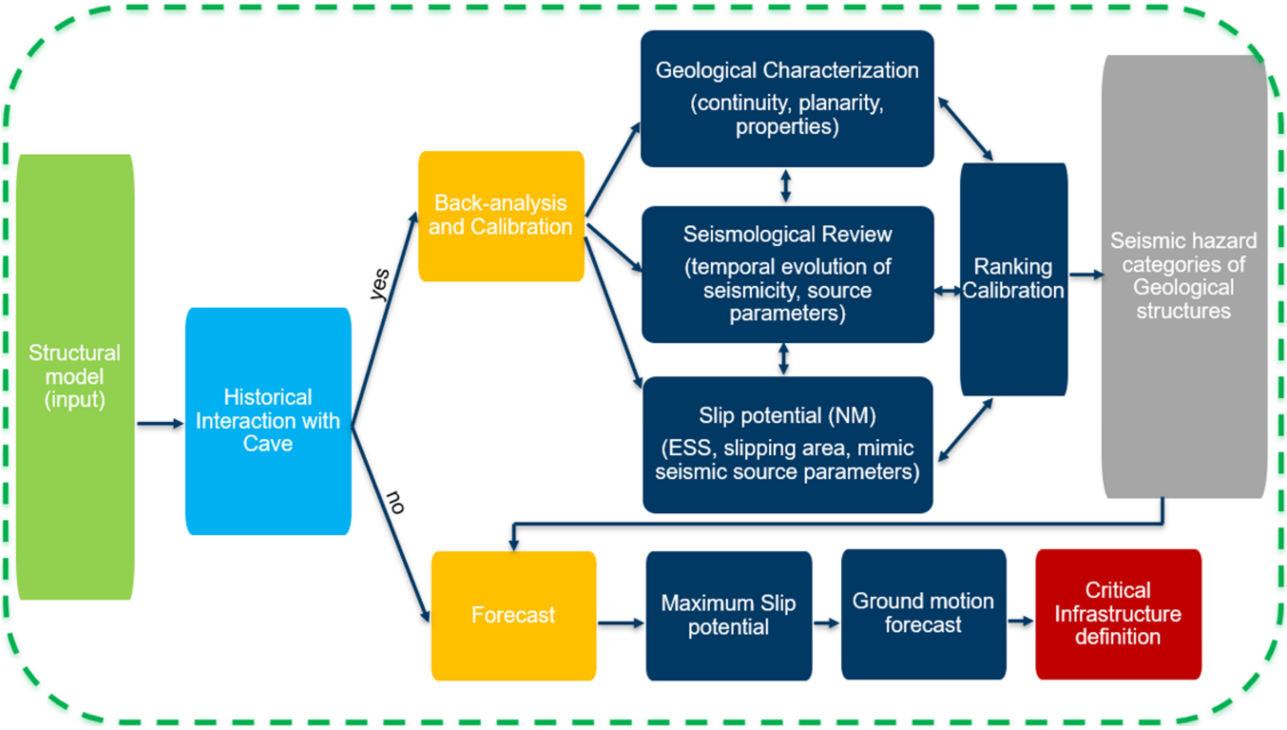


Figure 1 Schematics of seismic hazard assessment workflow

A wealth of information already exists from previously mined blocks at Cadia East mine on the characteristics of the geological structures and rock mass and their seismic behaviour, making this the ideal case on which to apply this methodology. A reduced workflow can also be applied to new block cave mines by incorporating geological data from cored data and adapting/adjusting expected seismic response from mines in similar rock mass and stress conditions, which will improve the seismic hazard forecast and aid in mine design decisions.

3 Seismic hazard ranking of structures based on physical characteristics

Mining-induced seismicity related to geological structures is a field that has gained a lot of attention, even predating the well-documented cases in deep gold and platinum mines in South Africa (Lawrence 1984; Ortlepp 1993; Dennison & van Aswegen 1993; Malovichko et al. 2012), where mining-induced seismicity was and still is a common occurrence. In deep caving operations mining-induced seismicity can lead to hazardous conditions and major business interruptions. Many large seismic events occur on geological structures and often within waste rock. It is generally accepted that for a large seismic event to occur on a geological structure, one or more of the following structural characteristics need to be met (Ortlepp 1992; Dennison & van Aswegen 1993):

- significant continuity
- smooth geometry
- discrete
- oriented appropriately to be activated by mining-induced stress changes
- appropriate structural and/or rock strength properties (e.g. contact type, infill, hardness, friction angle).

At Cadia East, seismicity has historically been associated with porphyry intrusions and major sericite-chlorite-clay (SCC) shears. More specifically, feldspar/pyroxene porphyry dykes in the waste rock have yielded the larger and more damaging seismic events. The spatially wider fractured zones, such as the calcite-laumontite

(Ca-La) fracture zones and carbonate (Carb) faults, are too materially soft to generate significant seismicity. Figure 2 shows the major Cadia East structural groups and their observed seismicity for local magnitude scale (ML) >2.0 events.

