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In situ stress data management and analysis: implications for numerical modelling

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Abstract

The measurement of in situ stresses is a costly and time intensive procedure, requiring significant experience, diligence and planning to obtain reliable results. Therefore, it is important to have good data management and analysis to maintain investment costs and reduce estimate uncertainty. Geotechnical design considerations rely on accurate estimates of the stress regime to predict subsurface rock behaviour. Some uses include cave deconfinement, cave preconditioning, planning drive orientation and ground support design. Two simple numerical models are presented. The first demonstrates stress redistribution around a cave zone and how it may influence optimal crusher chamber placement. The second model is of an undercut level and the stress experienced by the drawbell drives below. The models demonstrate the impact of in situ stress uncertainty, with potential consequences for design decisions by altering the stress trend and plunge. Currently, pragmatic workflows are not publicly available that holistically detail the key steps in in situ stress data analysis. In addition, rarely are end-users of the data demonstrated the uncertainty in the values provided. Instead, they are presented with a single stress average gradient and trend. This manuscript offers a workflow for those embarking on in situ stress testing campaigns and serves as a tool to communicate the complexities to potential end-users. The workflow utilises the Euclidian mean rather than scalar averaging of the stress tensor and relates 'loading methods' (hydrofracking) and 'other' (borehole breakout observations) methods of stress estimation with the full tensor resolved from relief methods (overcore and acoustic emissions). A software application within the mXrap suite is presented as a potential aid to stress data management and analysis. Implications of stress uncertainty are demonstrated and discussed concerning design, expected induced fracture orientations, and future workflow enhancements. The numerical models indicate optimal placement for a crusher chamber around a simulated cave zone was observed to be in the orientation of SHmax. Increasing the stress field plunge by 20° impacted optimal crusher placement. The second numerical model demonstrates that a rotation of the horizontal stress trend by 20° has noticeable impact on the differential stress in the backs of a tunnel where drawbells will be created, this has implications for planning the undercut veranda length.

Keywords: *in situ stress, uncertainty, numerical modelling, geotechnical design*

1 Introduction

Estimating in situ stress is key to predicting rock behaviour when working underground. Specifically, knowledge of the in situ stress field's orientation and magnitude is used to predict regions of development expected to have higher rates of damage, plan ground support requirements, optimise drive orientation, and predict induced fracture geometries for preconditioning (Flores & Catalan 2019; Hao et al. 2021; He et al. 2016; Naik et al. 2018; Zhu et al. 2015). For block caving operations, by considering the prevailing stress field and induced stress changes from caving, engineers can optimise the mine layout such as the orientation of extraction drives and the positioning of key infrastructure such as crusher chambers and declines. However, the benefits of in situ stress data can only be realised if the testing procedures are followed correctly, the data management is efficient, quality assurance quality control (QAQC) is carried out, and there is a proper understanding of the limitations and uncertainties when analysing numerical models involving the data.

Adding to the complexity, in situ stress databases often include different stress measurement methods such as overcoring, acoustic emissions, hydrofracking, observations of drilling induced-tensile fractures (DITF), or borehole breakout.

In situ stress analysis must consider the full stress tensor and calculate the Euclidean mean rather than the simple scalar mean when given a dataset of principal stresses (Gao & Harrison 2019). The analysis must also consider stress gradients changes with depth and lithology; these factors may have interpretive implications for the in situ stresses, which will alter the most stable orientation for development as well as how induced fractures may orientate (Anderson 1905; Camac et al. 2006; Hillis & Williams 1993; Hubbert & Willis 1957; Reynolds et al. 2006). Sometimes, considerable decisions are decided based on low-level study information at the pre-planning stage of mine design. The determination of resource and reserve is given great scrutiny, but in situ stress, which can have considerable impacts on feasibility and mine design, is not as thoroughly investigated, and the consequences are not fully communicated. By considering uncertainty in the stress field as part of numerical modelling, we can assess the need for flexibility in mine design and make informed decisions as new data becomes available. Knowledge of the level of in situ stress uncertainty and the effect on mine design can also help provide a rationale to management as to which datasets require prioritisation before a design becomes permanent or less flexible. While there is published information about each step of the overall workflow, there is no publicly available demonstration of a workflow that details the tools, methods and considerations made while managing in situ stress databases. In this paper, we show a number of considerations to be taken regarding the analysis and use of in situ stress data including common problems and QAQC options.

A relative demonstration of stress uncertainty on block cave mine design is provided. To do this, we show the change in horizontal stress trend by 20°. A 20° uncertainty in stress orientation is A/B class depending on the dataset as per World Stress Map (WSM) ranking (Heidbach et al. 2010; Morawietz et al. 2020). First, we will show the impact of stress redistribution around a block cave and how the uncertainty in stress plunge and dip may be considered as part of mine planning. Next, we show a blasted undercut level and assess the stress shadow from the veranda caused by the edge of the cave and its stress on the closest extraction drive. The cave zone model shows that the placement of a crusher chamber in relation to caved material and stress field will significantly change the expected volumetric strain, i.e. damage on the chamber. The undercut model shows uncertainty in the horizontal stress orientation of 20° (319°N to 339°N), resulting in the extraction drives experiencing higher stress in the backs and lower confining stress in the sidewalls as the orientation is suboptimal. The uncertainty also may impact the planned veranda length.

