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A coupled modelling approach for discontinuous subsidence at the Cadia East mine

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Abstract

It is known that in addition to the production schedule, a number of orebody, geologic and topographic features can influence the nature and extent of surface subsidence related to a cave mine. Some of these factors include the shape and depth of the orebody/extraction level in plan, strength of the rock mass including the intact blocks, joints and geological features such as faults and dykes, ground surface profile, including historical surface mining and the presence of nearby underground excavations (Sainsbury 2012).

Brady and Brown (2006) classify subsidence into two types, continuous and discontinuous. Continuous (or trough) subsidence refers to the formation of a smooth (gradual) change in profile that does not have step changes. Discontinuous subsidence involves large surface displacements (both tension and shear) and the formation of steps/breaks in the surface profile. Discontinuous subsidence is strongly affected by the presence of pre-existing features within the rock mass. As such, it cannot be accurately assessed without the inclusion of such features within a three-dimensional numerical model.

A coupled continuous–discontinuous approach has been developed to predict caving and subsidence efficiently and accurately at the Cadia East mine over an eight-year production life (or 150 MT drawn). Numerically simulated results with the coupled approach are compared to in situ observations. It can be seen that in the case of sub-vertical structures within the near-surface rock mass, traditional strain criteria applied alongside continuum models are unable to capture the true shape or extent of cracking and that discontinuum models provide greater accuracy.

Keywords: *caving, subsidence, continuum-discontinuum*

1 Introduction

A successful back-analysis of the cave propagation behaviour of the PC1 Cave at Cadia East was completed by Sainsbury et al. (2018). The back-analysis was able to accurately predict the initial yield advance, critical hydraulic radius, interaction with overlying infrastructure (5050 m RL and 5250 m RL levels) including the narrowing of the cave crown and eventual stall on the capping porphyry. Simulation of the preconditioning was conducted, and the re-initiation of the cave was also successfully recreated along with the surface break-through and location of the crater.

These behaviours were all accurately simulated within a continuum model using the ubiquitous joint rock mass (UJRM) technique for the simulation of discontinuities as described by Clark (2006) and Sainsbury & Sainsbury (2017). However, with ongoing interaction of the cave with the ground surface, subsidence mechanisms also need to be considered. A conceptual model describing the block caving subsidence process has previously been described by Abel & Lee (1980) and is presented in Figure 1.

