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Successful Construction of a Complex 3D Excavation Using 2D and 3D Modelling

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ABSTRACT: Austar Coal Mine (Austar) successfully constructed an underground coal storage bin at a deep mine in challenging conditions. SCT Operations (SCT) was involved in various geotechnical assessments related to the bin excavation including vertical separation of the bin drift and underlying seam roadways, bin top area roof design and support and seam roof support at the bin base. Traditional methods used for determining support recommendations can be difficult to apply to complex three dimensional excavations. SCT used a combination of two dimensional and three dimensional numerical modelling using FLAC 2D and FLAC 3D to understand the key drivers and modes of failure about the bin excavation.The staged process of construction and an interactive approach between Austar and SCT enabled review and validation of the modelling process to occur throughout the construction. A key lesson from this program of work is that there is value in an interactive approach whereby site monitoring and review of model properties during construction provides early validation of the model. This ensures that natural geological variability, which can have significant impacts on rock failure and deformation, can be incorporated into the model as an ongoing process.

INTRODUCTION

Austar Coal Mine (Austar) is located approximately 10 km southwest of Cessnock in the Newcastle coal fields, New South Wales, Australia, as shown in Figure 1. Austar is owned by Yancoal and mines premium coking coal from the Greta Seam of the Greta Coal Measures at current overburden depths of approximately 500-550 m.

Figure 1: Location of Austar Coal Mine.

In 2012-2013, Austar installed a 1500 t underground coal storage bin for their expansion into Stage 3 of their mine plan consisting of Longwalls A7-A19. The underground coal storage bin was constructed by Mancala using a technique of raise boring then benching down in 1.5 m levels to form an elliptical 24 m high bin with axes 10 m and 14 m. A conveyor drift was firstly driven from seam level to the top of the

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underground bin to gain access for construction. The base of the bin is at approximately 460 m overburden depth.

SCT Operations (SCT) was involved in design and support recommendations for various geotechnical scenarios relating to the bin installation. Specific assessments conducted by SCT include:

- Drift and Greta Seam roadway vertical separation
- Bin top roof support and design, and,
- Greta Seam roof support at the bin base.

This paper consists of a high level summary of the geotechnical approach used for the design and support recommendations highlighting key controls, model outcomes and model validation from underground monitoring.

BACKGROUND

The underground coal storage bin design consists of the bin, bin top area, bin base area and drift. The bin design is presented in Figure 2. The sequence of bin excavation consisted of the drift, followed by the widening and floor excavation of the bin top area, then the benching down of the bin, followed by the seam level widening of bin base area.
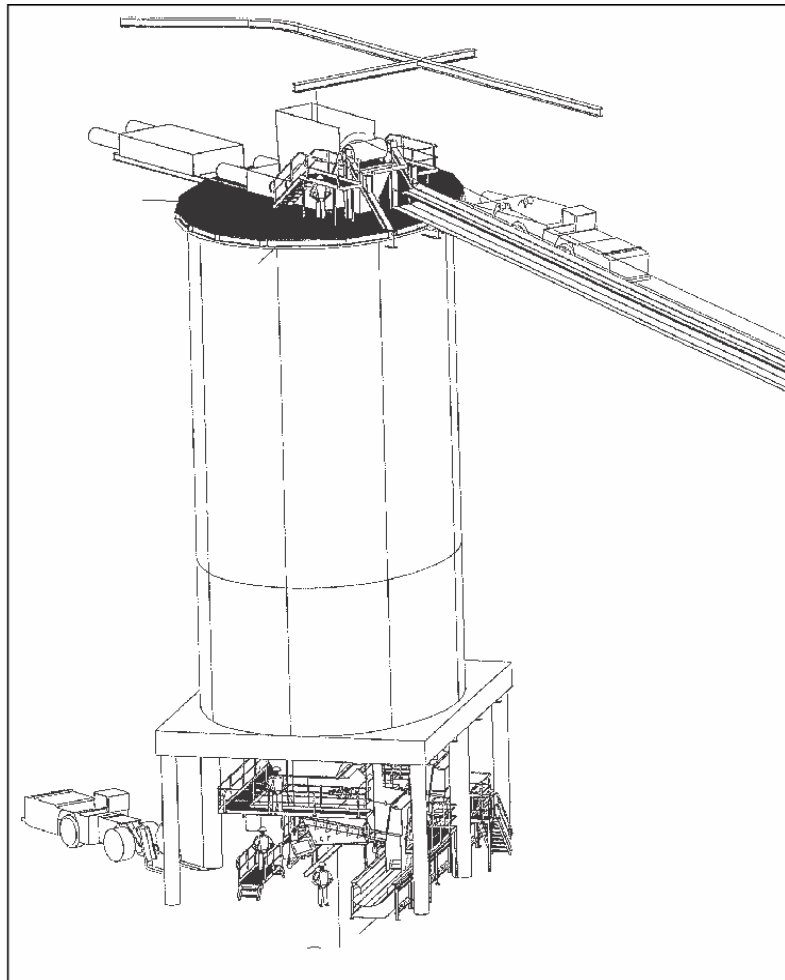