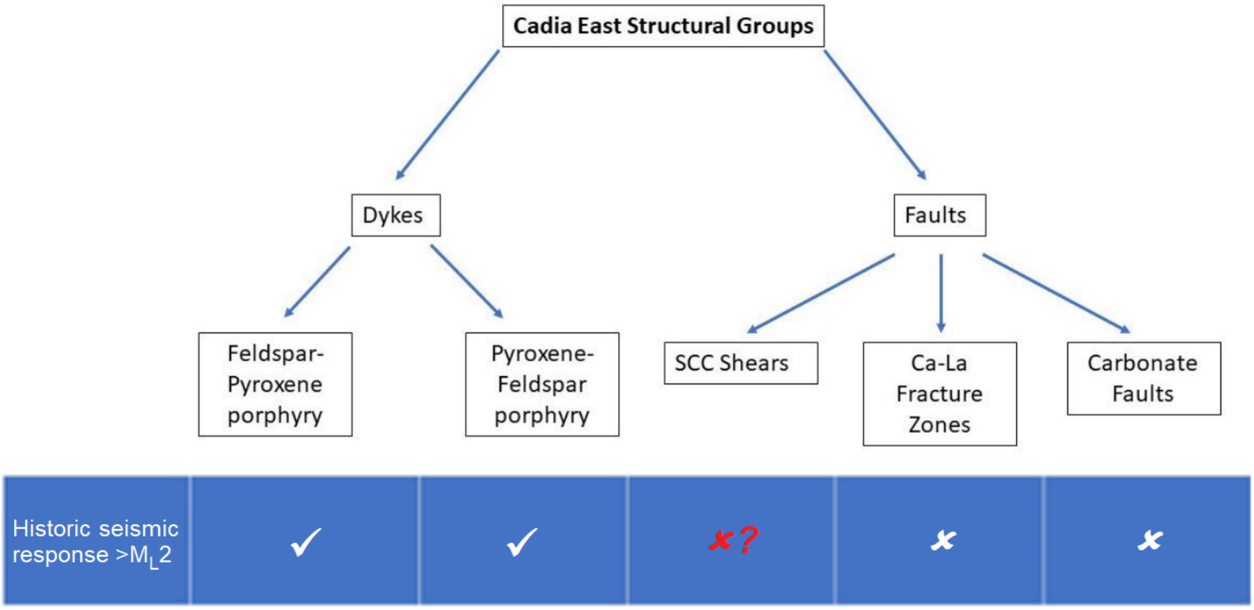


Figure 2 Cadia East structural groups and associated observed seismic response >ML2.0 (Tennant 2022)

Most modelled geological structures are represented as distinct and continuous features. At Cadia East, porphyry intrusions are represented as accurately as possible based on drillcore and mapping data. However, due to their inherent geometrical complexity, SCC shears are typically represented in the model as large continuous planes. In reality, SCC shears are anastomosing and discontinuous, hence the models tend to over-predict their seismic response. Figure 3 shows how these features appear in core and how they are represented in both reality and in the models.

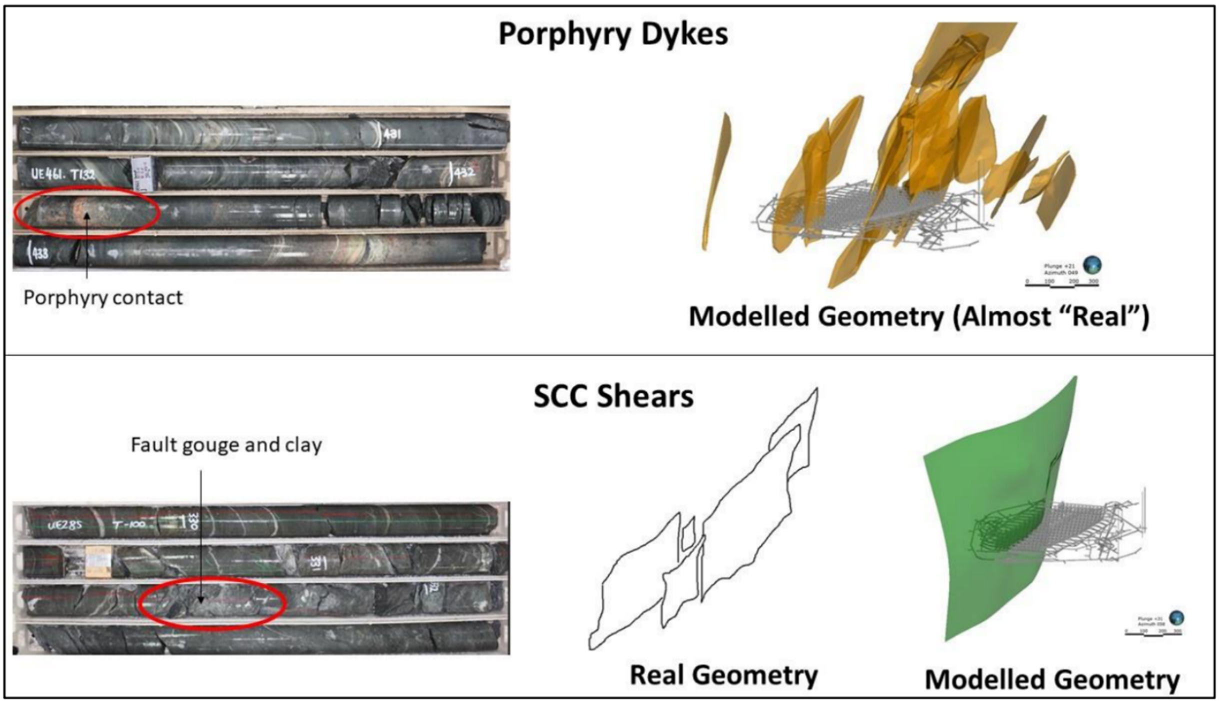


Figure 3 Core photos showing the geological features of porphyry intrusions and sericite-chlorite-clay shears and how they manifest in reality versus modelled geometry (Tennant 2022)

After interpretation and modelling, all structures are ranked to differentiate those which are more likely to present as a seismic hazard (Figure 4). This ranking is based on the structural characteristics required to generate larger seismic events, as highlighted in green in Figure 4. At Cadia East, some faults are continuous; however, they are not discrete, do not have a smooth geometry and are relatively weak, and are therefore more likely to behave in a ductile manner. Historically, larger seismic events have not been associated with faults that have these characteristics and as such, these structures are not seen as potential geological seismic hazards. Conversely, porphyry dykes satisfy all structural characteristics to be considered a potential seismic hazard, and these are highlighted in Figure 4 in red. An intimate knowledge of the geology and the structure of the mine is required to make these distinctions.

