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A mixed-method approach for major excavation ground support evaluation

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Abstract

The short and long-term stability of major excavations is crucial to the successful development and long-term performance of both the excavations and their mining function. Detailed geotechnical assessments and analyses are pivotal to understanding the causes of instability when planning a major excavation and are essential to performance forecasting and applying engineering and mitigation controls. This paper describes a mixed-method approach, which not only evaluates the suitability of a range of ground support regimes but provides a good practice framework that can be applied to future major excavation assessments during a feasibility study.

This approach includes the collection of geological and geotechnical data, rock mass classification, the specification of strength and stress parameters, preliminary identification of support requirements using empirical methods, such as the Q, RMR, and GSI systems, kinematic joint and wedge analysis, and 2D and 3D numerical modelling. These methods take into consideration the local rock conditions and structural geology and the ground support response based on cover hole data to evaluate best the suitability of an underground excavation and related support elements before construction begins.

The mixed-method approach was tested by assessing the construction of a new major excavation for an unnamed block cave operation. Detailed geotechnical data was obtained from two cover holes. The results identified the stress environment, the likely modes of failure, mean joint sets, potential wedge formations and key influences of joint properties, the likely failure zone, and the potential impact of the void created by caving. In addition, the approach allows a wide range of suitable support regimes to be assessed. The result was a support evaluation unique to the operation and local conditions.

This framework helps to successfully determine the rock conditions and the effectiveness of various support designs in two and three dimensions where this type of analysis is essential to safely work in underground conditions that are adequately supported, which can be determined quickly and effectively using the mixed-method approach for evaluating ground support and rock mass conditions. Further steps are suggested to improve the approach's usefulness subject to more data and analytic capabilities, including downhole geophysics, numerical modelling with a discrete fracture network, and synthetic rock mass modelling.

Keywords: *ground support, numerical modelling, sublevel cave*

1 Introduction

This paper is the result of a geotechnical assessment and associated analyses relating to the evaluation of a new major excavation for a crusher chamber as a part of an unnamed block cave mining operation in Australia, where the data was provided to the author by the operators of the mine. Detailed geotechnical assessments and models are vital to the successful development and long-term performance of underground excavations, which are governed by their short and long-term stability; therefore, it is essential to understand the drivers of local instability within the surrounding rock mass to best plan the design of a new excavation and associated support system (Hoek et al. 2000).

The mixed-method approach was tested by identifying appropriate ground support systems for the new excavation based on real-world data obtained from two cover holes, and is the focus of this paper to highlight a good practice framework when conducting a mixture of traditional empirical methods and computer-based numerical modelling (using Rocscience software in this case) to determine support requirements for new major excavations. The approach includes an assortment of raw data interpretation, empirical schemes, kinematic analysis of discontinuities, and 2D and 3D numerical modelling, further described in section 2. The geometry of the excavation relative to the working level studied for this work is shown in Figure 1, which also highlights the main 11 × 15 m horseshoe-shaped chamber that is the primary focus of the empirical and 2D numerical analysis; this is because the chamber is the tallest of the nearby development, therefore representing the most conservative scenario regarding geotechnical support requirements as the equivalent dimension (De) will be greatest for a larger span.