Figure 2: 3D diagram of underground coal storage bin arrangement. *(Courtesy of Arkhill Engineers.)*

The bin is an elliptical design with its long axis oriented in line with the maximum horizontal stress. The bin top area is an irregular shape of approximately 14 m by 20 m, with the drift entering approximately from the south. The bin top area design is presented in Figure 3a. The bin base area is an irregular area with an approximate roof span of 14 m by 8 m adjacent to the bin. The bin base area design is presented in Figure 3b. The location of the bin and its orientation to stress is presented in Figure 3c.
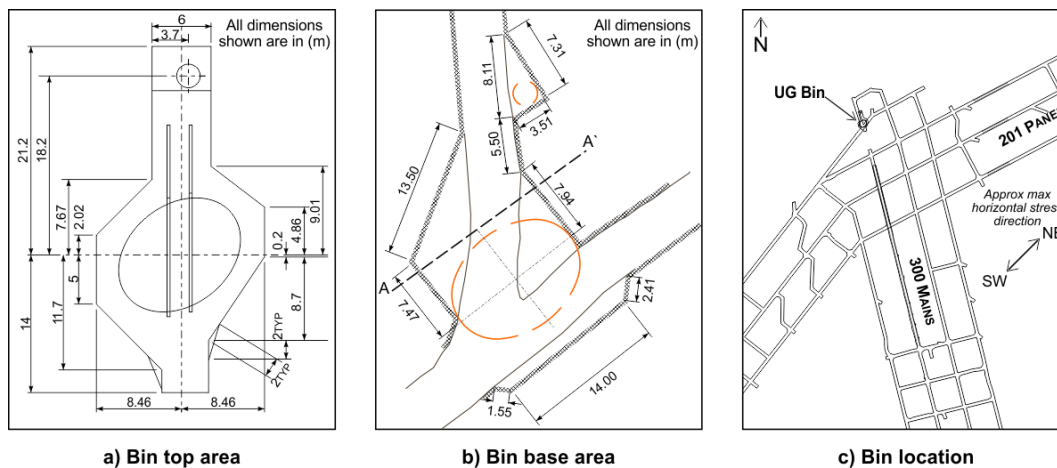
a) Bin top area   b) Bin base area   c) Bin location

Figure 3: Bin location with bin top and bin base area dimensions.

SCTs investigations were staged with the sequence of bin construction where drift separation was conducted first, followed by bin top and then bin base investigations. The sequence of assessments allowed validation and refinement of the model inputs during the investigations.

METHODOLOGY

A combination of two dimensional and three dimensional numerical modelling, using FLAC 2D and FLAC 3D, was used to assess the key drivers for deformation about the bin and associated excavations. Project time constraints dictated a combination of two dimensional and three dimensional models.