Structure Name	Comments	Historical Interaction with Cave (Yes/No)	Structural Characterisation			Proximity to Infrastructure 1-5	Preliminary Total
			Continuity 1-5	Planarity 1-5	Properties 1-5		
SSP	Intersects coveyor decline, Hydro-fractured	Yes	5	4	4	4	17
Freddy Dyke	Potentially longer than modelled to SW, 3.0 event	Yes	4	4	4	5	17
Porphyry 13	North of PC2 and PC2-3	No	4	4	4	4	16
Isa Dyke	Initial 2.7 of 14/4/2017 seismic incident	Yes	4	3	4	5	16
Roger Fault	SCC shear	Yes	5	3	3	4	15
Barry Dyke	Antithetic to SSP, not as active	Yes	4	4	3	3	14
Monzonite SE	Mostly below footprint	No	4	4	3	3	14
Monzonite W	Located in modelled high stress zone (NW corner)	No	4	4	3	3	14
Horace Fault	SCC	No	4	3	3	4	14
NSP	Likely several planes (dyke swarm)	Yes	4	4	4	2	14
Matthew Fault	SCC	No	5	2	3	4	14
Boris Fault	SCC	No	5	2	3	4	14
P2 Fault	En echelon array, anastomosing	No	5	2	3	4	14
Maurice Fault	En echelon array, anastomosing	No	5	2	3	4	14
Geoff Dyke	Active during proximal development, may extend to SW	No	2	3	4	5	14
Gibb Fault	Occasional seismicity, continuous	Yes	5	5	3	1	14
Carb 5 Fault	Higher stress than other carb faults	No	5	1	2	5	13
Porphyry 10	Will be claimed by cave	No	3	3	4	3	13
Victor Fault	SCC	No	4	2	3	4	13
Patrick Fault	SCC	No	4	2	3	4	13
Roger Fault	SCC	No	4	2	3	4	13
Quentin Fault	SCC	No	4	2	3	4	13
P1 Fault	En echelon array, anastomosing	No	4	2	3	4	13
Stephen (Northern Normal)	Dip-slip mechanism, properties unknown	Yes	4	3	4	2	13
Clarence Dyke	Offset by Barry and SSP	No	2	4	3	3	12

Figure 4 Subset of Cadia East's structural dataset detailing the relative ranking of each characteristic for each structure (Tennant 2022)

The determination of whether a structure is oriented adversely and likely to be activated by mining-induced stress changes or not is assessed by modelling the slip potential, which is discussed in Section 5. There are more than 50 mapped geological structures at Cadia East, and ranking the geological structures in terms of their capacity to generate large seismic events allows the prioritisation of important or potentially hazardous structures, eliminating structures that are not seismically active and saving computational time.

In the numerical modelling described in Section 5, the explicit interfaces of the geological structures are used for the estimation of the slip potential, which is calculated for their surfaces. When presented with a large database of individual fault/structural surfaces and volumes, modelling can give the unrealistic impression that too many structures have the potential to slip dynamically. Also, assigning large slip potential to structures that are physically unable to generate damaging seismic events despite their wireframe representation can give erroneous results.

4 Seismicity review

Cadia East mine has a rich seismicity catalogue containing seismic events recorded over the caving stages of the two existing block cave panels. The underground seismic system has been operating since September

2011 and predominantly uses triaxial 14 and 4.5 Hz geophones. The initial network system has been expanding over time with the development of new block cave panels, and with the necessity of monitoring greater regions surrounding the block caves. The current monitoring system uses more than 80 operating seismic sensors. In the Cadia East catalogue, seismic events are reported in both moment magnitude scale, MW (Hanks & Kanamori 1979), and an ML that uses contributions of both seismic moment and seismic energy and is assumed as equivalent to the generic ML. The Cadia East seismic catalogue has more than 288,000 events, 99% of which have MW ≤ 0.0 (ML ≤ –0.3 and [logarithm of seismic potency] log P ≤ –1.5). More than 37,000 events have moment tensor (MT) solutions, which started to be regularly processed in the mid-2015. For the purposes of this study we selected seismic events associated with specific geological structures. We are exclusively interested in events with fault slip mechanisms, mobilised by the redistribution and rotation of the stress field caused by the development and growth of the two cave panels. The dimensions of the selection box containing the events associated with each structure depend on the average event location uncertainty for the area. The distance of the selection box limit to the geological structure surface/wireframe increases as location uncertainty increases, within a range of 25 to 125 m, as appropriate. To ensure the events have a uniform distribution, a minimum cut-off magnitude of MW ≥ –1.0 was used, based on the sensitivity of the acquisition system for the areas of interest. MW ≥ –1.0 is equivalent to log P ≥ –3.0, and approximately equivalent to ML ≥ –1.5. Events associated with raisebores and development blasting, which have mechanisms with small percentages of double-couple components, were identified and removed from the selected events catalogue, using MT solutions, when available. For this project we gathered seismicity associated with nine geological features in which larger magnitude events have been recorded.