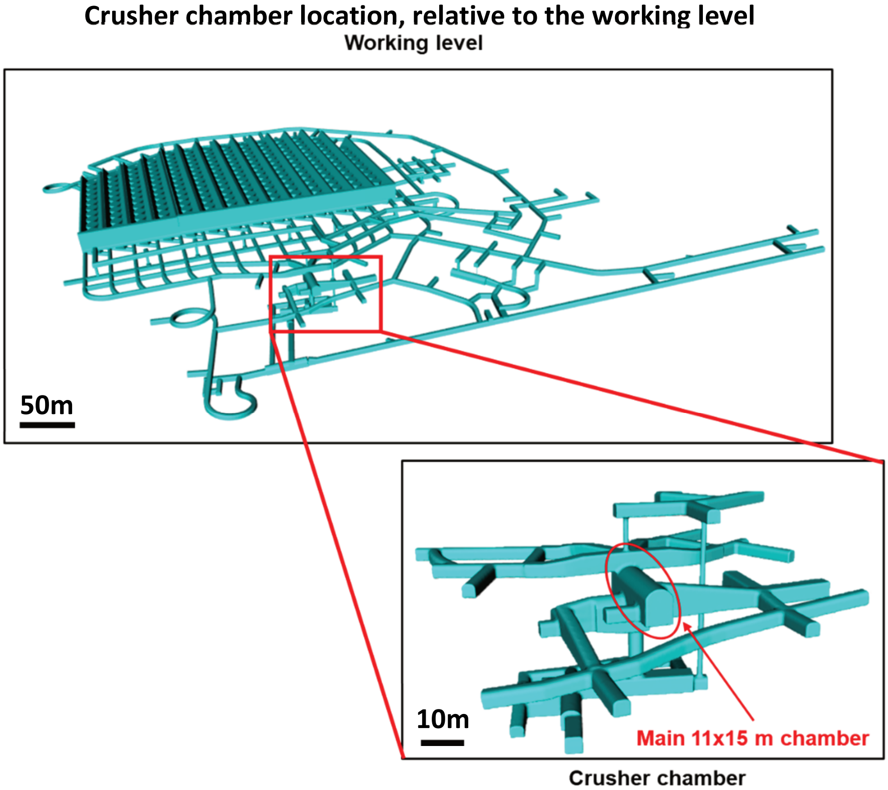

Figure 1 View showing the crusher chamber studied relative to the block cave working level

2 Methodology

The mixed-method approach developed for the geotechnical and support evaluation for the block cave crusher chamber was considerably inspired by previous work focusing on the assessment of ground support of similar chambers, such as the Ernest Henry Mine, Australia (Campbell et al. 2013) and the Deep Ore Zone (DOZ) Mine, Indonesia (Casten et al. 2000); the methods of these works were deemed appropriate to build upon as both mines extract ore using block caving as well a crush and convey system similar to the mining operation examined in this paper.

The following methodology yielded a sensible workflow for the major excavation evaluation, which included the collection of geological, geotechnical and structural data, rock mass classification and determination of strength parameters, the initial identification of support requirements using empirical methods, as well as kinematic analysis and simple 2D numerical modelling of the main/largest chamber, followed by basic 3D numerical modelling of the larger geometry.

Recommended support requirements that were suggested by empirical schemes and literature guidelines were then tested over numerous iterations in the 2D numerical modelling to identify which support system(s) produced the most favourable results, including various strengths and lengths of spot and cable bolts as well as the use of different shotcrete parameters (Li 2017; Hoek 2007; Barton et al. 1974; Lang 1961). The most favourable result was then taken forward into 3D numerical modelling. Concerning the set-up parameters in the modelling software, the Hoek–Brown failure criterion was selected over the Mohr–Coulomb criterion as it performs more effectively at depth, as suggested by Eberhardt (2012).

3 Geotechnical setting

The crusher chamber is hosted within a granitic basement unit at approximately 1,500 m depth. The discontinuities examined by cover hole A, which intersects the chamber, are recorded as mainly undulating, almost all rough, and a majority with a spacing between 0.4 and 0.6 m. The persistence values of 3–10 m are inferred from underground observations. Table 1 shows the stress regime data provided to the author, where the k ratio is equal to 1.72 and represents a horizontally dominant stress field.

Table 1 Stress magnitudes and orientations for the principal stresses

Principal stress	Magnitude (MPa)	Dip (°)	Dip direction (°)
σ_1	0.0498 × depth (m)	0	319
σ_2	0.0370 × depth (m)	1	49
σ_3	0.0290 × depth (m)	89	221

Figure 2 shows the relative positions of cover holes A and B relative to the crusher chamber location where cover hole A intersects the planned excavation area with cover hole B adjacent to the main chamber. Core obtained from cover holes A and B is the primary source of geotechnical, geological and structural data.