Unless stated otherwise, the two dimensional modelling using FLAC 2D uses SCT's "in house" rock failure code based on Mohr-Coulomb criteria relevant to confining conditions in the ground. The code in FLAC 2D uses a coupled mechanical and fluid flow system to simulate rock failure and pressure effects A detailed description of SCT's rock failure routines used in FLAC can be found in a number of references, in particular Gale *et al.,* (2004) and Gale and Tarrant (1997).

The modelled strata is based on geotechnical properties from a combination of Austar's rock test data, geophysical relationships and prior experience. The model UCS based on geophysics and rock test data from Austar, for both the drift separation models and the updated bin models, is presented in Figure 4. The UCS is determined from borehole sonic velocity and laboratory UCS relationships empirically described by various researchers such as McNally (1987) and Hatherly *et al.,* (2008).

The three dimensional modelling used the constitutive model of the bilinear strain-hardening/softening ubiquitous joint model in FLAC 3D. Rock properties were again based on Austar's rock test data, geophysical relationships and prior experience. The three dimensional models were generally used to assess the stress distribution around the bin and to assess bolt loads. The three dimensional models were not used to assess detailed rock failure due to the larger element sizes required to run the models in a shorter time frame.

Numerical modelling using FLAC 2D was conducted by SCT to assess the deformation between the Greta Seam roadway and the drift to determine a minimum vertical separation to prevent roadway instability. The key design guideline is to keep the seam roof deformation and the drift floor deformation separate. A conservative separation is also advised due to unknown joints and structure.

SCT's original modelling recommended a minimum separation of a 20 m rock head between the seam roadway roof and the drift floor. This recommendation took into account an upper bound of estimated tectonic stress where the model results showed a barrier between deformation of the two excavations.

For the purpose of validation, models were run at roadway separations coincident with the actual excavated separations for A, B and C Headings of 12.5 m, 16.5 m and 21.5 m. These models included simulation of both roadway and intersection scenarios where the mine site monitoring and observations were found to be consistent with the model results.
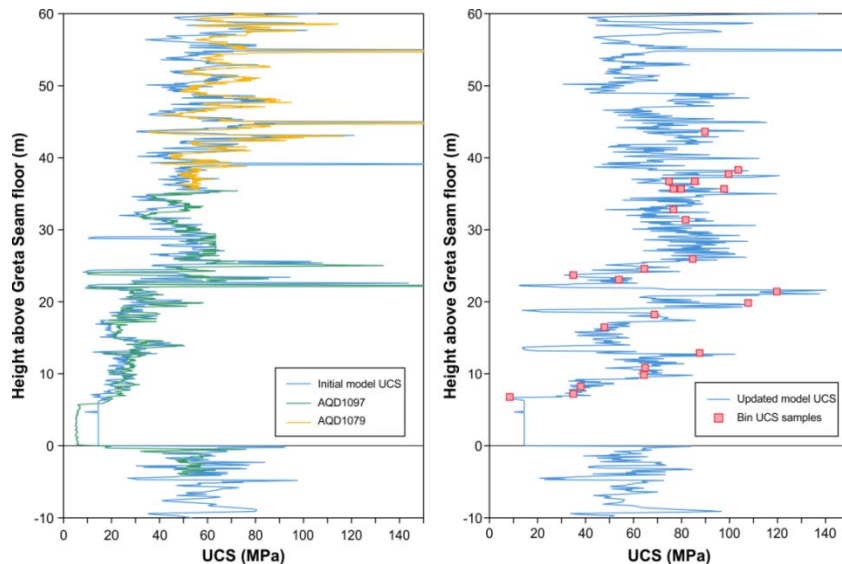
Figure 4: Modelled UCS for a) drift separation model, and b) bin models.

DRIFT AND ROADWAY VERTICAL SEPARATION ASSESSMENT

Pogo sticks in 1 cut-through between C and B headings monitored roadway convergence and showed convergence up to 120-140 mm. The model results for roadway convergence from 12.5-16.5 m separation were approximately 105-120 mm which is in the same order of magnitude as the pogo stick monitoring.