2 In situ stress: methods, analysis and limitations

A variety of methods exist to estimate the magnitude and orientations of the principal stresses (σ_1, σ_2 and σ_3) which are referred to as the maximum, intermediate and minimum stresses. The principal stresses that align with the cartesian coordinates can be referenced as σH, the maximum horizontal stress, σh, minimum horizontal stress and σv vertical stress or overburden stress (also written as SHmax, Shmin and Sv). The relative magnitudes of the cartesian aligned stresses will determine the fault regime. Reverse (SHmax (σ_1) > Shmin (σ_2) > Sv (σ_3)), strike-slip (SHmax (σ_1) > Sv (σ_2) > Shmin(σ_3)), Normal (Sv(σ_1) > SHmax(σ_2) > Shmin(σ_3)). In situ stress measurement methods can be broken down into three types: loading, relief, and other methods (Morawietz et al. 2020).

2.1 Loading methods

Loading methods relate to the pressurisation of boreholes by the injection of fluids, this can take the form of leak-off tests or extended leak-off tests (also known as mini-frac). Loading methods can be conducted at great depths >3 km, the temperature is not as detrimental to pressurisation tests as overcoring, where glue bonding can become an issue (Ask 2006; Sjöberg & Klasson 2003). The test starts by sealing an area with packers and pressurising a section of the well until σ_3 and the tensile strength of the rock is overcome (Zoback 2010). The point at which the pressure rate is no longer increasingly linearly (because a fracture has been created, and fluid is lost to it) is known as the leak-off point (Postler 1997; White et al. 2002). The pressure change on the flow back is known as the instantaneous shut-in pressure (ISIP) which is equivalent to σ_3. The fracture can be re-opened and closed again in a multiple cycle test, extended leak-off.

Loading methods have their limitations, and not all the components of the stress tensor are resolved, so other observations will need to be made to determine the trend and plunge of the stress field. After σ_3 is resolved, the other principal stresses will need to be determined. In strike-slip (SHmax > Sv > Shmin) and normal faulting environments (Sv>SHmax>Shmin), this is not too much of an issue as Shmin = σ_3 (when the orientation of the borehole is perpendicular to one of the principal stresses). The vertical stress or overburden stress can be resolved by the integration of wireline geophysical density logs (Equation 1) (Bell 1996; Musolino et al. n.d.-b) or by using a correlation with sonic velocity (Gardner et al. 1974; Ludwig et al. 1970). SHmax can then be constrained by a number of observations such as the occurrence of breakouts, the measurement of breakout widths or by the occurrence of DITF (Barton et al. 1988; Hubbert & Willis 1957; Kirsch 1898; Molaghab et al. 2017; Moos & Zoback 1990; Zoback 2010).

However, in reverse faulting environments (SHmax > Shmin > Sv), this is not as straightforward as fractures will open against Sv and resolving Shmin in this environment is complex. The uncertainty is probably insufficient for design purposes (Bailey et al. 2016; Couzens-Schultz & Chan 2010; Musolino et al. n.d.-a).

$$\sigma v = \int_0^z \rho(z) g dz \quad (1)$$

Furthermore, the method assumes the boreholes alignment is parallel to at least one of the principal stresses, and this may not always be the case as boreholes in hard rock mining may be produced for other primary goals like resource logging or hydrofracking. For purposes of QAQC, practitioners will need to assess the orientation of the hole and have an idea of the stress regime. One option is to compare overburden stress and leak-off values. If the values of Sv and Shmin are similar, you may be in a transition stress regime or reverse faulting (Baumgärtner & Zoback 1989). Another consideration is where the actual leak-off point and ISIP occur on the pressure–time graph, modern gauges take pressure data frequently, but legacy data and some operators will just note pressures from the gauge by hand, creating interpolation issues (Musolino et al. n.d.-a).

2.2 Relief methods

Two relief methods commonly used in hard rock mining are acoustic emissions testing and overcoring; they are indirect stress measurements that are inferred from the elastic response of stress relief by the overcoring process (Gray & See 2007; Hakala et al. 2003; Kanagawa et al. 1986; Worotnicki 1993). The strain gauge data is used to determine the complete 3D stress tensor (Figure 1). It should be noted that the assumption is a homogeneous isotropic linear elastic response, which may not always be the case (Hakala et al. 2003). Hakala et al. (2003) found that variations in Young's modulus has close to 100% proportional effect on interpreted stress magnitudes while variation in Poisson's ratio can vary between a 20–60% effect. The effect on stress trend is less, varying by only a few degrees. Another factor is temperature which significantly impacts overcore measurements, leading to the development of temperature compensation tools (Cai 1991; Li et al. 2019).

Another relief method is the acoustic emissions (AE) test, which utilises the Kaiser effect (Holcomb 1993; Kaiser 1964). When loading and unloading a sample, the technique relies upon the rock not having a significant increase in acoustic emission response until the stress of the previous loading and unloading cycle is exceeded, giving an estimate of maximum stress the rock was subjected to in situ (Lavrov 2003). Naturally, this only resolves the highest stress the rock is subject to and may not reflect current in situ stress, although it is thought that over long periods the Kaiser effect seems likely to reflect more recent history than paleo stresses (Lavrov 2003; Momayez & Hassuni 1992). A methodological uncertainty associated with this method is the method used to identify the point of sudden increases on the total AE count–time graphs (Bai et al. 2018; Momayez & Hassuni 1992). Under lab conditions, acoustic emissions at AE methods have been shown to correlate within ±10% of overcore and hydraulic fracturing (Seto et al. 1999). Acoustic emissions testing in our dataset produced stress magnitudes similar to that of overcore however, the mean orientations rotated 83°, 309°N for overcore and 32°N for AE, requiring other methods to determine reliability.