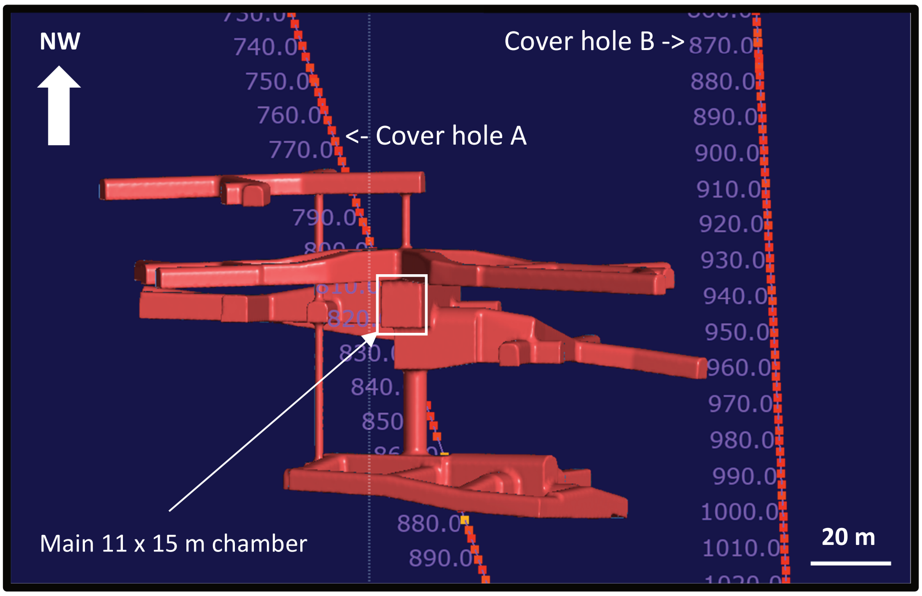

Figure 2 View showing the relative position of cover holes A and B to the crusher chamber

3.1 Empirical ground support selection

A plot of the depth relationship (10 m averages) to the rock quality (Q) is shown in Figure 3 for both cover holes at the crusher region, highlighted in red for Stress Reduction Factor (SRF) values of 2.0 and 5.0, based on the equation relating the uniaxial compressive strength (UCS) and Sigma 1, which indicate the two most likely sets of values for the stress conditions in Table 1 (Barton et al. 1974). The rock quality for the crusher region was found to be between fair and extremely good, considering both SRF values, with the rock being, on average higher quality in cover hole A that intersects the area of interest.