The primary modes of failure determined in the FLAC 2D models are shear failure and bedding shear failure. The roadway roof failure and drift floor failure are observed to connect for a 12.5 m separation while no connection is observed for the deformation of the 16.5 m and 21.5 m separation model. The mode of failure for the 12.5 m and 16.5 m models are presented in Figure 5. Models were also run with a widened roadway representing an intersection at seam level. In this scenario there is a connection between the intersection roof deformation and the drift floor deformation at 16.5 m separation, however a barrier exists for the 21.5 m separation.

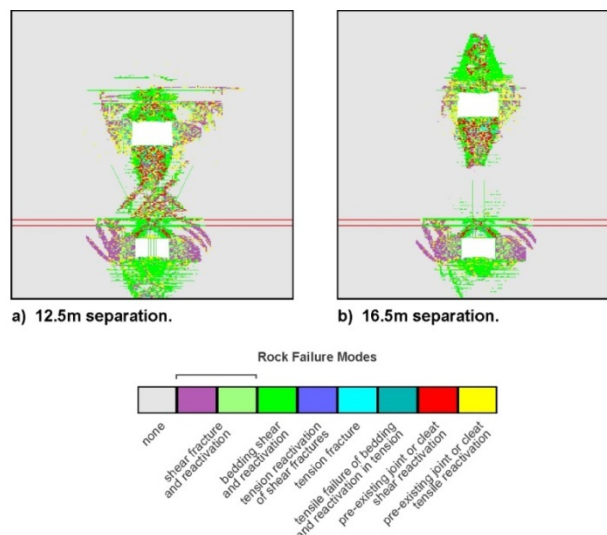a) 12.5m separation.   b) 16.5m separation.

Figure 5: Mode of deformation for roadway interaction models at
12.5m and 16.5m and 21.5m separation.

The model results for vertical displacement between the roadway and drift are presented in Figure 6a. Negative displacements are downwards related to the roof of the coal seam intersection, while positive displacements are due to floor heave and failure in the floor of the drift. Figure 6b shows the vertical displacement relative to the seam roadway roof in order to compare the GEL extensometer and Tell Tale data. The monitoring data is consistent with the model data. The Tell Tales and GELs located between
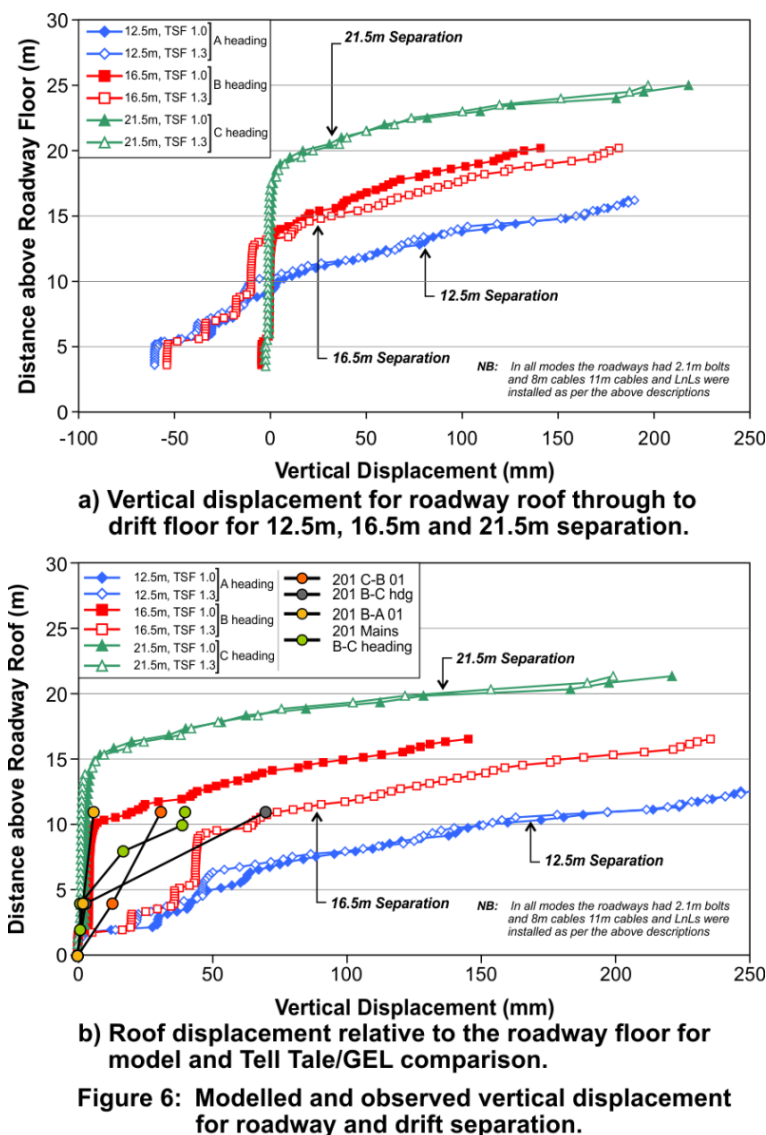
C and B heading are between the B and C heading extensometer profiles within the models. The Tell Tale between A and B heading is between the 16.5 m and 21.5 m model extensometer outputs. The monitoring data for the seam roadway intersections is also consistent with the model extensometer results.