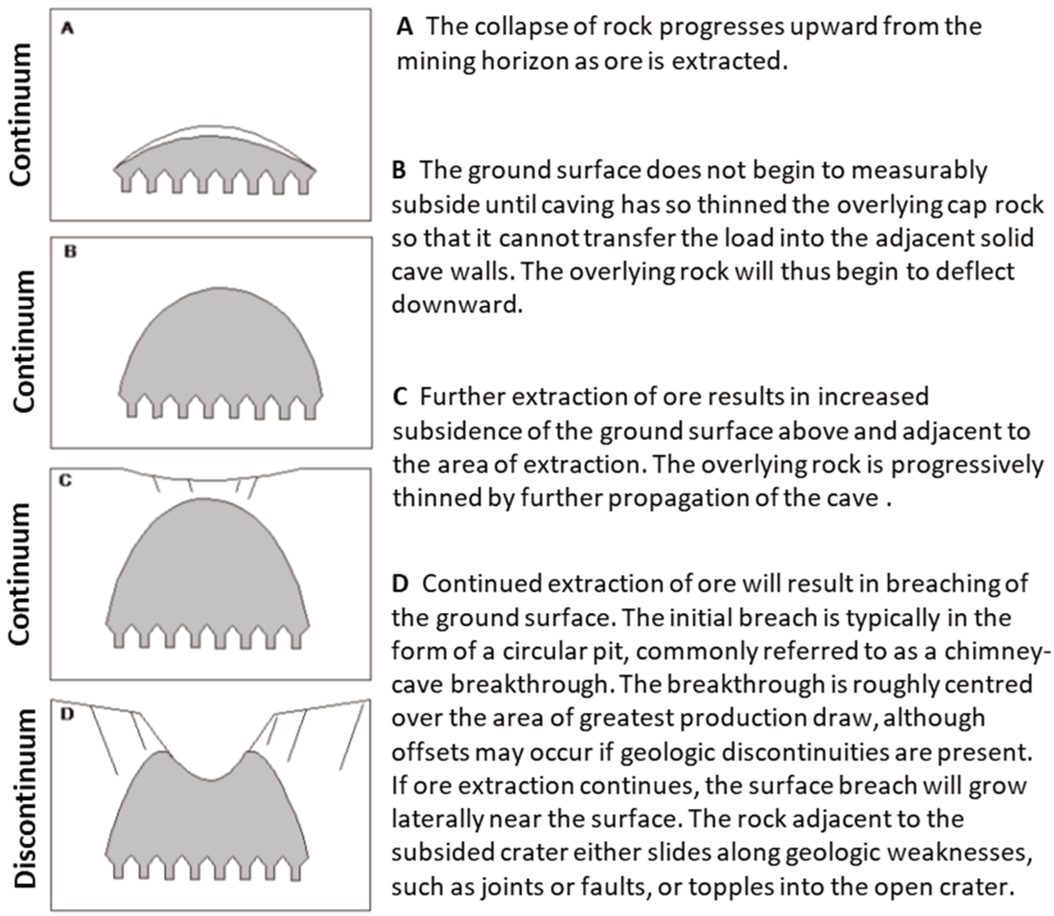

Figure 1 Conceptual model of the development of block caving subsidence (modified after Abel & Lee 1980)

An empirical total strain criterion of 0.5% has previously been used to calibrate the limits of large-scale cracking in continuum models at the Kiruna sub level cave (Sainsbury & Stokel 2012), Grace mine panel cave (Sainsbury et al. 2010), Century open pit (Sainsbury et al. 2016b), El Teniente cave (Cavieres et al. 2003) and Palabora block cave (Sainsbury et al. 2016a). The zone of large-scale fracturing consists of an area in which the ground surface is broken and has large open tension cracks, benches, and rotational blocks. The primary failure mechanism of surface cracks associated with cave mines is shear and tensile failure of the side rock, which results in stepped benches and scarps. Other types of failure mechanisms, such as toppling and block rotation, are also present, but they appear to be secondary mechanisms that form after the primary shear failure develops. This total strain criterion provides a reasonable estimate of the crater (and toppling) limits, but is limited in its ability to provide detailed responses of the ground surface to the kinematic response of the intermediate and small-scale structures which are likely to cause damage to infrastructure.

Based on the visual observations of the crater scarp at Cadia East as observed in Figures 2 and 3, it is clear that intermediate-scale geological features within the silurian sediment domain have an impact on the surface subsidence features and extent of cracking limits. Large differential movements are observed along the structures resulting in an irregular crater shape and surface scarp around it.