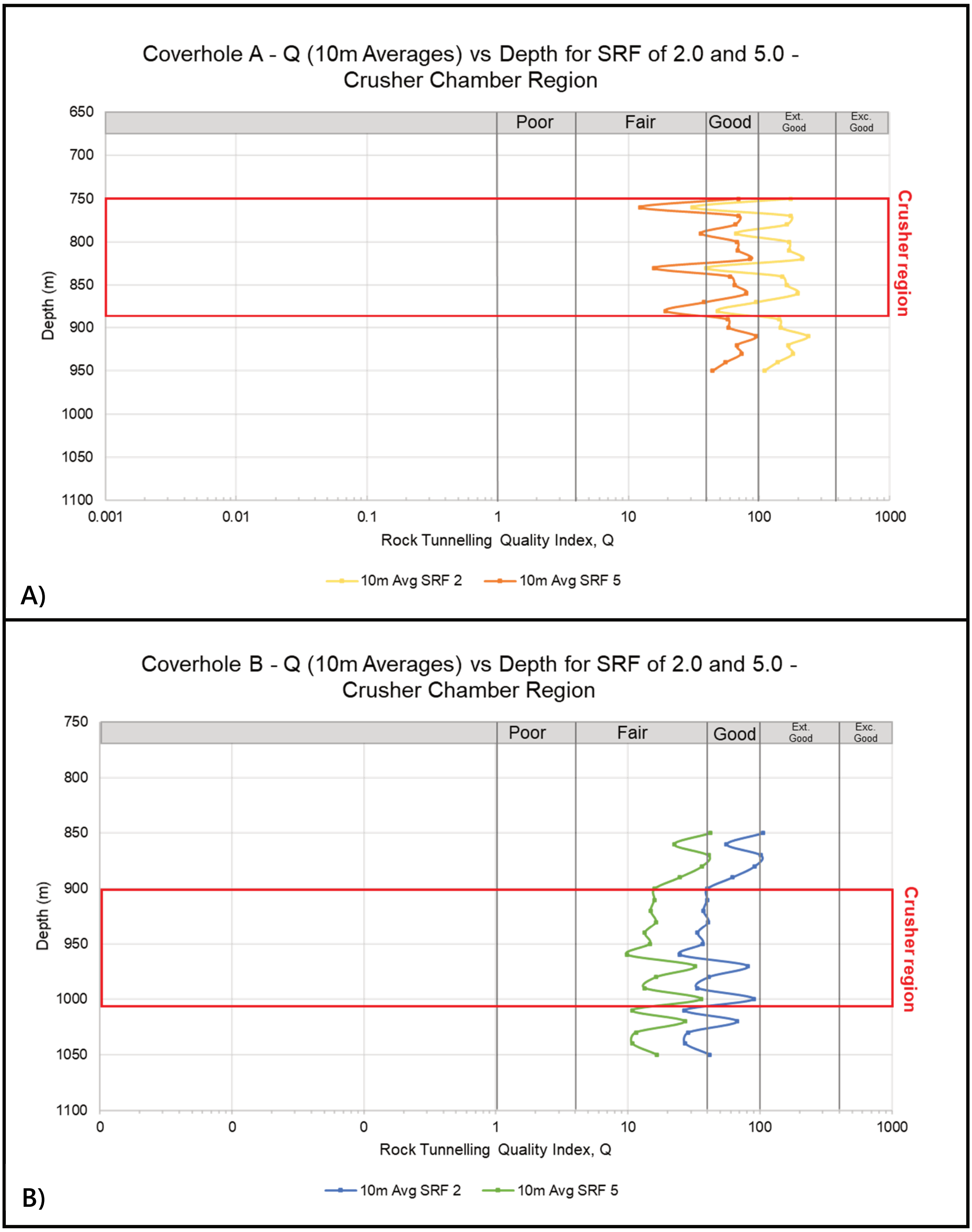

Figure 3 Rock quality (Q) at 10 m averages versus depth with SRF of 2.0 and 5.0. (a) Cover hole A; (b) Cover hole B

Q support categories have been determined using Barton's Q system support chart (Norwegian Geotechnical Institute (NGI) 2015; Barton et al. 1974). An excavation support ratio (ESR) of 1.3 was selected to represent a long-term civil engineering excavation, which was deemed suitable for the anticipated use of the chamber and operational significance (NGI 2015). An equivalent dimension (De) of 8 was used for an excavation span of 11 m in line with the main chamber previously shown in Figures 1 and 2. The results show that the support categories range from 1 to 4, including the more conservative SRF value of 5.0 (Figure 4).