Key outcomes from the drift separation assessments are as follows:

- Numerical modelling provided a means for determining an appropriate vertical separation between the seam level roadways and drift
- Monitoring and observations validated the model outputs

BIN TOP ROOF SUPPORT ASSESSMENT

The bin top area is a roof expanse of approximately 20 m by 14 m with the long axis oriented with the major horizontal stress direction. SCT conducted numerical modelling of the 14 m and 20 m roof expanses using FLAC 2D to assess the deformation in the roof and determine appropriate support recommendations. The bin top area is a three dimensional problem, however due to time constraints the approach was limited to two dimensional representation whilst taking into account the limitations of the two dimensional model.

a) Vertical displacement for roadway roof through to drift floor for 12.5m, 16.5m and 21.5m separation.

b) Roof displacement relative to the roadway floor for model and Tell Tale/GEL comparison.

Figure 6: Modelled and observed vertical displacement for roadway and drift separation.

The two dimensional models show the height of softening for the bin top roof at approximately 7-10 m for the 14-20 m roof expanse. Height of softening to this extent is problematic due to cables of similar

lengths not being able to pin back into intact strata. Figure 7a shows the mode of deformation for a 20 m wide bin top excavation with modelled primary and secondary support required to limit the roof deformation.

The height of softening is due to the reduction in vertical stress in the roof reducing confinement. The reduction in confining stress reduces the strength of the immediate roof and exposes the strata to the horizontal stress concentrations above the excavation. An arched roof model shows that the height of softening does not increase with the increase in roof height. The arched roof design removes the unconfined strata without redistributing stress. The mode of deformation for the arched roof of the 20 m roof expanse model is presented in Figure 7b where the secondary support is observed to extend into competent ground.
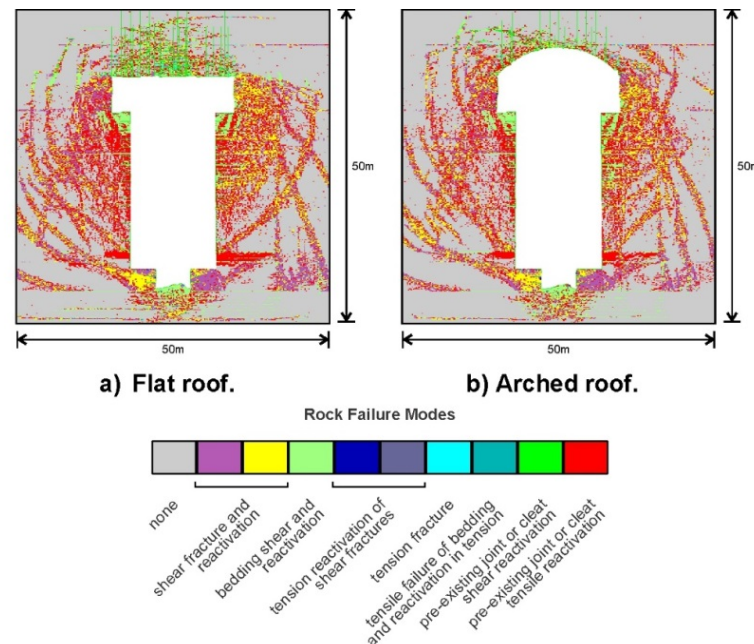

Figure 7: Mode of deformation for a 20m wide bin top section for a 14m wide bin.