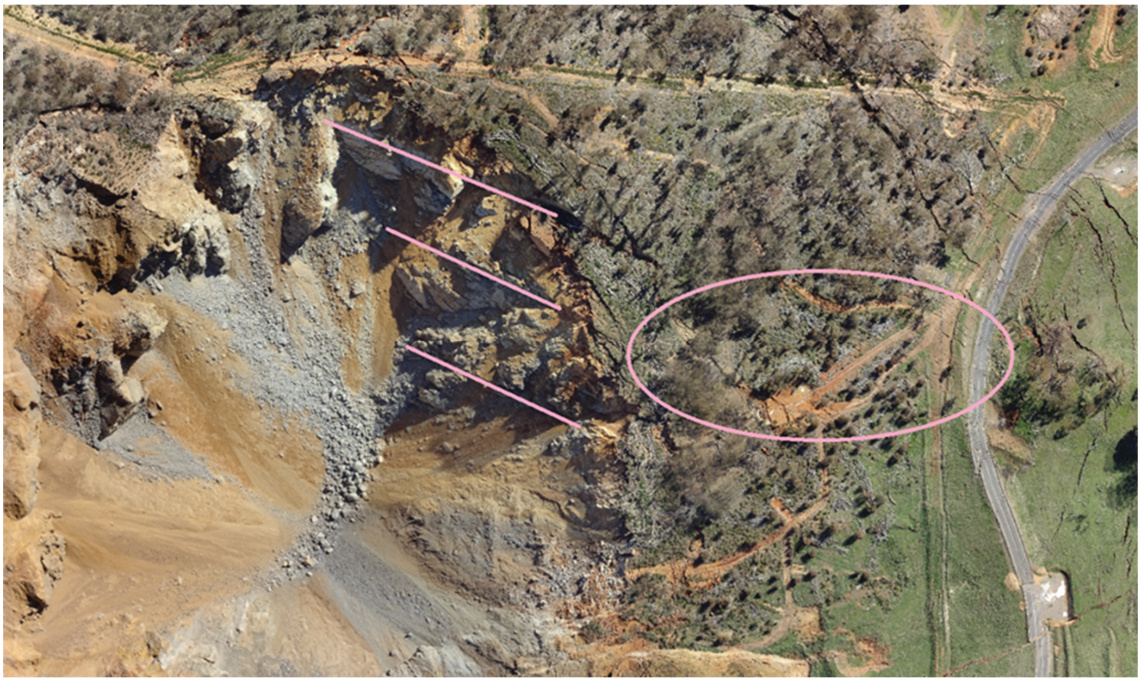

Figure 2 Predominant discontinuity orientation and impact of surface cracking beyond the crater limits

Figure 3 Crater limits clearly defined by existing structure

As such, to more accurately predict surface cracking behaviour, a numerical model must account for the fracture features. In the case of Cadia East, a three-dimensional model was constructed with the discontinuum program 3DEC (Itasca Consulting Group 2022a) to simulate the near-surface intermediate-scale structures that are observed to influence the crater formation and cracking within the subsidence zone of influence. 3DEC has been coupled with the results of the continuum model constructed in FLAC3D (Itasca Consulting Group 2022b) that is able to accurately reflect the subsurface conditions. This coupling allows the evaluation of the low stress fracture slip and separation around the evolving cave mass to better predict small-scale discontinuous displacement. The separate FLAC3D and 3DEC models are coupled by importing the predicted mobilised zone from the FLAC3D cave propagation model into the 3DEC model as illustrated in Figure 4. The 3DEC model covers the same area/volume as the FLAC3D model to simulate the evolving abutment stresses.

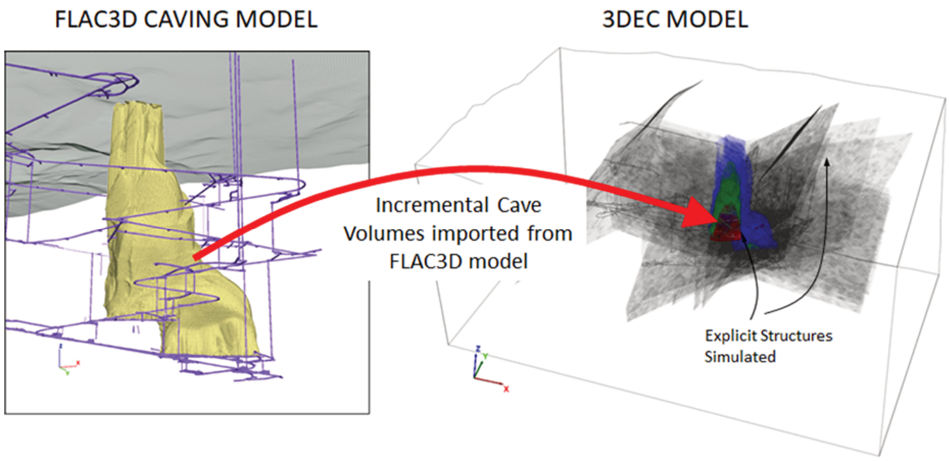

Figure 4 Coupling of FLAC3D and 3DEC models

This coupling technique is more rigorous in the consideration of existing fractures on the behaviour of the rock mass near the surface (e.g. in low stress conditions). Since, at the surface, rock mass failure is expected to be tensile/gravity driven and not stress driven and few new fractures are expected to be created as a result of the caving process. Therefore, failure can be expected along the pre-existing fracture network.