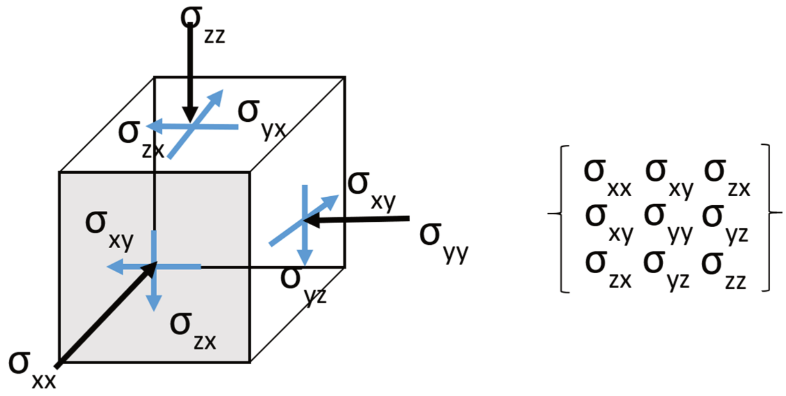

Figure 1 Stress tensor where σ_{xx} σ_{yy} and σ_{zz} are the stresses acting perpendicular to the surface

2.3 Other methods

Other methods of stress measurement involve observing or measuring borehole breakouts and observation of DITF. These methods provide bounds to SHmax in strike-slip and normal faulting environments (Barton et al. 1988; Couzens-Schultz & Chan 2010; Hubbert & Willis 1957; Kirsch 1898; Molaghab et al. 2017; Moos & Zoback 1990; Zoback 2010). To determine σ_1 magnitude through these methods requires knowledge of σ_2 and σ_3, as well as compressive strength in the case of methods utilising borehole breakouts. The occurrence of borehole breakouts and DITF indicate a limit to the stress. In the presence of DITF SHmax can be estimated by Equation 2 where Pp = pore pressure (MPa), Pw = Pmud = mud weight pressure (MPa) T_o = tensile strength (assumed zero if DITF present) (MPa) $\sigma\Delta T$ = thermal stress determined by the linear coefficient of thermal expansion (C°) multiplied by Young's modulus (MPa) multiplied by change in rock temperature (after mud) divide one minus Poisson's ratio (Hubbert & Willis 1957; Kirsch 1898; Zoback 2010). In the presence of borehole breakouts, SHmax can be estimated by Equation 3, where C_o = compressive rock strength (MPa) (Molaghab et al. 2017; Moos & Zoback 1990). If acoustic televiewer logs are available, specialist geophysical log software can allow for the measurement of borehole breakouts (Figure 2). Maximum horizontal stress (in the plane perpendicular to drilling) can then be estimated using the width of the borehole breakouts in Equation 4, where C_0 = Compressive rock strength (bar) $2\theta_b \equiv \pi - W_{bo}$ (wellbore breakout width) ΔP = difference between the wellbore pressure and the pore pressure (bar) (Barton et al. 1988). Borehole breakouts occur perpendicular to the maximum stress orientation, with tensile fractures occurring parallel with the maximum stress orientation. Some complications in these observations are determining a true breakout from drill reaming weak rock or key seating (where a groove is cut due to drill string rotation) key seats can usually be identified since they will occur on only one side of the borehole.

$$\text{SHmax (MPa)} = 3 \times \text{Sh} + \sigma^{\Delta T} - \text{Pp} - \text{Pw} - T_0 \quad (2)$$

$$\text{SHmax (MPa)} = 0.33 \times (\text{Sh} + \text{Pw} + \text{Pp} + C_o) \quad (3)$$

$$\text{SHmax (bar)} = (C_o + 2\text{Pp} + \Delta P + \sigma^{\Delta T}) - \text{Shmin} \times (1 + 2\cos 2\boldsymbol{\theta}_b) / (1 - 2\cos 2\boldsymbol{\theta}_b) \quad (4)$$

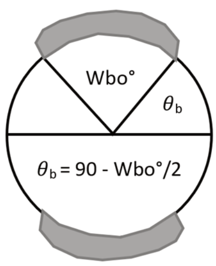

Figure 2 Vertical view of borehole geometry for Equation 4. Where Wbo is the width of the breakout in degrees

Observations of breakouts and DITF can be used to determine the orientation of the principal stresses (Nelson et al. 2006) (Figure 3). For example, a series of borehole breakouts in four raise bores were observed with the average SHmax trend of 307°N. The overcore measurements indicate a SHmax trend of 309°N. Of the four raise bores, one showed a 42°N rotation from the average estimate SHmax orientation from the borehole breakouts and 40°N north from the overcores. As a QAQC step we assessed the raisebore proximity to known faults. In this case a fault was 15–20 m proximal to the raisebore and the stress shadowing effect had likely rotated the stress field, a known phenomenon (Lin et al. 2010). Mine development also redistributes stress around excavations, so measurements taken within the influence zone will likely be affected as well (De La Vergne 2003; Martino & Chandler 2004). Important to note, In mines that host magnetic minerals such as magnetite, compass orientations and some drilling survey tools may be erroneous (McElhinney et al. 2000).