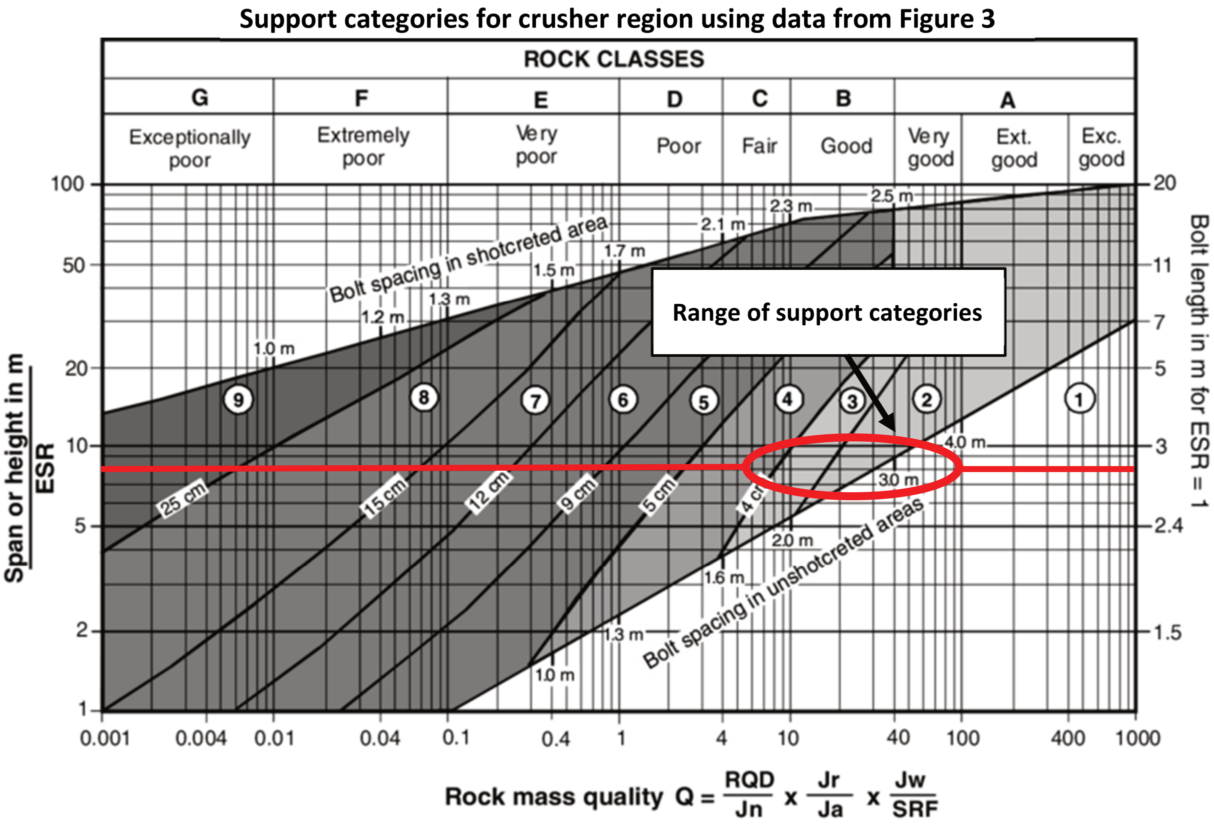

Figure 4 Results of empirical ground support selection using the Q system (NGI 2015; Barton et al. 1974)

For the main chamber, the effects of stress and the associated ground response to the creation of the excavation have been predicted using relationships between in situ stress, UCS and rock quality defined by Hoek (2007). Using a σ_1 value of 75 MPa (1.5 km depth; Table 1), UCS of 110 MPa, and average rock mass rating (RMR) data of the crusher region to classify the rock as moderately fractured, the ground response was predicted to be 'Brittle failure of intact rock around the excavation and movement of blocks' (Hoek 2007). Results from the Q system specified that the required ground support for the crusher should be:

- Systematic bolting using bolt lengths of approximately 2.7 m on a 2.2 × 2.2 m pattern (possibly inadequate as the bolt length axis is designed around an ESR of 1.0, as opposed to 1.3).
- Fibre-reinforced shotcrete (FRS) of a thickness between 4 cm and 10 cm.

The bolt lengths and spacings suggested by the Q system vary compared to good practice guidelines suggested by Li (2017) to support a natural pressure arch. As a function of span, Li (2017; equation 3) suggests a bolt length of 3.3 m and a spacing approximately 3–4 times the mean joint spacing, which in this instance is on average 0.6 m from cover hole data suggesting a minimum spacing of 1.8 m. During numerical modelling, the impact of this was taken into account when designing the support system for the crusher chamber.

3.2 Kinematic analysis

A stereographic and kinematic analysis using DIPS and UnWedge software (Rocscience 2003, 1998) was conducted for the rock mass and main crusher chamber. Orientation data was supplied using alpha and beta values relating to the orientated core, with the Terzaghi weighting applied. The stereonet results found three joint sets that satisfied the conditions for gravity falls and the azimuth of some development lying parallel and subparallel to sets 1 and 3, indicating that gravity-induced failure is probable and to be anticipated in further analysis. The joint sets identified have been tabulated in Table 2.

Table 2 Joint sets identified from stereographic analysis

Joint set	Dip (°)	Dip direction (°)
1	67	206
2	51	296
3	38	54
4	66	155

For the wedge analysis, a joint friction angle of 30° was used with Barton and Bandis (1991) joint parameters derived indirectly from the Q system parameters (Salminen et al. 2017; Barton 1988), as this was found to be more suitable for the dataset, compared to Mohr–Coulomb parameters. For the wedge analysis, joint roughness coefficient was equal to 9, joint compressive strength was equal to 100 MPa, and the persistence varied from 3–10 m. The persistence was found to have a profound impact on wedge volume. A value of 10 m was taken forward in the modelling to represent the worst-case scenario as it was associated with larger wedge volumes.