Elastic models were run in FLAC 2D and FLAC 3D to compare the horizontal stress concentration in a flat roof, shown in Figure 8. Elastic models do not simulate stress transfer due to rock failure, however they provide an indication of the initial stress concentrations about the excavation. The stress concentrations in the two dimensional model are approximately 1.4 times the stress concentrations in the three dimensional model. The reduction in horizontal stress concentration in the roof indicates that the deformation may not be as much as observed in the two dimensional models and that the two dimensional models are a worst case scenario. The excavation is also expected to be controlled by its minimum width (such as an infinite roadway is). The deformation in the 14 m model is therefore expected to be more indicative of the three dimensional deformation than the 20 m model.
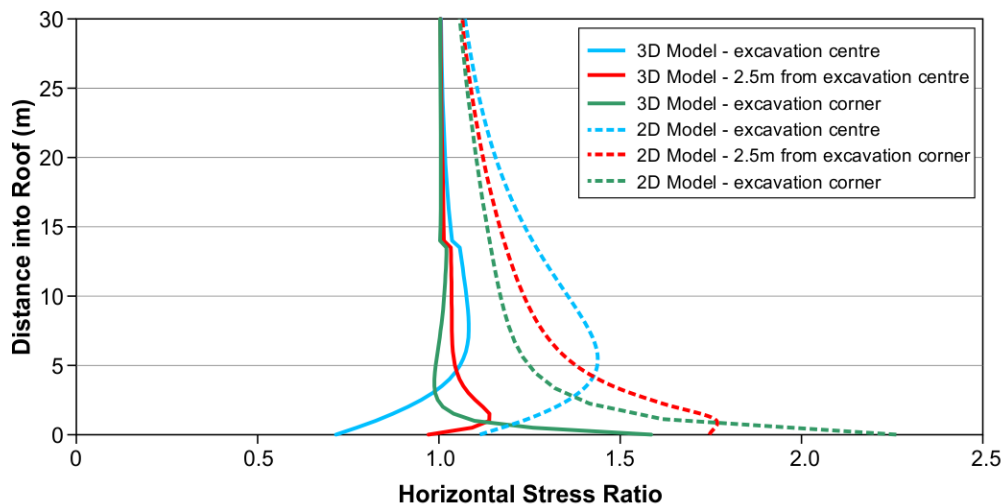

Figure 8: Horizontal stress profile for the roof of the bin top excavation.

The two dimensional model overestimates the stress concentration in the roof and the 14 m expanse model is likely to be the controlling expanse on the height of softening. Therefore a support pattern was recommended that involved a lower level of primary support (8 m cables at 2 m by 2 m grid), followed by a secondary support pattern (11 m infill cables creating 1 m x 1 m support pattern) if and after significant deformation occurs. This allows the strata to deform before adding in secondary support, thus adding confinement to the deformed strata using pre-tension cables, whilst also allowing a lower level of support to be used in the likely case that less deformation is observed than in the models.

Validation of the bin top modelling shows the arched roof is a stable shape with a maximum of 10 mm roof displacement measured, see photograph in Figure 9 of arched roof. The bin top deformation shows greater displacement in the modelling than observed which prompted a review of the rock model properties which included a new borehole drilled at the bin site. Rock properties were changed to fit the local rock test data with a higher Modulus to UCS ratio and less tectonic stress for higher strength lensing units. A 1x1 m constitutive Mohr Failure Model, to check the differences in rock properties, shows significantly less failure about the bin and bin top with the updated rock properties. There appears to be a different set of properties in the Branxton Formation that reduces rock failure in the bin top.