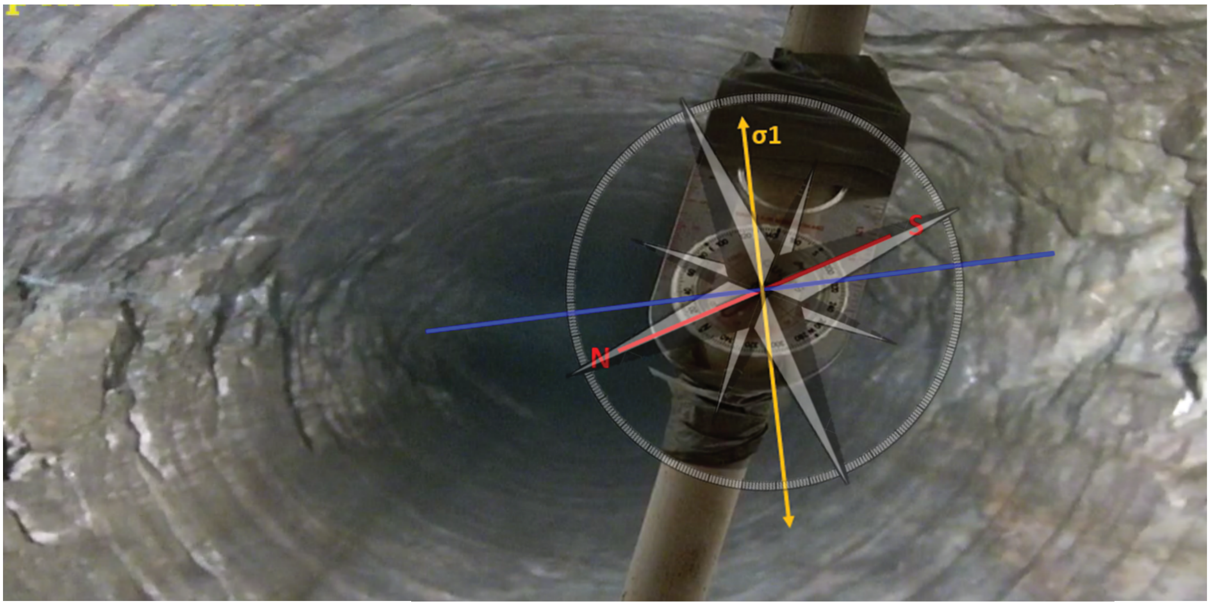

Figure 3 Example of borehole breakouts in raisebore, 90° to the orientation of SHmax (σ_1)

2.4 In situ data analysis and uncertainties

While each method has uncertainties and limitations individually, by understanding their methodologies and looking at the stress dataset, loading relief and 'other' methods can increase confidence in situ stress magnitudes and orientations. There still exists a challenge of implementing observations of stress orientations into datasets other than as a QAQC tool. Overcore or AE results are generally provided with estimated principal stress magnitudes, their plunge and trend. Simply averaging the stress magnitudes, plunges and trends from multiple tests using scalar methods may yield non-unique and non-orthogonal mean principal stresses, deviating significantly from the Euclidean mean (Gao & Harrison 2019) (Table 1).

Table 1 Example of difference between scalar and Euclidean mean results from Gao & Harrison (2019)

	σ_1 (MPa)	σ_1 (trend)	σ_1 (plunge)	σ_2 (MPa)	σ_2 (trend)	σ_2 (plunge)	σ_3 (MPa)	σ_3 (trend)	σ_3 (plunge)
Scalar/vector	41.51	317	18	26.17	81	65	20.51	176	83
Euclidean	34.86	294	7	31.49	25	6	21.84	155	80

The Euclidean mean method translates the stress magnitudes, plunges and trends to the cartesian coordinate system where each vector of the stress tensor is averaged independently, gradients can be determined using depth of measurement information and then the values are turned back into principal stresses using the matrix equation (Brady & Brown 2006). The Australian Centre for Geomechanics and OZ Minerals have developed a stress app for the mXrap platform that has automated this process (Harris & Wesseloo 2015).

There has not yet been a method to objectively rate the quality of individual methods in a way that impacts their weighting in a non-binary way (retain/remove) for mean stress gradient averaging. Practitioners have long been aware of factors affecting the quality and reliability of overcores, discussed in Section 2.2. However, there is sometimes a subjective binary approach to including or excluding data points, or a correction is applied (in the case of thermal effects) before inclusion in the dataset (Ask 2003; 2006; Pine et al. 1983). When assessing the quality of a given stress estimate, a quality system has been proposed (Heidbach et al. 2010; Morawietz et al. 2020). SHmax orientation (A) quality calls for 11 overcore measurements >300 m and a standard deviation <12°. For (B) tier there are eight measurements with depths >100 m and a standard deviation of <20°. For σ_3 magnitude overcores in (A) quality are 11 consistent measurements at depths >300 m with temperature effects noted. For (B) this is eight consistent measurements at >100 m, and temperature effects recorded. However, the quality is based on the number of datapoints and still does not consider individual data point confidence. In version two of the mXrap stress app we plan to humbly invite professionals from academia and industry for their input in creating a more objective, less binary system for quality ranking which allows for the weighting of individual data points. We are aiming for a consistent method that can separate individual tests into four categories, excellent, adequate, poor and invalid. Each category is then given a weighting, allowing for the weighted average of each stress tensor component in the cartesian coordinate system. As an example, the equation to calculate a weighted σ_{xx} (σ_{xx}w) is proposed (Equation 5). Where W_1 is the weighting of the excellent category (0.5), W_2 is the weighting of the adequate category (0.3) and W_3 is the weighting of the poor category (0.2). Where $N\sigma xx_E$ is the number of tests in the excellent (E) category, A for the adequate category and P for the poor category. The invalid category is entirely excluded.