Rather than simulating the complex production draw and resulting cave propagation in the 3DEC model, the effect of the propagating cave and evolving abutment stresses on the surrounding large-scale structures, the mobilised/CMZ (comminution/mobilised zone) was initialised within the 3DEC model as illustrated in Figure 4. This was completed at three monthly increments. Within the 3DEC model, the mobilised zone was simulated with material properties equivalent to a fully bulked rock mass as described in Sainsbury (2018). Once the cave was imported, from FLAC3D the model was stepped to equilibrium and the slip and separation of the structures surrounding the crater were observed. The FLAC3D model used is consistent with that described in Sainsbury et al. (2018).

2 Development of a discrete fracture network

A discrete fracture network (DFN) is primarily a modelling framework for fractured geological systems that aims to integrate field data into simulations of flow and/or deformation. It is complementary to the traditional continuum methods described by Sainsbury (2012) with both advantages of easily integrating the statistical properties of fracture networks, and of not assuming any homogenisation scale (Davy et al. 2018).

Fracture characteristics of the silurian sediments have been estimated based on description of the fractures from aerial photography presented in Figures 2 and 3 and in consultation with the Cadia East structural geologist (Stonestreet, pers. comm., 2019).

> *"The flyover of the crater .. has outcropping Ordovician which shows a strong joint set with a strike of MGA ~110, which equates to CMG ~080. It appears to be sub-vertical, my estimation of mean dip/dip direction in Cadia Mine Grid would be 80 at 170. The trend is indicated by the pink lines in the Crater image which are about 150m long. The circled area is shown in Cracking – east of crater and shows the continuity of this strong set in the Ordovician rocks on the western (upthrust) side of the Cat Fault..."*

A conceptual intermediate-scale fracture network was developed within 3DEC and extended to 150 m below the ground surface as illustrated in Figure 5.