Figure 9:   Panoramic photo of bin top area.

Key outcomes form the bin top modelling are as follows:

- The arched roof design provides a more stable roof shape than the flat roof
- The smaller roof span of 14 m diameter is likely to be the controlling diameter
- Two dimensional models are likely to overestimate deformation due to:
  o Overestimating the stress concentration in the roof, due to the two dimensional model not redistributing the stress in three dimensions, and,
  o Underestimating the rock strength due to not correctly modelling the confining stress in the third dimension
- The roof support recommendations allowed a lower level of support to be used with a response plan for additional support

SEAM ROOF SUPPORT ASSESSMENT AT BASE OF BIN

The bin base area consists of a roadway intersection widened to accommodate bin infrastructure. This creates a roof expanse of approximately 14 m by 8 m adjacent to the bin. The stress and deformation is a complex three dimensional problem where the widened intersection is unconfined in one plane and hosts bin deformation in the seam roof before widening of the seam intersection. The model approach used a combination of FLAC 2D and FLAC 3D to assess the key controls of roof deformation.

The impact of the bin excavation on the seam roof stability was assessed in three dimensions using a bilinear strain-hardening/softening ubiquitous joint model in FLAC 3D. The reduction in stress about the bin shows that the bin deformation extends across the span of the seam roof. The major and minor horizontal stresses show stress redistribution around the whole excavation leaving minimal stress transfer and confinement in the seam roof. Figure 10 shows a slice of the stress distribution at 1 m from the edge of the bin while at 5m from the bin a similar stress distribution where the stress transfer is near zero is observed.
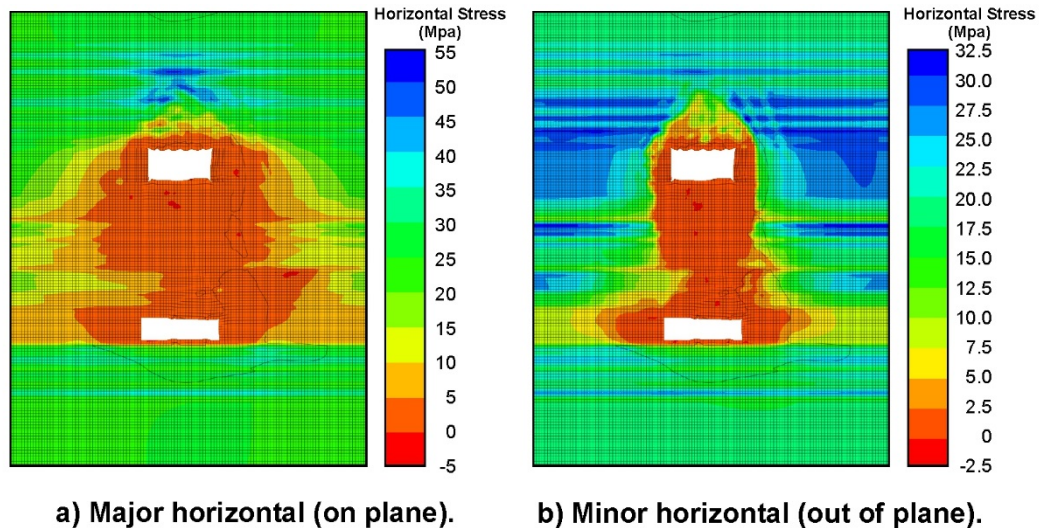
a) Major horizontal (on plane).   b) Minor horizontal (out of plane).

Figure 10:   Stress redistribution about bin on vertical plane A-A' (See Fig 3b).

Two dimensional modelling was aimed to assess the seam roof deformation for expected residual rock properties due to rock failure from the excavation of the bin. The main limitation of the two dimensional modelling is that it assumes an infinite roadway, where as in reality the roof span is confined on one side and open on the other where it meets the bin. Residual rock properties and stresses input into the seam roof prior to the widening of the bin bottom roadways reduce the appearance of shear failure in the roof however due to the residual rock properties and the lack of confinement, large displacements were observed in the roof strata of the model.