$$\sigma_{xx_w} = \left(W_{1(0.5)} \times \frac{\Sigma\sigma_{xx_E}}{N\sigma_{xx_E}}\right) + \left(W_{2(0.3)} \times \frac{\Sigma\sigma_{xx_A}}{N\sigma_{xx_A}}\right) + \left(W_{3(0.2)} \times \frac{\Sigma\sigma_{xx_P}}{N\sigma_{xx_P}}\right) \quad (5)$$

Lastly practitioners should be cautioned with using a single stress field as stress magnitudes may not increase linearly with depth. Extrapolating stress measurements taken at shallower depths is fraught with uncertainty, especially if there is complex topography or changes in lithologies (Haimson 2010). There is evidence in Australia of stress transitions where Sv and Shmin switches between σ_3 to σ_2 (Reynolds et al. 2006; Tavener et al. 2017). The orientation of the stress field may also change with depth, in Rittershoffen France, a clear example of stress decoupling was observed by borehole breakouts and DITF, SHmax trend rotated from 155°N to 20°N between the sedimentary sequences and basement (Hehn et al. 2016).

2.5 In situ stress and cave mine design considerations

Stress regime transitions could result in the rotation of expected fracture orientation in block cave preconditioning. Preconditioning in block cave mines involves the production of complex fracture networks to enhance caveability. In different stress environments, the orientation of these fractures will impact how boreholes are designed to create the desired fractures (He et al. 2016). Fractures will open against σ_3 and propagate in the direction of σ_1. In reverse faulting environments, fractures will open vertically and propagate horizontally, and in strike-slip and normal faulting environments, they will open horizontally and propagate vertically. It is difficult to tell from borehole images which way fractures propagate. Generally, fractures will open in the borehole wall and rotate to the orientation dictated by the prevailing in situ stress as they propagate away from the borehole stress influence (Zoback & Pollard 1978).

Orientating development tunnels in line with the maximum principal stress trend is optimal for stability (Hao et al. 2021; Naik et al. 2018; Zhu et al. 2015). However, the maximum principal stress orientation can rotate with depth and has been observed by borehole breakouts (Camac et al. 2006; Hehn et al. 2016). Due to the rotation of stresses with depth, shallower interpretations may not be optimal for designing longer life span working floor levels at much greater depths. Orientation of the drive in the prevailing stress field will affect the differential stress magnitude. The difference between σ_1 and σ_3 is important as the confining pressure is a factor in the rock mass strength. Some damage criteria consider the differential stress as well as rock strength (Martin et al. 1999). Using differential (σ_1–σ_3) stress-based criteria on plastic numerical models may be misleading or unrealistically low as the stresses have been redistributed with damage. In these cases, a measurement of volumetric strain can be a more useful tool. Volumetric strain represents damage severity and degree of disintegration within the rock mass, it is the unit change in volume related to deformation, a negative volumetric strain represents rock contraction and a positive value represents dilation (Rajmeny & Vakili 2017; Watson et al. 2015). To use volumetric strain as an interpretative tool for damage, calibration of numerical models to observed damage would need to be carried out. However, the relative difference can be used for demonstration purposes.

In cave mining, the caved zone will have a zone of influence dictated by its shape, size, depth and the prevailing principal stress orientation. There will be regions of higher stress perpendicular to the maximum principal stress and lower stress parallel with the maximum principal stress.

3 Numerical modelling methodology

All numerical models used in this study were constructed in Itasca's finite difference package FLAC3D (Itasca Consulting Group 2019) using Cavroc's StopeX add-on (Vakili et al. 2020) and Cavroc's Improved Unified Constitutive Model (IUCM) (Vakili 2016). Cavroc's StopeX plugin is a simple graphical user interface that streamlines the setup and analysis of FLAC3D models. StopeX allows for complex simulations to be constructed and simulated without the extensive training and experience that FLAC3D typically requires. The results of any StopeX model are automatically exported as *.vtk and *.csv files for manipulation and viewing with free software packages such as Paraview. The IUCM is a commercially available constitutive model that aims to collate and replicate rock mass failure documented in academic literature and conference proceedings. This approach has been documented and validated in both open pit and underground applications (Ford et al. 2020; Vakili 2017). Technical details relating to the implementation of the IUCM are published (Lorig & Varona 2013). But as a brief overview, the IUCM includes the following key features in all simulations:

- A non-linear peak strength envelope consistent with the generalised Hoek–Brown criterion.
- Zone dependant strain softening relationships for rock mass strength derived as part of the international caving study.
- A linear Mohr–Coulomb like failure envelope for the residual strength state of the rock mass.
- The incorporation of intact rock strength anisotropy due to foliation or planes of weakness.
- Dynamic post-peak response (dilatant and softening) as a function of the confining stress. This replicates increased rock mass dilation in low stress or tensile conditions, cohesion softening, friction softening for low confining stress and cohesion softening friction hardening for high confining stress.
- Rock mass modulus softening to account for reductions in stiffness due to failure.