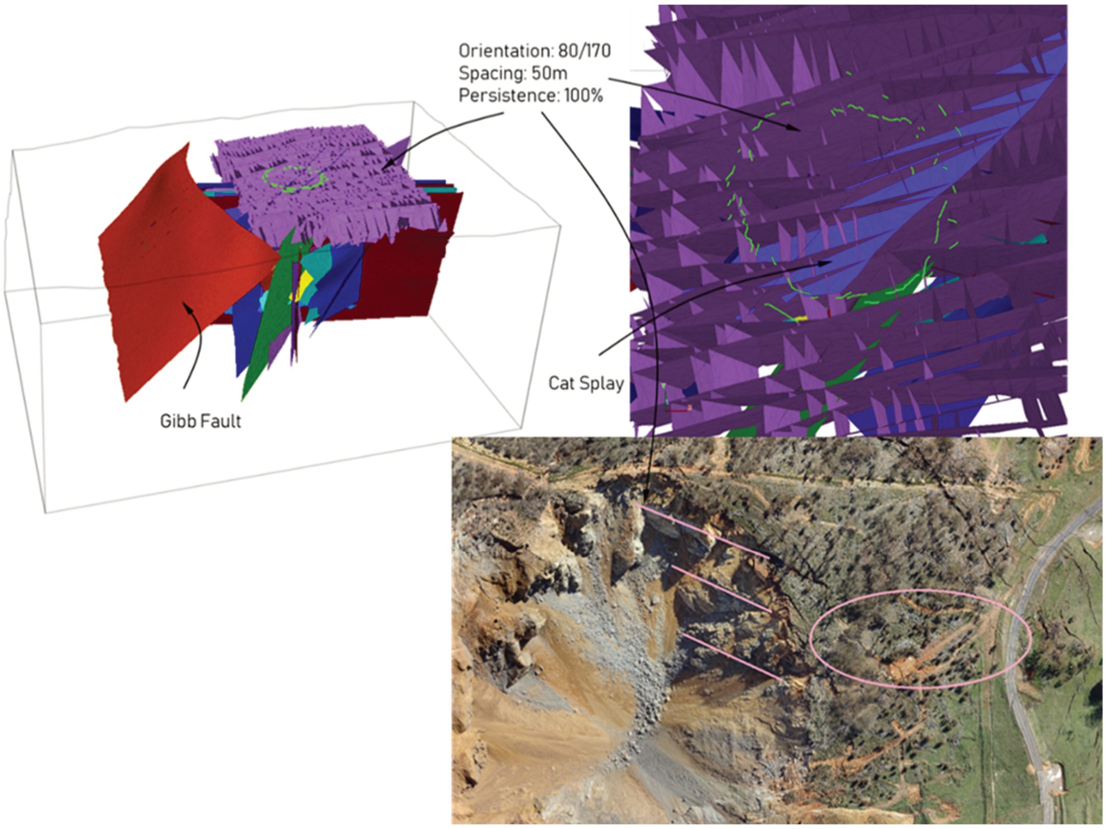

Figure 5 Characterisation of silurian sediment DFN from aerial photography

A primary fracture set with dip = 80° (+/- 10°), dip direction = 170° (+/- 10º), spacing = 50 m (+/- 10 m) and 100% persistence was analysed based upon visual observation of intermediate-scale structures observed in the current crater (Stonestreet, pers. comm., 2019). An orthogonal fracture set to this with 50% persistence was also simulated as observed in Figure 5.

In considering the subsidence prediction at Cadia East based on a DFN that was developed directly from the failure zone, the results can be considered a 'C1' type that represents a prediction made after the event with the results known (Lambe 1973). Establishing a calibrated model based on such a prediction allows for a more reliable Class 'A' prediction that can be made before a future event.

2.1 Shear strength of intermediate-scale structure

A brittle softening Mohr–Coulomb shear strength criterion with peak and residual parameters has been used to simulate the behaviour of the intermediate-scale structures. In lieu of detailed characterisation of the structures a single set of parameters were used to simulate each structure, which is provided in Table 1.

Table 1 Joint properties applied in 3DEC (discontinuum model)

Kn (*Pa/m*)	*Ks* (*Pa/m*)	C_p (kPa)	ϕ_p	C_r (kPa)	ϕ_r	σ_t (kPa)
50	5	20	30	0	25	0.0

The material properties of rock blocks have been derived from a calibration procedure as described in Sainsbury & Sainsbury (2017) to match the overall rock mass response. The rock mass beyond the DFN area in the 3DEC model has been simulated with material properties consistent with those used in the continuum model.

3 Subsidence results

At the end of each production increment simulated in 3DEC, the response of the joint fracture network was assessed in the model and compared with historical results. Approximately 100 mm of displacement along the structures was observed to match with the existing cracking limits – based on data from 2016 to 2021.

Since the commencement of mining of PC1-1 in 2013 and the surface breakthrough on 22 October 2014, the cracking limits on the surface have been progressing north and eastwards – following the trend of the production front. A comparison of the continuum versus discontinuum results for the same time periods of June 2017 and June 2018 is presented in Figure 6.