Without any support elements, the only critical wedges were identified in the roof of the excavation with a falling failure mode. Across all joint set combinations, the largest wedge volume was 66 m^3 with a maximum support pressure of 0.015 MPa. The addition of the rock and cable bolts resulted in factors of safety between 1.6 and 3.5 for the wedges, with this rising to the hundreds with the inclusion of 25 MPa FRS, indicating that short-term stability is likely achieved with bolts as the FRS cures over the following 28 days.

The shotcrete strength was chosen based upon a high strength being considered as 50 MPa (Saw 2015) and then reduced for modelling to 25 MPa, taking potential spraying and curing environment factors into consideration of a more conservative strength estimate. The support element parameters used in the wedge modelling and further numerical modelling are shown in Table 3. 10 m long cable bolts were used on a 3 × 3 m pattern for the initial assessment.

Table 3 Support element parameters and capacity

Support	Tensile capacity (MN)	Plate capacity (MN)	Bond strength (MN)	Shotcrete UCS (MPa)
Grouted dowel	0.17 MN	0.1 MN	0.25 MN/m	N/A
Cable bolt	0.2 MN	0.5 MN	0.34 MN/m	N/A
Fibrecrete (10 cm)	N/A	N/A	N/A	25 MPa

4 2D numerical modelling in RS2

Two-dimensional numerical modelling was completed on the largest 11 × 15 m chamber to examine the stress regime's impacts and estimate the likely extent of the failure zone by wall deformation. The model was created using RS2 software (Rocscience 2008) and set up using the Vlachopoulos and Diederichs (2009) core replacement technique, simulating the three-dimensional excavation of a tunnel in 2D. In the model, support was installed 2 m from the tunnel face, with the in situ rock mass having an initial elastic modulus of 60,000 MPa, which decreased to 10,000 MPa at the excavation stage. For further details of the core replacement method, the reader is guided to the RS2 tutorial for this process (Rocscience 2021). The model included a discrete fracture network (DFN), which was representative of the joint sets previously identified.

Results of 2D numerical modelling:

- Maximum displacement was observed in the excavation floor at 43 mm, with the sidewalls experiencing approximately 32 mm of displacement.

- The excavation experienced significant stress relaxations in the floor and sidewalls, indicating likely block fall-out and concentrations in the roof.
- The rock mass yielded up to 4 to 5.5 m in the excavation walls, 6 m in the floor, and 2 m in the roof. The addition of a wire mesh (6 mm diameter, 0.6 m spacing) in the FRS slightly reduced the likely failure zone by approximately 0.3 m.
- Reducing the bolt spacing to Li's (2017) recommendations was found to have a slightly favourable effect on the depth of the failure zone, but not a significant decrease (approximately 20 cm).

Figure 5 shows an example of the various support elements and DFN in RS2, where the extent of the failure zone is represented by areas with a strength factor > 1.

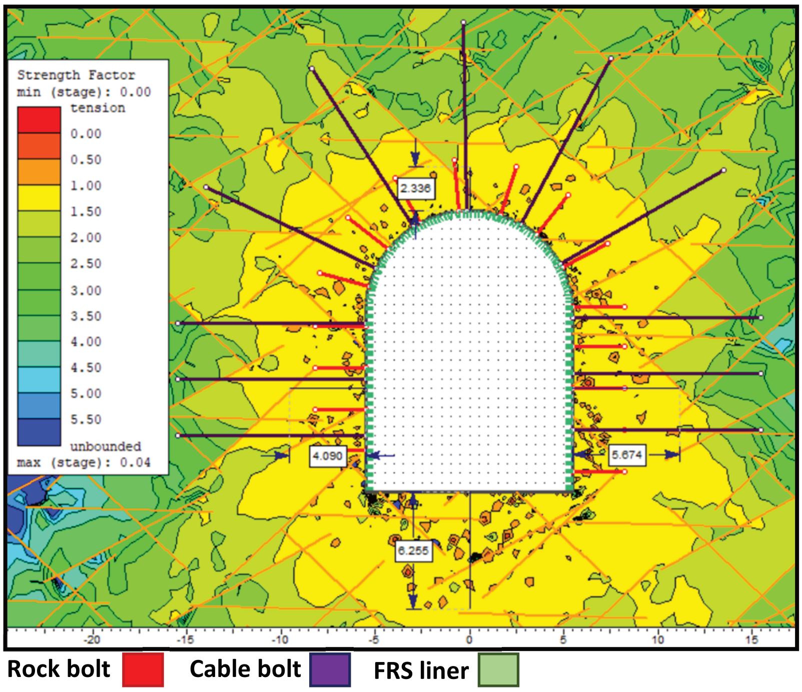

Figure 5 Example of the RS2 modelling, showing the support system and depth of failure zone