In each simulation, excavations were mined sequentially. Depending on the firing simulated, different simulation rules were applied. The following rules were applied for each simulation: excavations, development, and infrastructure remain open voids during the entire simulation. Caved material, or undercut firings are treated as 'blind' or 'crush' firings with no free void being simulated. This is achieved by first treating the firings as open voids to redistribute the field stresses. During this step, the rock mass and caved material is treated as an elastic material so it cannot fail. After the model has come to equilibrium, the caved material is initialised in the undercut firing and the stresses are allowed to damage the rock mass. This approach is required to correctly account for the confinement dependency and dilatancy of the cave boundary near the undercut firings and to limit unrealistic displacements or stresses that may occur if the void is treated as open. Note that this simulation approach does not include automated methods of including an airgap and assumes that the cave void is 'choked' at all times during the simulation.

The numerical models demonstrate how changes in stress orientations based on uncertainty from in situ stress measurements may influence design decisions. Both models are set up in a homogeneous rock unit with granite material parameters, the stress regime is a reverse faulting environment where SHmax (σ_1) > Sh (σ_2) > Sv (σ_3). The model shown in Figures 4 and 5 occurs in two steps. The first step shows four crusher chambers excavated in the default stress field orientation. The next step is introducing a caved zone between the four crusher chambers to assess effect of stress redistribution onto the crusher chambers. For this model the stress field is shown as σ_1 and due to stress relief from damage, volumetric strain has been projected onto the crusher shapes. The model is repeated with plunge of σ_1 and σ_3 increased by 20° (Figure 5A2/B2).

The stresses are orthogonal, and a default SHmax trend is chosen as 319°N with 0° plunge (after removing some anomalous AE and overcore tests from the dataset). The second model presented is of a working level below a block of caved material (Figure 6A). Note that drawbells are not modelled connecting the working level to the caved material; this avoids a complex stress interaction hindering a simple, clear demonstration. The first step in the model excavates the working level, drawbell drives, and simulates caved material with a 20 m veranda between the edge of the cave material and the last working level drawbell drive. The next step is rotating the stress field trend 20°N (Figure 6B). A 20° trend change was chosen for demonstration since our stress dataset contains 11 overcores and five AE tests. However, we are confident in eight of the overcore tests, going by WSM rankings B quality ranking has a SHmax orientation ±15–20°. Additionally, within the overcores there are some within 10 m of another that have an interpreted SHmax trend 20° apart. Both A and B models of Figure 6 are repeated with an increased cave zone veranda of 12.5 m to assess the stress around the last drawbell drive. Stress is represented as the differential stress (σ_1 - σ_3). There was very little volumetric strain for this model, meaning stress did not reduce due to damage, making analysis of the differential stress relevant (Rajmeny & Vakili 2017; Watson et al. 2015).

4 Results

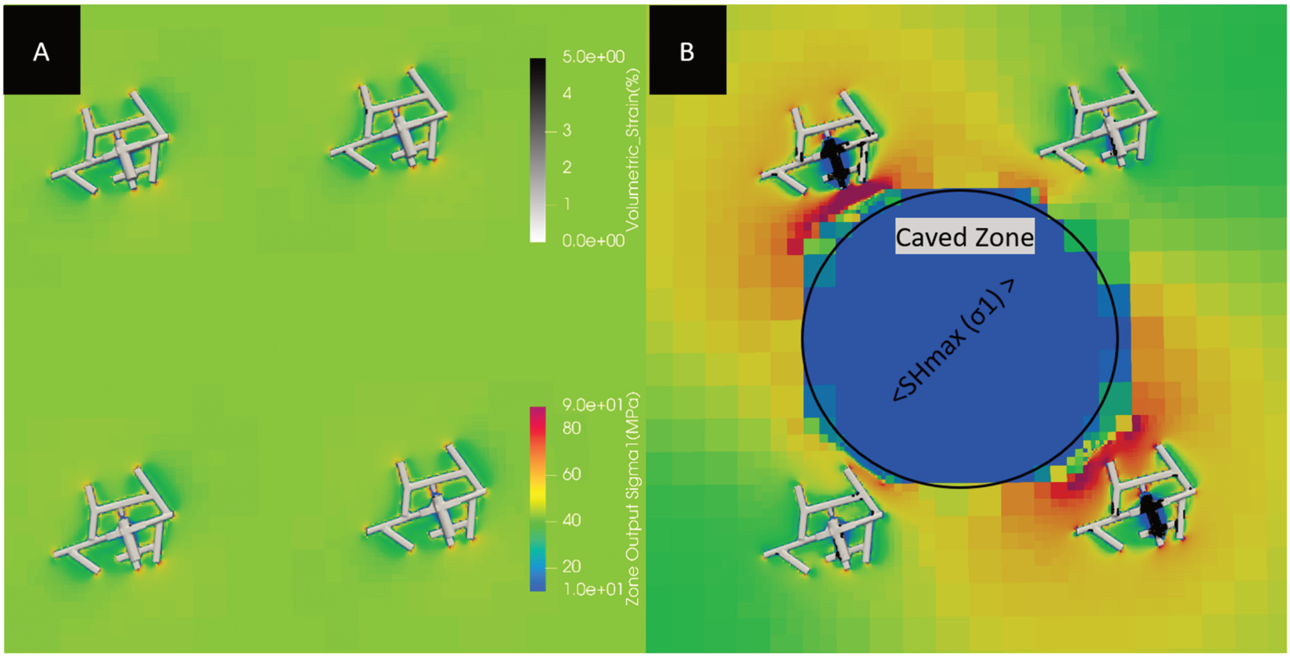

Figure 4 Four crusher chambers are placed at the same orientation, spaced apart as to not interact with each other. (A) σ_1 magnitudes around the crushers are identical. (B) A cave zone is placed in the centre of the four chambers. The caved zone has a clear impact on stresses around it with higher stresses being experienced in the crushers perpendicular to the orientation of σ_1. The crushers in (B) are coloured based on volumetric strain.