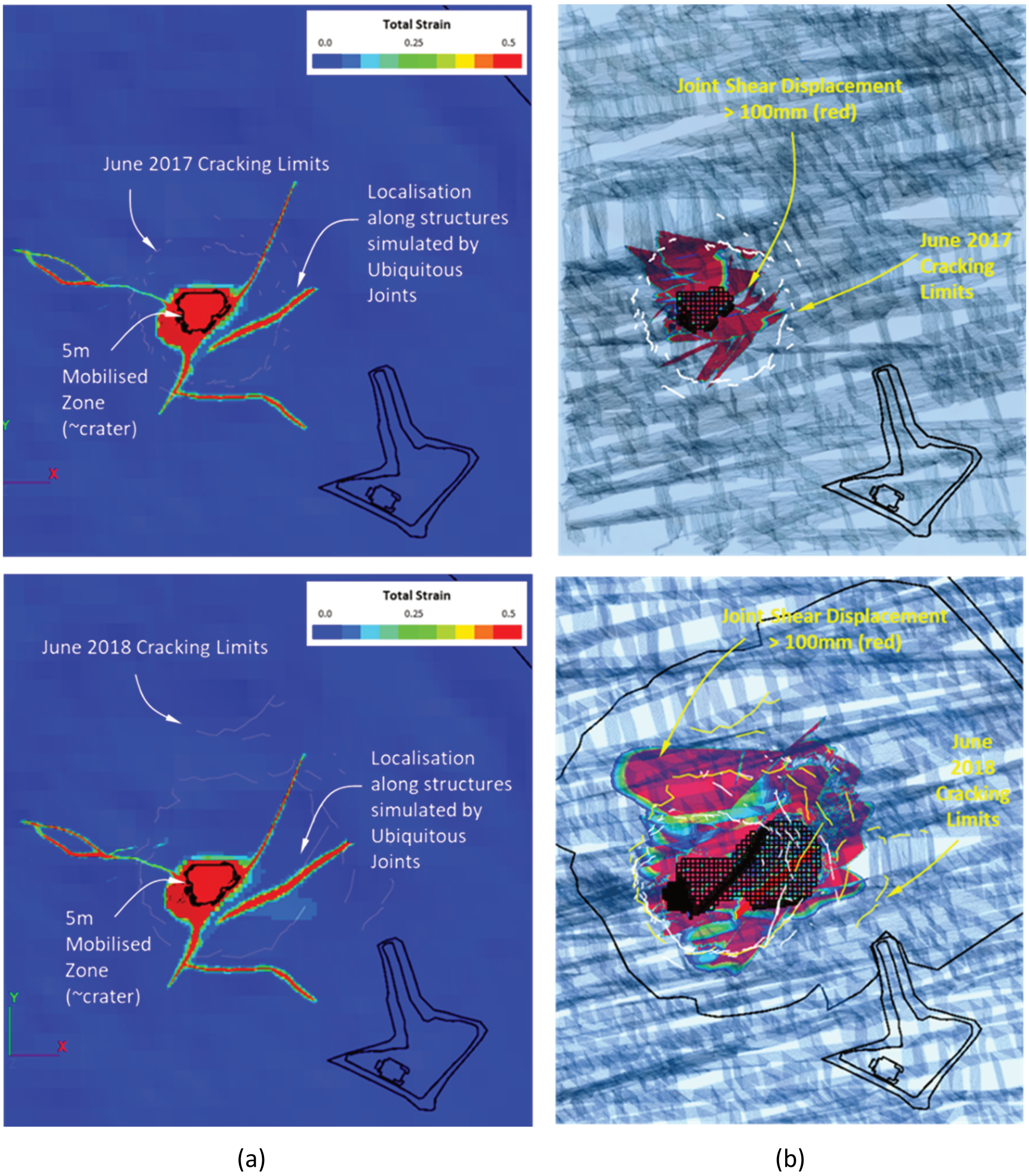

Figure 6 Comparison of existing cracking limits observed and simulated by (a) continuum and (b) discontinuum methods at June 2017 and 2018

The results show that:

- Using the UJRM technique, the continuum model is able to capture slip along large-scale structures.
- The 0.5% total strain limit underestimates the extent of surface cracking when compared to the actual cracking that has been mapped.
- The 3DEC discontinuum model is able to better reflect the extent of cracking at the surface through a relationship with 100 mm slip along discontinuities in the model.
- The shape of the surface cracking is better reflected in the discontinuum model through the inclusion of the explicit structures and their interaction with the developing cave.

A comparison of the 3DEC model response from 2017–2021 shows that it is able to accurately capture the evolution (extent and shape) of surface cracking at Cadia East up until the present time (Figure 7).