5 3D numerical modelling in RS3

Three-dimensional finite element modelling was carried out using RS3 software (Rocscience 2020) and used to examine more of the development as opposed to a single 2D chamber in previous analyses. Unlike the 2D analysis, the influence of a DFN was not investigated.

Figure 6 shows four views of the crusher chamber geometry with a blue iso-contour of 1 for the Strength Factor once support was installed; this value indicates the extent and location of areas that are likely to experience failure and correspond with the distribution of yielded elements. The distribution of the Strength Factor iso-contour suggests that failure is most likely to occur in the sidewalls and portions of the roof and floor. The maximum extent of the failure zone was interpreted to be approximately 3–5 m, which is reasonably similar to the RS2 results. It is thought that this estimate is conservative as the DFN was not included.

The modelling process was repeated with the addition of a large void, which was a simplified representation of the adjacent block cave. The results showed that the addition of the block cave increased the depth of the likely failure zone in some regions up to 1 m, in addition to failure areas becoming more widespread, particularly in the upper half of the geometry proximal to the block cave. The increase in the depth of the failure zone may indicate that the rockbolts would have to be extended to penetrate at least 1 m beyond the failed zone under Li's (2017) guidelines. Total displacement was recorded to be a maximum of 16 mm in the roof of the main excavation and sidewalls (Figure 7).

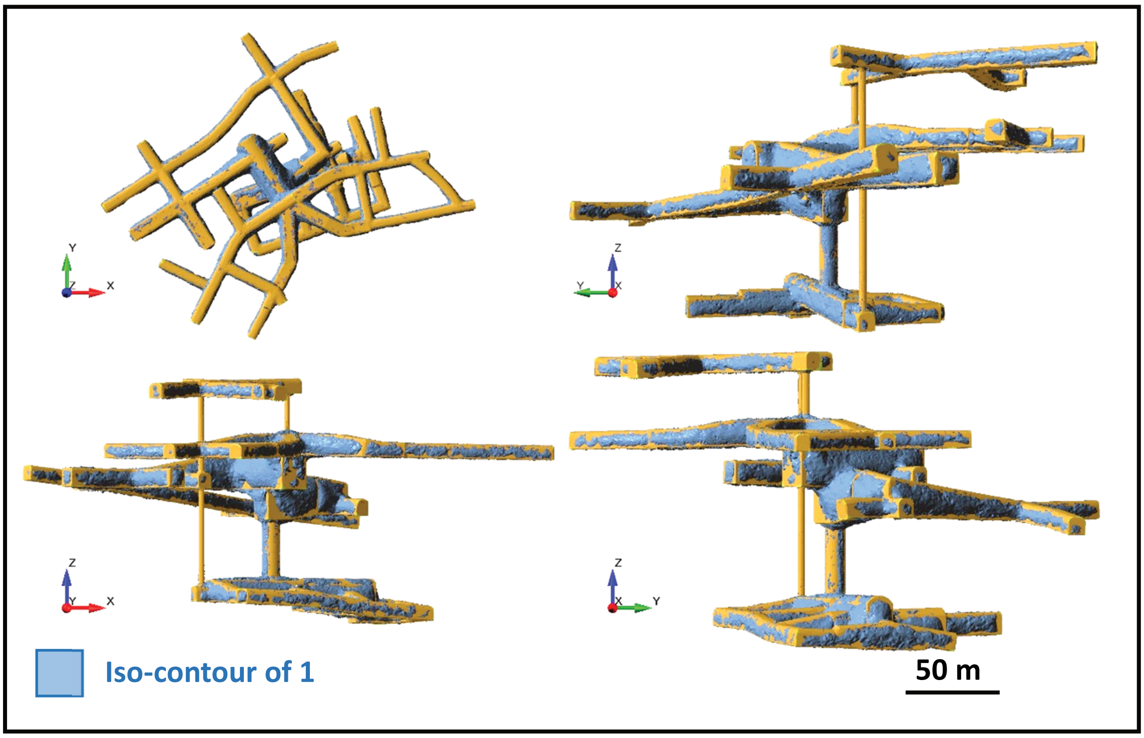

Figure 6 RS3 modelling showing Strength Factor iso-contour of 1 indicating areas of failure (blue)