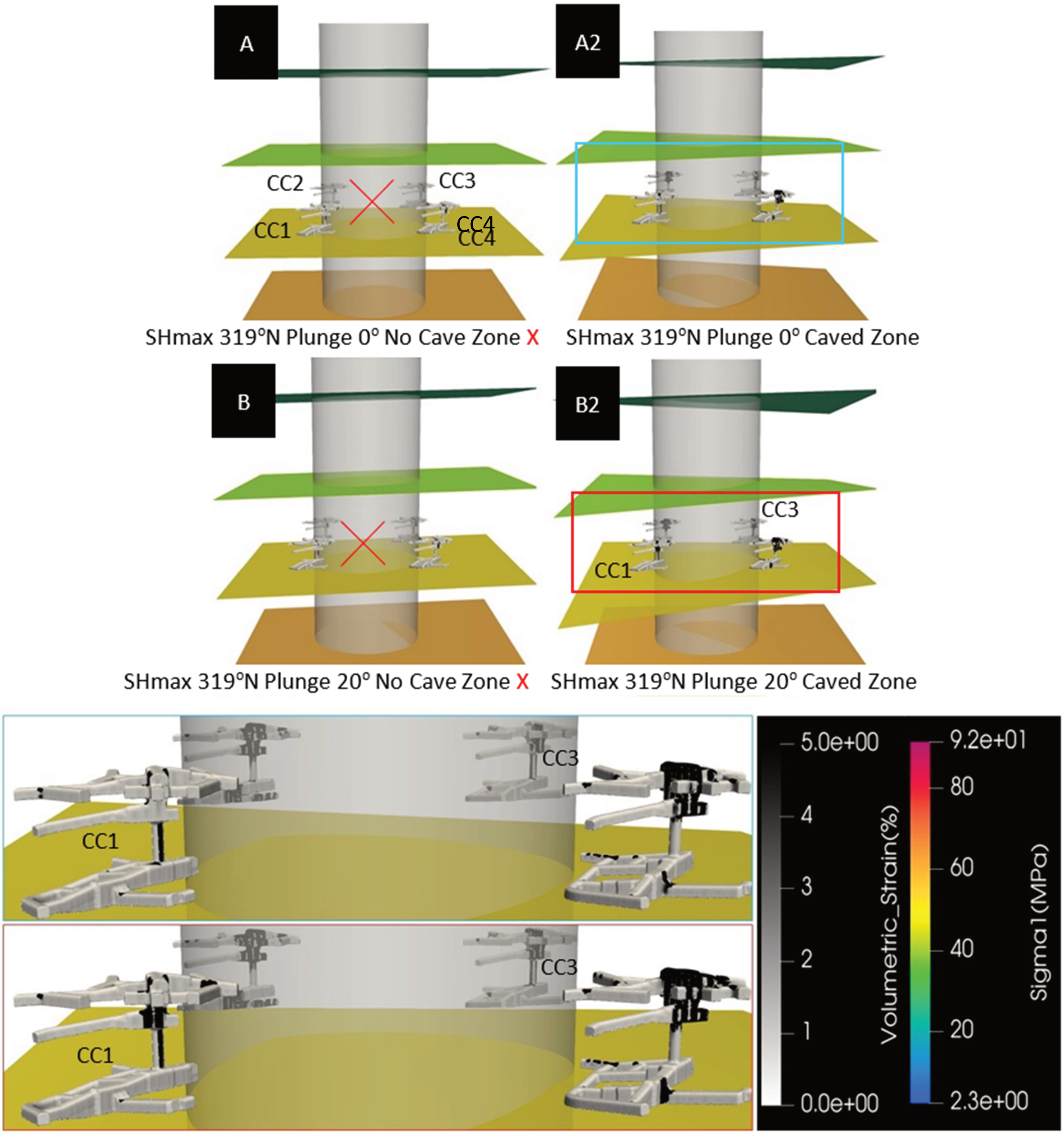

Figure 5 **The plunge of σ₁ is increased from 0° (A) to 20° (A2), (σ₃ plunge is also changed from 90 to 70 to ensure orthogonality). Contours of σ₁ are shown in slices, A and B show stress conditions before the caving, indicated by a red crossover the cylinder indicating the cave zone. Once the cave zone is applied A2 and B2 show the complex change in stress contours. Volumetric strain, represented by black colouring on the geometry is increased when the cave zone is introduced. Considerably higher volumetric strain can be observed in the crusher chambers after the cave zone has been applied, particularly in the orientation 90° to SHmax trend. The change in stress plunge is visually represented by the dipping planar stress contours after caving in B2, shows that of the two crusher chambers the crusher chamber (CC1) would experience less in situ stress at the same depth as (CC3)**