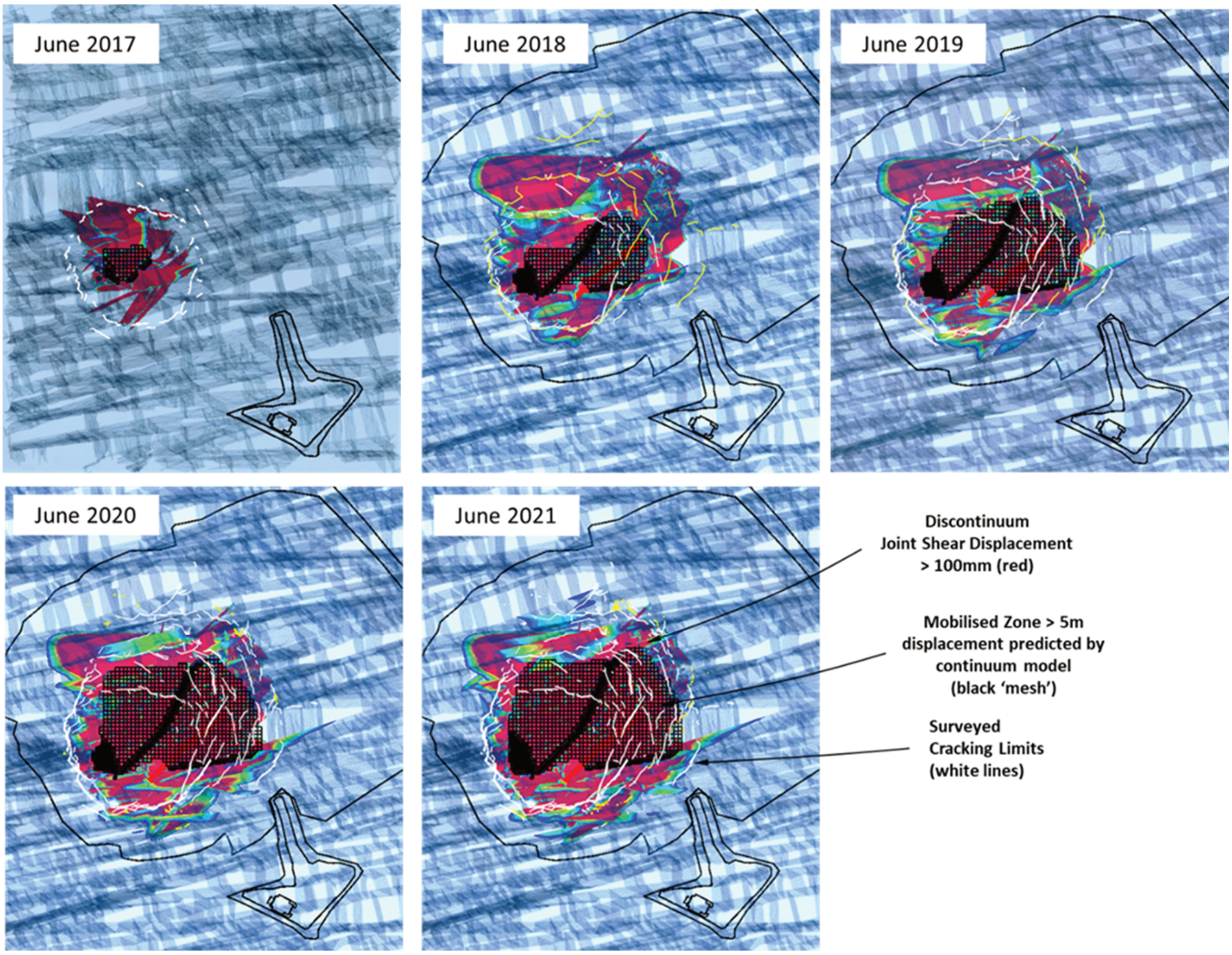

Figure 7 Existing cracking limits observed and simulated by discontinuum from June 2017 to June 2021

Previous studies conducted by Vyazmensky et al. (2008) suggest that sub-vertical joint sets dominate the cave propagation direction. Furthermore, asymmetrical subsidence is observed in the presence of both sub-horizontal and sub-vertical joint sets with sub-vertical joint sets dominating the surface expression producing kinematic failures.

Through the simulation of the DFN in the 3DEC model, each one of these conclusions can be confirmed at Cadia East and observed in the surface photos presented in Figures 2 and 3. As such, it is proposed that subsidence assessments for caving operations that are characterised by a near-surface rock mass that has sub-vertical joints must include a discontinuum analysis.

4 Conclusion

A coupled continuous–discontinuous approach has been developed to predict caving and subsidence efficiently and accurately at the Cadia East mine over an eight-year production life (or 150 MT drawn). Numerically simulated results are compared to the in situ observations to match the crater, limits of cracking and continuous subsidence profile. Based on the results it is proposed that subsidence assessments for caving operations that are characterised by a near-surface rock mass that has sub-vertical joints must include a discontinuum analysis. The discontinuum analysis ensures the extent and shape of the surface feature of the cave are accurately predicted and not underpredicted by continuum models.

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