5 Modelling slip potential

The slip-potential numerical model (SPM) was constructed on top of the existing Cadia subsidence model (CSM) (Ghazivinian et al. 2020) and incorporates the identified seismic hazard-prone geological structures for evaluation of their slip potential. The base CSM was developed to study the impact of the undercut and draw strategy on the cave shape and subsidence, cave stresses during operation, cave initiation and airgap formation, and has been carefully calibrated to closely match fracture limits, mobilised zones and cave extent, based on field observations. The CSM model uses a FLAC3D-REBOP coupled approach where REBOP simulates the growth of flow zones and airgap as a function of draw and mass balance, and FLAC3D solves stresses due to the presence of flow zones and voids, and estimates yielded zones. Having as a base a fine-tuned and well-calibrated caving model gives us confidence that the rock mass properties are being well represented and the stress field is well modelled. The SPM model uses FLAC3D to solve slip potential and other associated seismic parameters on all the points of the selected geological structure's wireframes, which were built based on geological and seismic information. This assessment exclusively models fault-slip mechanisms, which are the mechanisms of the observed seismicity associated with these structures. Initial mapping of the slipping area used excess shear stress (ESS) > 0 Pa and assumed a cohesionless friction angle of 30° and a seismic efficiency of 10%. The SPM model calibration was achieved using to-date recorded seismicity associated with the individual geological structures, and solving for friction and cohesion angles associated with each individual structure; obtaining, in the end, differentiated properties for the two main groups of hazardous structures.

In the calibration process the log P generated on a specified geological structure is used, instead of moment or local magnitudes, to simplify model assumptions. Note that seismic potency is the slip area times the average slip, and the seismic moment is the seismic potency times the shear rigidity of the source rock. As such, and considering that moment magnitude is calculated from the logarithm of the seismic moment following Hanks & Kanamori (1979), moment magnitude is equal to 2/3 of log P plus a constant whose value depends on the shear rigidity of the source rock, and is roughly around 0.9 for volcanic rocks. Clustered elements of high potency in a structure wireframe will be associated with the location of larger magnitude events. In a first approximation we use the total log P in a time step to conservatively estimate the maximum magnitude of a synthetic event. Figure 5 shows an example of the calibration process in terms of the observed versus modelled cumulative log P generated on the Isa dyke (a porphyry intrusion where the largest event recorded at Cadia East occurred, in April 2017), as well as the spatial distribution of areas with log P ≥ –3 on the dyke surface and the associated observed seismicity for two time periods. We see an overall good agreement regarding total and evolving cumulative potency, and in terms of areas where slip occurs and seismic event locations.

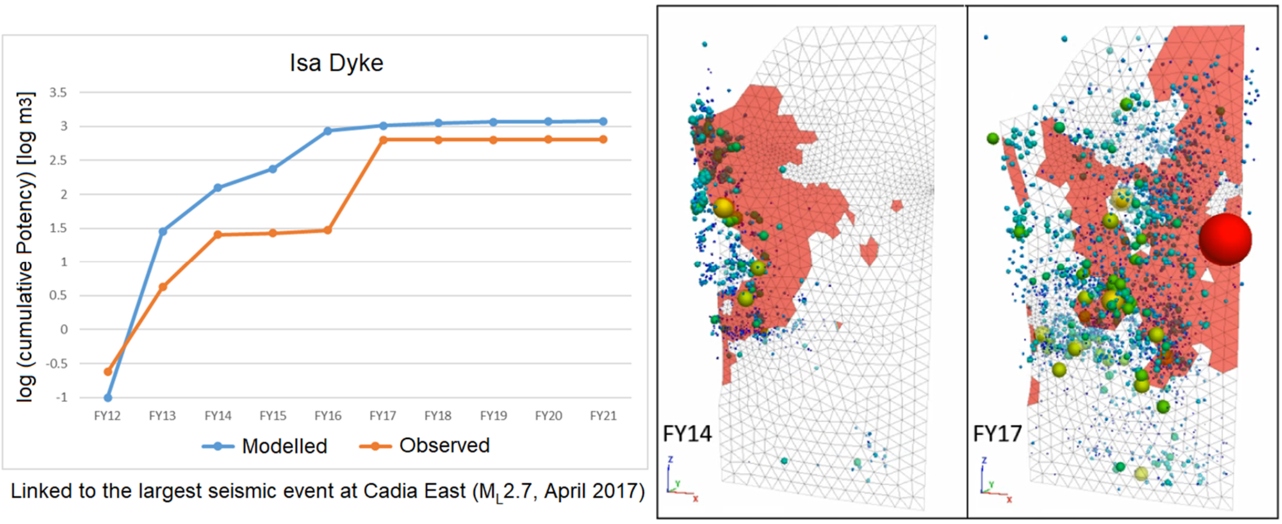


Figure 5 Example of model calibration for the Isa dyke from FY12 to FY21. This porphyry intrusion was linked to the largest seismic event at Cadia East, which occurred in April 2017. The graph on the left shows the modelled and observed log of the cumulative potency over time. Panels on the right show the dyke wireframe, areas with modelled log P ≥ –3 in red and observed seismicity (spheres scaled and coloured by local magnitude scale for two time periods

6 Seismic hazard forecast

Once the model is calibrated we use it to forecast seismic hazard for a future block cave panel. This phase is divided into three tasks consisting of forecasting the maximum slip potential of geological structures over time, generating a catalogue of synthetic events representative of the maximum slip potential, and forecasting peak ground motion on critical infrastructures and overall workings. During the new cave study period the estimated seismic hazard can impact the mine design and placement of important infrastructure and ground support requirements. It can also lead to proactive measures in seismic hazard reduction, such as hydraulic preconditioning of areas deemed hazardous.