A two dimensional plan view Mohr failure model was run in the horizontal plane to observe the stress vectors about the bin excavation. Figure 11 shows the major stress vectors running tangentially around the bin excavation with the minor stress running perpendicular to the bin surface. The vertical stress is also larger than the minor horizontal stress and fractures would therefore form in the vertical plane about the bin.
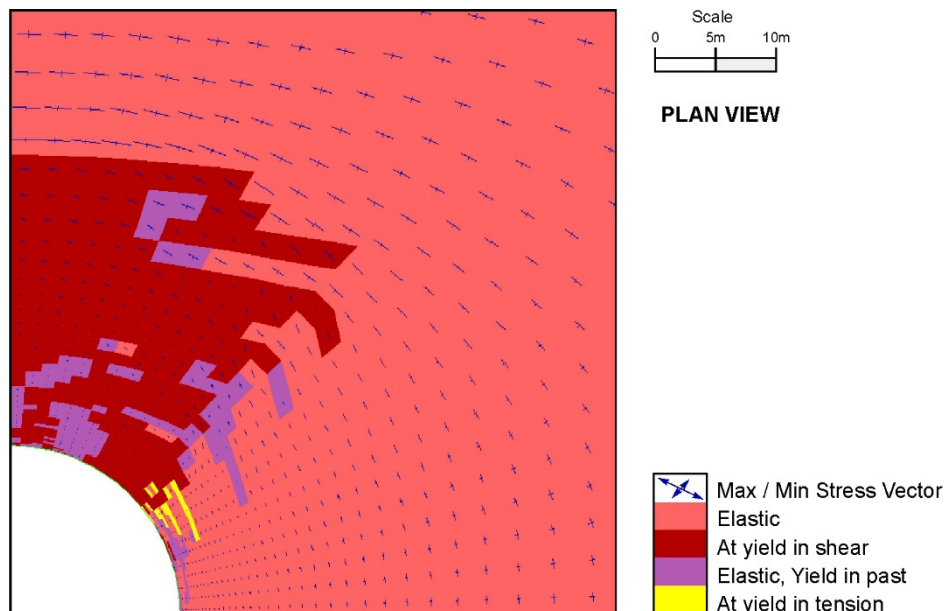

Figure 11:   Mohr Failure model with stress vectors around bin excavation.

Parallel horizontal 8 m cables extending from the bin wall at 3 m spacing per 1.5 m bench were recommended to provide seam roof confinement. Fifteen degree from vertical 10 m cables angled away from the bin were recommended at a 2 m by 2 m grid. The three dimensional bilinear strain-hardening/softening ubiquitous joint model shows that secondary support in the recommended

pattern does not yield, thus creating the required confinement on the vertical fractures formed about the bin.

Key outcomes from the seam roof support assessment at the base of the bin are as follows:

- There is very little confinement in the immediate roof and so there is a need to generate confinement with pre-tensioned secondary support
- Horizontal and angled vertical cables are required to confine the vertical fractures forming around the bin
- The models show that although primary support yields, secondary cables do not yield and therefore create the required confinement in the seam roof strata

CONCLUSIONS

A combination of two dimensional and three dimensional numerical modelling enabled assessment of a complex excavated volume to be assessed. Each model was designed to assess specific controls on deformation about the bin excavation, ensuring that the key controls of deformation were assessed.

The underground coal storage bin at Austar was successfully excavated and constructed without significant deformation. The deformation at the assessed locations adjacent to the bin was controlled by the support recommendations determined in this program of work.

This program of work highlights that numerical models are a valuable tool if used to their strengths and limitations.

A key lesson from this program of work is that there is value in an interactive approach whereby site monitoring and review of model properties during construction provides early validation of the model. This ensures that natural geological variability, which can have significant impacts on rock failure and deformation, can be incorporated into the model as an ongoing process.

ACKNOWLEDGMENTS

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