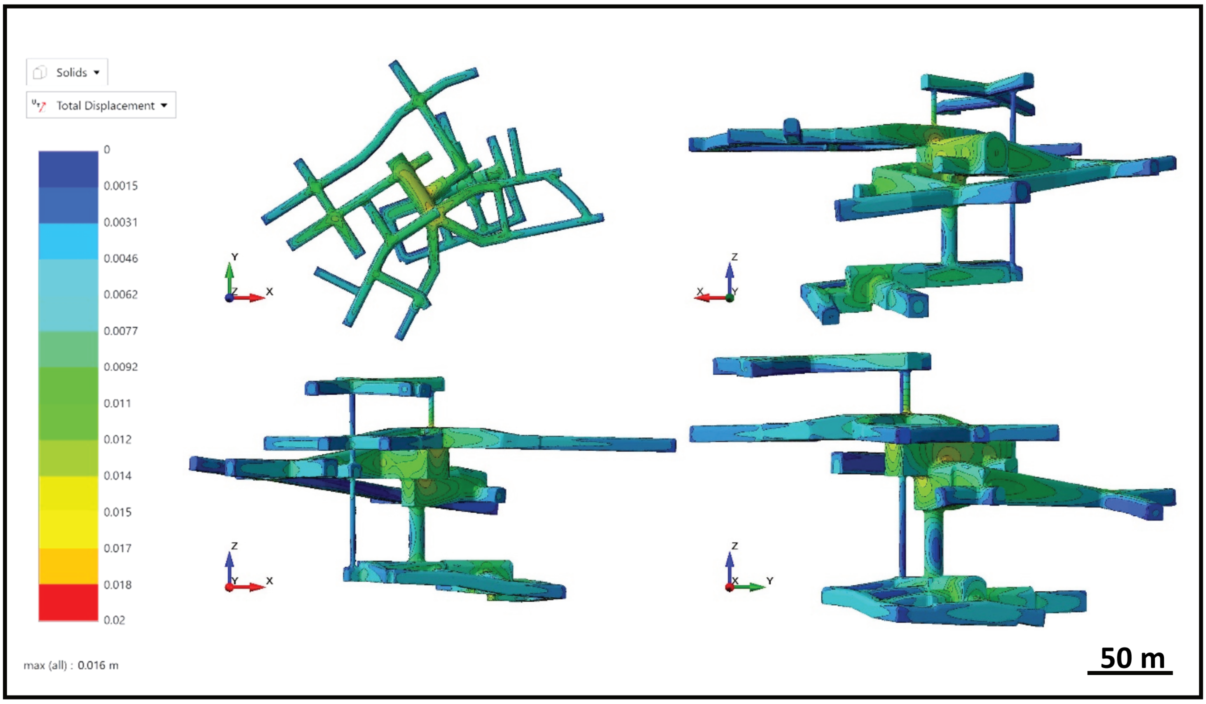

Figure 7 RS3 modelling showing the total displacement on the 3D geometry

6 Conclusion

This paper has demonstrated that the mixed-method approach can be successfully used within the workflow of underground support assessments to model numerous variations of support systems and ground conditions through the example use of data relating to an unnamed block cave project. The Rocscience suite of software has been shown to aid in identifying structural relationships, wedge formations, stress conditions, and total displacements, in addition to creating adequate 2D and 3D models of the development geometry to test suggested empirical support systems and other literature-based recommendations.

In the used example, empirical schemes were shown to offer a sufficiently good first pass when arriving at adequate support recommendations for the specific stress and rock conditions at the operation. The testing of empirical support within the Rocscience models proved critical in identifying whether the support system required modifications as well as identifying the adverse impact of the adjacent block cave on stability. Further steps could be taken to improve the proposed approach with more data and analysis capabilities, such as downhole geophysics, calibrated numerical modelling with a DFN, and synthetic rock mass modelling.

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