6.1 Maximum slip potential

Following on from the model calibration described for the new block cave panel we forward model the seismic response of the porphyry intrusions (dykes) and SCC shears due to the establishment of the new block cave. The forecasted modelling results are shown in Figures 6 and 7 for the porphyry intrusions and SCC shears, respectively, as well as an example of the estimated slip areas on the structures for a time step.

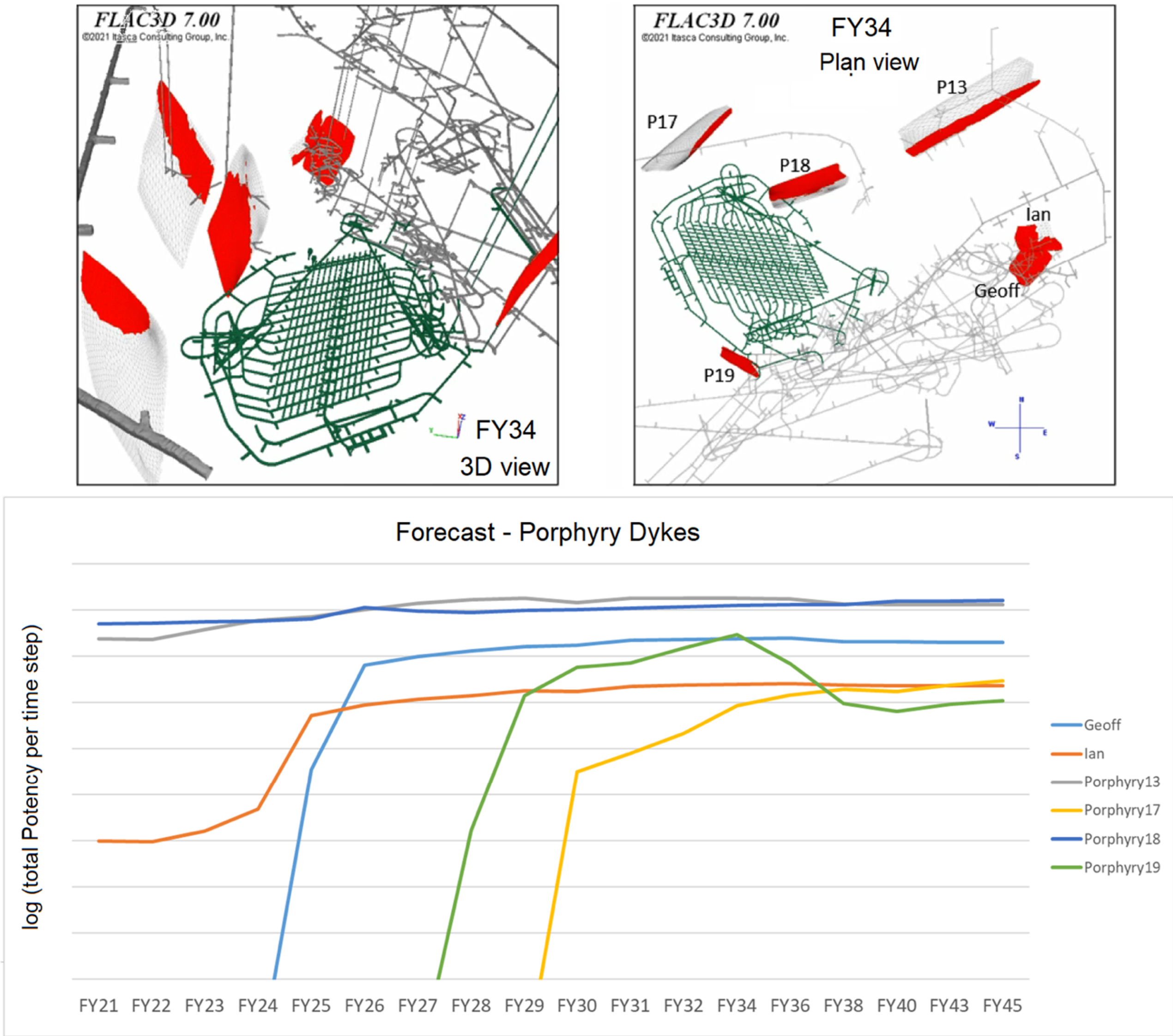


Figure 6 **Forecasted seismic response of the porphyry intrusions (dykes) during the establishment of the new panel cave (bottom) and an example of the estimated slip areas on the structures for a time step (top)**