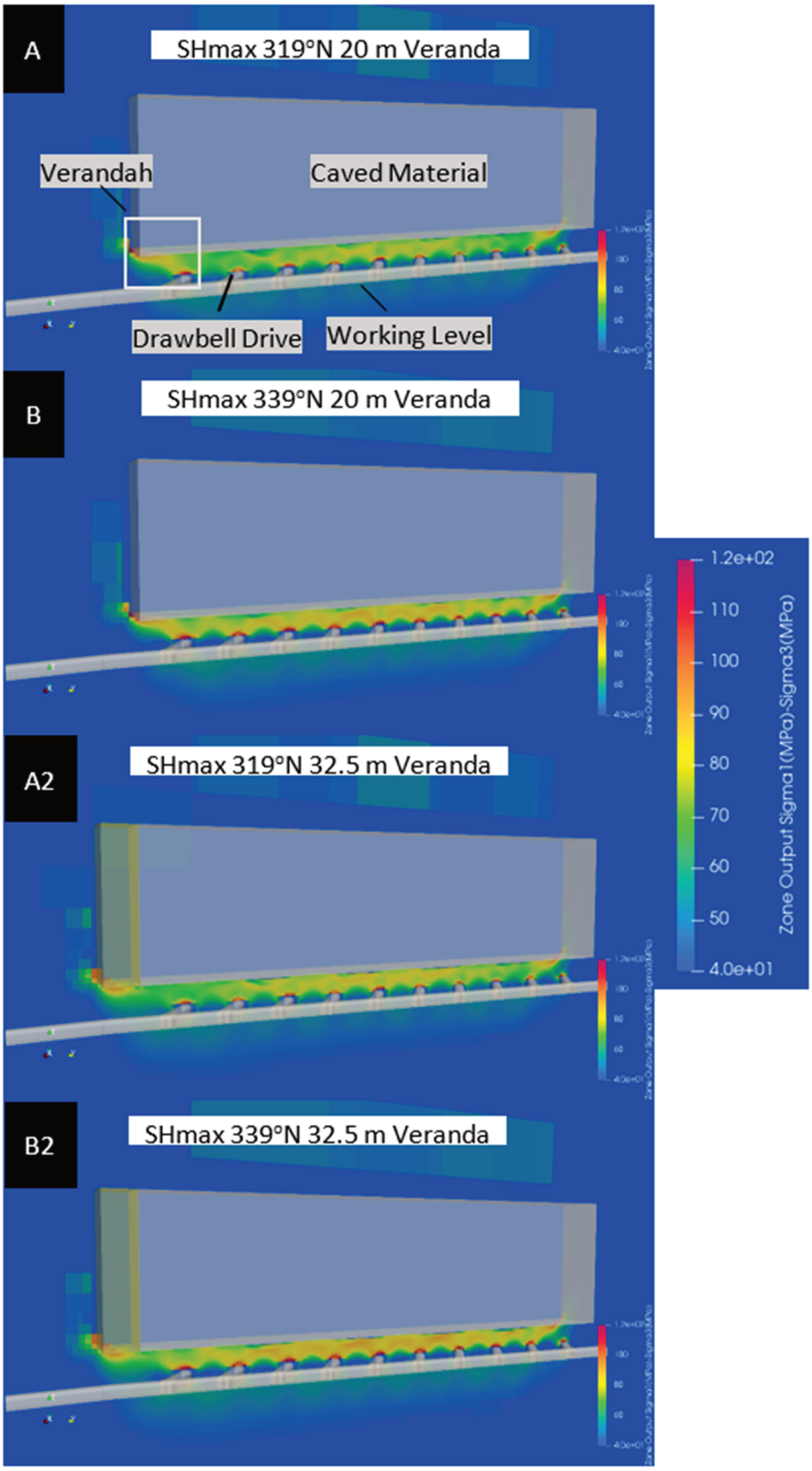

Figure 6 **Example of the stress veranda created at the terminal ends of a hypothetical cave zone on top of a working floor level. Shown is the differential stress (σ_1–σ_3). (A) The veranda has clear interaction with the terminal end of the caved zone. (B) The stress regime trend is rotated 20°N. The interaction between the last drawbell drive and veranda is more pronounced, the differential stress in the backs of the drives is higher than in (A). (A2) The veranda is extended by caving 12.5 m more material away from the last working floor drive, the interaction in the last drawbell drive is noticeably less. (B2) The veranda remains extended with the stress regime rotated 20 degrees north. The interaction in the veranda zone is less than (B) but higher than (A2)**

5 Conclusions and future work

We have shown that uncertainty regarding the management and analysis of in situ stress data can noticeably affect numerical models with the potential to impact design choices. Regarding cave mining methods, the placement of major long-lived developments such as crusher chambers would benefit from knowledge of the stress orientations that may not be adequately inferred without QAQC of the dataset, or by methods not considering the Euclidean mean. Deciding the length of the extra cave zone veranda over the drawbell drives may be influenced by the uncertainty of in situ stress magnitudes estimated in numerical models brought on by uncertainty in stress orientation. There are still challenges regarding the integration of 'loading and 'other methods' of in situ stress estimation methods with relief methods to determine average stress gradients, trends and dips. However, we have shown how 'loading' and 'other methods' can be used as QAQC tools. Objectively quantifying confidence for individual relief tests is not widely done. We have suggested a method on how a weighting system can be achieved and further investigation will focus on being able to better quantify weightings and quality rankings for individual tests. To integrate in situ stress estimates and mine design, a comprehensive plan for stress testing at set depth intervals away from developments and faults should be undertaken to guide early level design for cave mines. As cave mines become deeper and have longer operating life, understanding in situ stress in the design stages will be vital to optimise mine stability and reduce failure and rehabilitation rates.

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