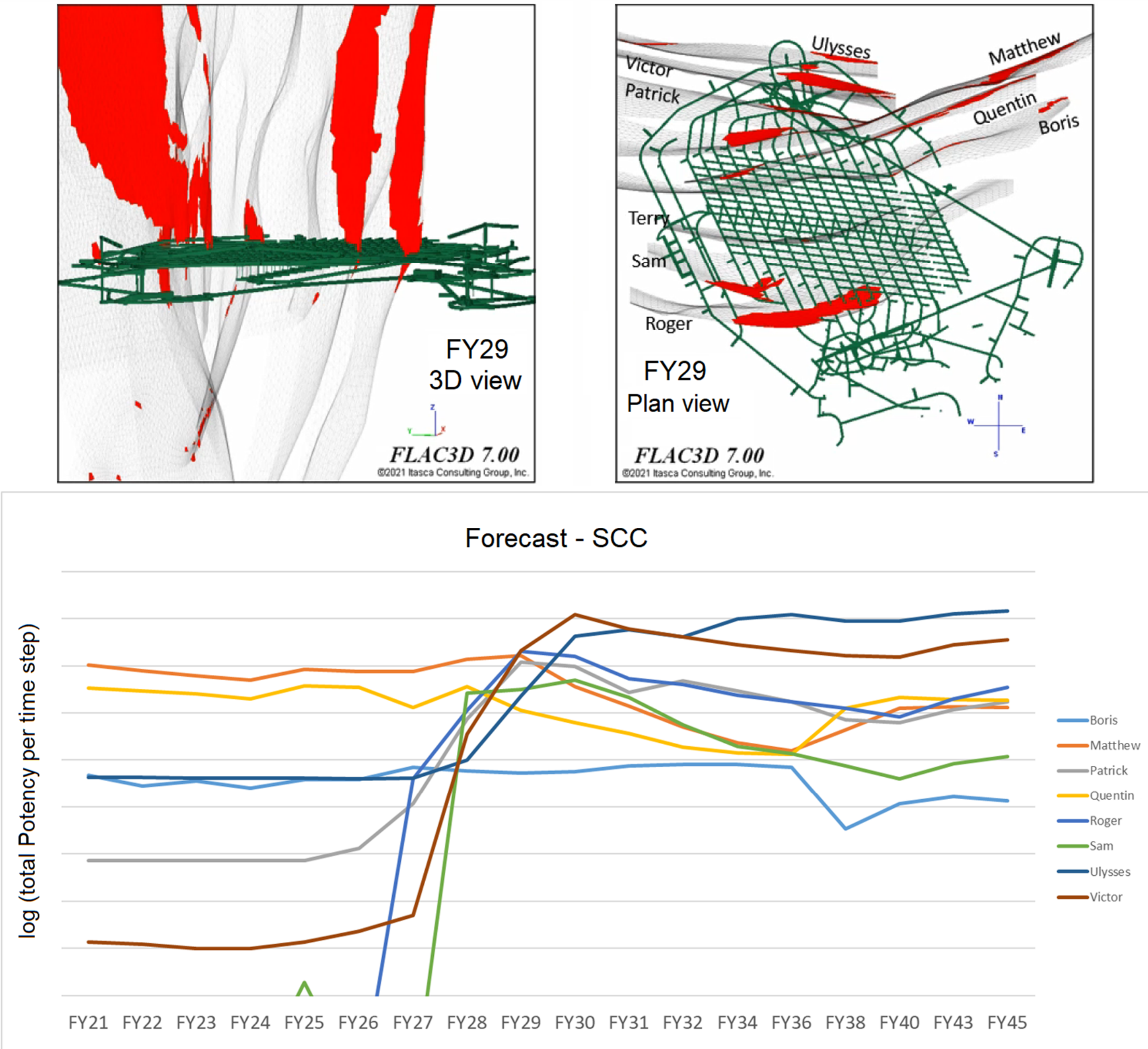


Figure 7 Forecasted seismic response of the sericite-chlorite-clay (SCC) shears during the establishment of the new panel cave (bottom) and an example of the estimated slip areas on the structures for a time step (top)

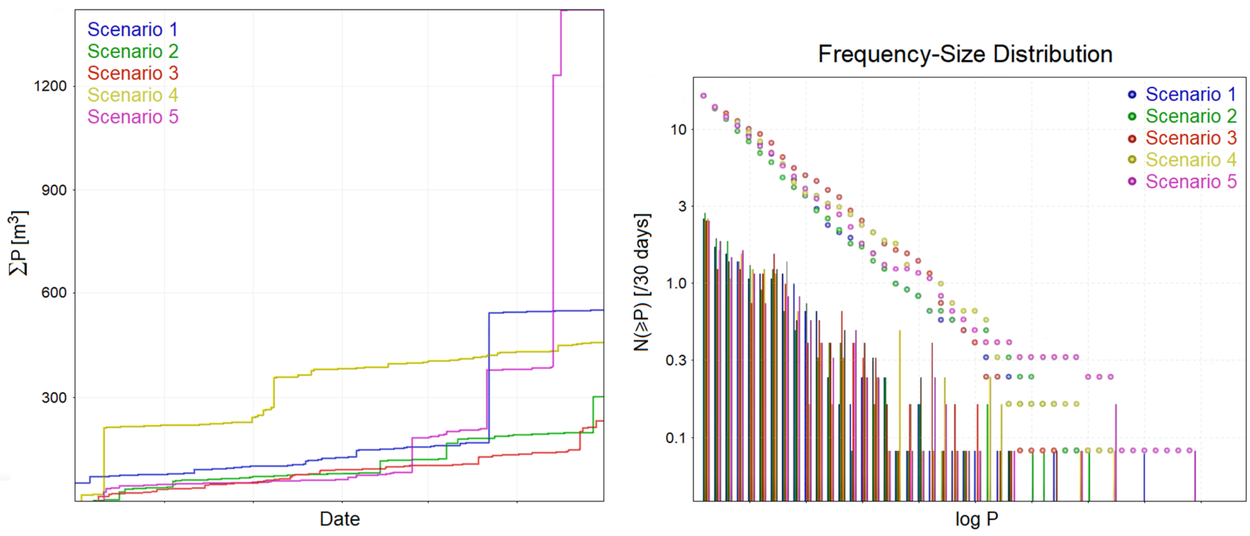
From the forward prediction assessment, and conservatively considering the total log P for each structure at each time step, we can make the following conclusions and practical considerations:

- Some porphyry intrusions and some SCC shears can generate high log P during the new cave establishment.
- Some SCC shears (Quentin and Matthew Faults, in yellow and orange in Figure 7 bottom) have been forecasted to have the ability to generate moderate log P events during undercutting (earlier periods); however, these two faults are both currently influenced by the presence of the adjacent existing cave and have not been observed to produce seismicity. The other structures present are forecasted to produce lower log P seismicity during the undercutting phase.
- Structures with high log P potential should be treated with heavier fit-for-purpose ground support regimes to ensure that potential seismic events and strainbursts are contained.
- Confirm that the planned buffer zone implemented for the infrastructure preconditioning program is appropriate for managing the forecast seismic hazard.

- Confirm that the max log P and minimum distance to infrastructures of the design events considered for undercutting and cave propagation are appropriate for ground support input parameters.
- Assess the placement of critical infrastructures in lower seismic hazard areas during the design phase.
- Identify infrastructures outside the cave and footprint areas to target with future hydraulic preconditioning programs.

6.2 Ground motion forecast

To refine the forecast of potentially damaging ground motion at critical infrastructures (for example, crusher and transfer chambers, crib rooms and conveyor belt drives) and excavations in general, we follow the method described in Malovichko (2017), which provides a probabilistic approach to the deterministic values from modelling. The method is implemented in Vantage (Institute of Mine Seismology 2024), an Institute of Mine Seismology toolkit that allows visualisation and analyses of seismicity. The goal is to further enhance the predictive capabilities of the models by generating a power law distribution of synthetic events within a range of potencies instead of assigning the total estimated potency to one single large event, which is physically unrealistic and too conservative of an approach. This more realistic frequency distribution of synthetic seismic events is generated following a clustering logic and is calibrated with observed seismic scaling relationships, including estimated a- and b-values from the Gutenberg-Richter relationship (Gutenberg & Richter 1944). Another improvement in ground motion forecasting comes from replacing the deterministic approach with a statistical approach in which multiple synthetic-event nucleation points are considered, and a distribution of peak ground velocities (PGVs) is estimated with the associated confidence intervals, instead of a single overestimated maximum PGV value emanating from a unique source point. The Malovichko (2017) method is implemented in Vantage in such a way that all elemental potency values estimated on the wireframes of the geological structures by numerical modelling are directly imported as individual seismic events, without the need of further manipulation. From these individual seismic events, multiple event catalogues are then generated using a Monte Carlo simulation method (e.g. Assatourians & Atkinson 2013) constrained by a b-value estimated from the frequency-size distribution of the observed seismicity and by a maximum log P event. The value of the maximum log P event is obtained from the largest of two values: (1) 95% of the largest total estimated potency, or (2) the potency value of the next recorded breaking event, obtained by applying record theory (Mendecki 2016) to the catalogue of observed seismicity. Figure 8 shows an example of five synthetic-event catalogues generated from modelling log P elements of a subset of three structure wireframes. In the example, the structure that generated the largest seismic event at Cadia East, the Isa dyke, is included in the subset, and the modelled time period encompasses the date in April 2017 in which the largest seismic event occurred (see Figure 5 for observed data). We observe that one of the synthetic catalogues (Scenario 5) contains a large log P event of similar size to the largest seismic event at Cadia East and is also occurring at a similar time, which gives us confidence in using this procedure for seismic hazard forecast. From the multiple synthetic-event catalogues we selected the one that has the largest log P event to evaluate seismic and ground motion hazard.



(a) (b)

Figure 8 Example of five event catalogues generated from modelled log P elements of a subset of three structure wireframes. (a) Evolution of cumulative potency over time; (b) Frequency-size distribution of the events in the catalogues. The Isa dyke is one of the modelled wireframes and the selected time period includes the date of the largest seismic event at Cadia East. The catalogue of Scenario 5 was able to mimic the observed seismicity

We follow the Malovichko (2017) method, which discretises the selected event catalogue into a grid and estimates the probabilities of occurrence of events exceeding a specific potency for each grid point. The probabilities can be colour mapped over the excavations or displayed using iso-surfaces. Other hazard likelihoods can be represented in terms of a risk assessment matrix for selected points. To estimate ground motion hazard we use the Cadia East site-specific GMPE, which include an amplification factor for the skin of the excavation. The estimated values are obtained using a Monte Carlo simulation method and are constrained by the GMPE standard deviation to limit the ground motion variability to observed values. Figure 9 shows an example of the ground motion hazard estimated for a time period mapped over excavations and displayed as a risk matrix. The probabilistic forecast of seismic and ground motion hazard is estimated for sequential time periods so that the evolution of the forecasted probabilities of exceedance of particular log P values and PGV levels are captured. With this information we can capture the overall maximum PGV that corresponds to the likelihood of exceeding a selected risk level from the risk assessment matrix over all excavations for the full forecasted period, which will be a key input for ground support designs, particularly for critical infrastructure.

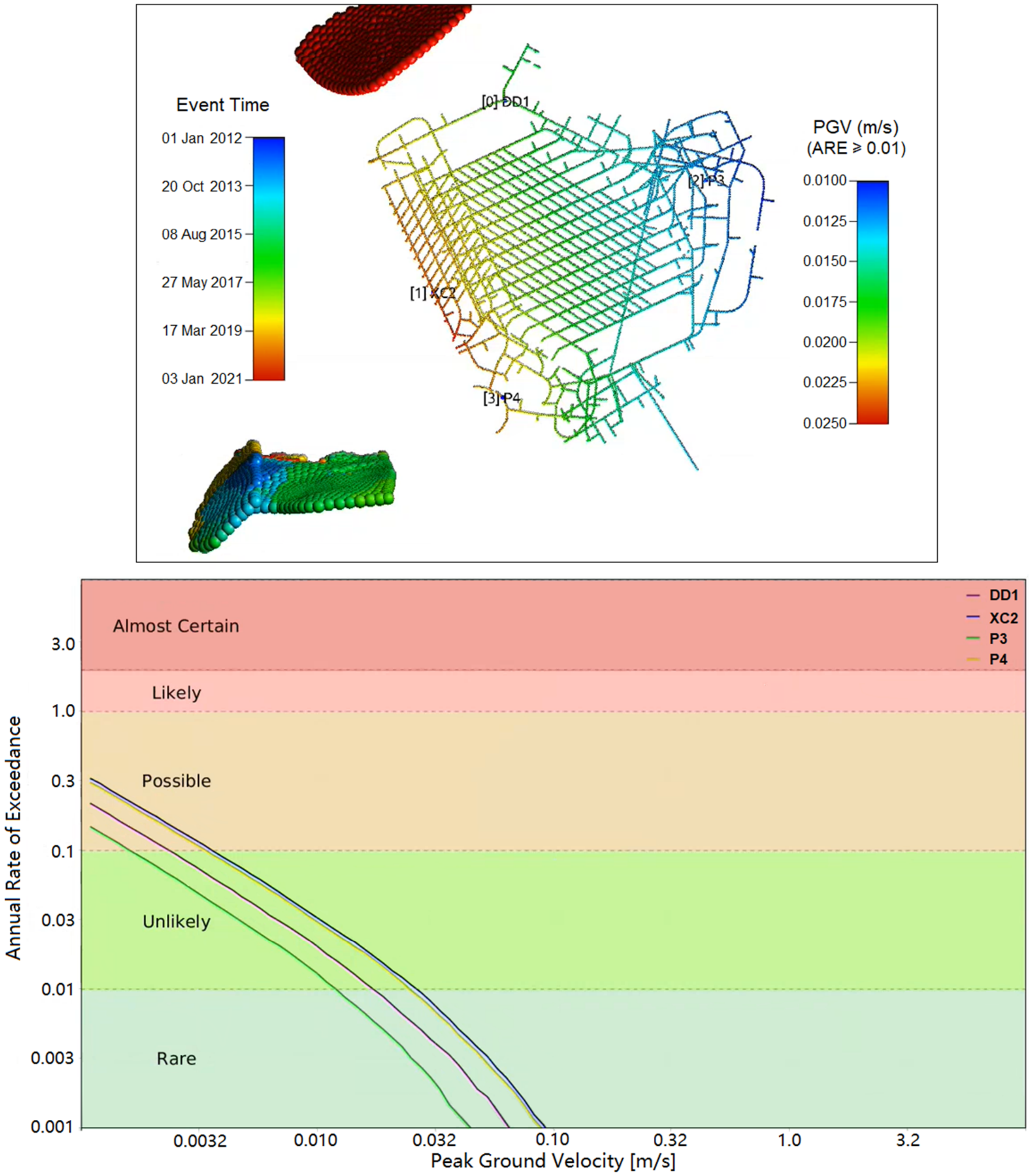


Figure 9 Top plot: Example of peak ground velocity (PGV) mapping over the extraction level of PGVs corresponding to an annual rate of exceedance of 0.01 (unlikely/rare transition) at a certain time step, for modelled potencies at three wireframes represented by time-coloured spheres. Bottom plot: Curves of the annual rate of exceedance versus PGV at four points of interest (labelled in the map above), overimposed on likelihood of a risk assessment matrix

7 Conclusion

We developed a workflow to evaluate seismic hazard from potential slip failure on geological structures activated by stress redistribution as a resultant of block cave mining, and successfully applied the approach to the study of a new block cave panel at Cadia East mine. The multidisciplinary and collaborative approach takes advantage of gathered knowledge from geotechnical, geological and seismic data obtained during the development of two previous block caving panels. The approach relies heavily on numerical modelling to assess the slip potential of geological structures over time and integrates the physical properties of the structures to better constrain the seismic hazard assessment. It uses observed seismicity to calibrate and validate the numerical model, and to aid in the seismic hazard forecast of future blocks. During the design study/phase of a new block cave panel, forecasted peak ground motions are used as input into ground support design at critical infrastructures and workings within the mine, assisting in the optimisation of the ground support to match the predicted hazard. The seismic hazard assessment allows the testing of multiple scenarios of the mine design and making informed choices to minimise exposure in areas of high seismic hazard. It can also lead to proactive measures in seismic hazard reduction, such as hydraulic preconditioning of specific geological structures.

A limited workflow can be developed for new block cave mines in greenfield sites for which little geophysical information is known, and limited geological information exists, by incorporating the geological data in the model and by adapting the seismic response of mines with similar rock mass and stress conditions. The resulting seismic hazard forecast will indicate improvements that will aid in mine design decisions.

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