A Combined 2D and 3D Modelling Approach to Provide Adequate Roof Support in Complex 3D Excavations

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ABSTRACT

Traditional methods for assessing effective roof support can be difficult to apply to complex three-dimensional excavations. Through worked examples, the approach of combined two-dimensional and three-dimensional numerical modelling has been shown to be successful in understanding mechanisms of rock failure for unique excavation geometries and geotechnical properties and, in turn, provide adequate roof support recommendations for complex three-dimensional excavations in Australian coal mines. An interactive approach of monitoring and model review during the excavation process is an important part of model support recommendations to ensure rock failure and deformation in the model are representative of actual conditions, to provide effective and practical controls.

INTRODUCTION

Traditional methods for determining support requirements can be difficult to apply to complex three-dimensional excavations. A combination of two-dimensional and three-dimensional numerical modelling can be used to determine key drivers for failure about complex three-dimensional excavations in order to recommend adequate geometry design and roof support.

Excavations, such as gate roads and main headings, are commonly designed with two-dimensional modelling and empirical assessments, while large complex three-dimensional excavations, such as drifts, underground bins, acute roadway intersections, and high cut roadways, are more difficult to represent in simple two-dimensional models and are generally out of the range of empirical datasets.

Numerical modelling can be a valuable tool for assessing the key drivers of rock failure around complex excavations, which, in turn, feed into the design of the excavations and support recommendations. The value of numerical modelling is that site-specific stratigraphy and rock properties can be incorporated into the model in order to assess a unique combination of excavation geometry and geotechnical properties.

A numerical model should not be used as a "black box" where rock inputs are entered and a unique outcome solves the problem at hand, without an understanding of the rock failure mechanisms. An interactive approach of continual validation through site monitoring is a key component in ensuring the models correctly represent the site-specific rock failure mechanisms.

This paper uses case studies as examples to show how a combination of two-dimensional and three-dimensional modelling can be used to understand the mechanisms for failure about complex excavations in Australian coal mines, with three examples from Austar Coal Mine and one from an unnamed mine.

IMPORTANT DESIGN CONSIDERATIONS

Important design considerations that need to be understood to achieve excavation stability are typically a combination of all, or some, of the following geotechnical parameters:

- Strain softening characteristics of strata for intact and residual strengths
- Dynamic and permanent stress distribution around the excavation
- Confinement and generation of confinement
- Mode of failure (e.g., shear, bedding shear, tensile)
- Excavation geometry
- Support design and specification
- Structure or discontinuities

Understanding how each of these parameters interact with each other will provide for implementation of effective design and support to control stability of a complex excavation. The numerical modelling process allows for parametric modelling to assess the sensitivity of individual parameters.

METHODOLOGY

A combination of two-dimensional and three-dimensional numerical modelling is typically used to assess the key drivers for deformation about complex excavations. Model time constraints often dictate a combination of two-dimensional and three-dimensional models to be used to gain detailed rock failure together with three-dimensional assessments.

Unless stated otherwise, the two-dimensional modelling using FLAC 2D incorporates SCT's in-house rock failure code where the constitutive model is based on Mohr-Coulomb criteria relevant to confining conditions in the ground. The model is similar to FLAC's strain-softening ubiquitous joint model where the model includes pre-existing joints and exhibits both intact and post failure behaviour. The code in FLAC 2D uses a coupled mechanical and fluid flow system to simulate rock failure and pressure effects. A detailed description of the SCT 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 site-specific rock test data, geophysical relationships, and prior experience. The unconfined compressive strength (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-softening ubiquitous joint model in FLAC 3D. Rock properties were again based on site-specific rock test data, geophysical relationships, and prior experience. The three-dimensional models were generally used to assess the stress distribution around the excavations, the extent of failed strata, and support loading.

AUSTAR COAL MINE EXAMPLE

Background

Austar Coal Mine (Austar) is located approximately 10 km southwest of Cessnock in the Newcastle coal fields, New South Wales, Australia. Austar is owned by Yancoal Pty Ltd and mines premium coking coal from the Greta Seam of the Greta Coal Measures at current overburden depths of approximately 500–550 m. Austar constructed an underground coal storage bin where design input was required for various geotechnical scenarios related to the bin construction. This example outlines the modelling approach used to understand the key drivers for rock failure and deformation about specific features of the bin construction.

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 1. 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 an existing intersection at the bin base area.

The bin location, maximum horizontal stress orientation, and bin top and bin base area designs are presented in Figure 2. 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 base area is an irregular area with an approximate roof span of 14 m by 8 m adjacent to the bin.

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 is based on geophysics and rock test data from Austar, for both the drift separation models and the updated bin models and, in the area of extraction, generally ranges from 20–80 MPa for the original models and 40–100 MPa for the updated models.

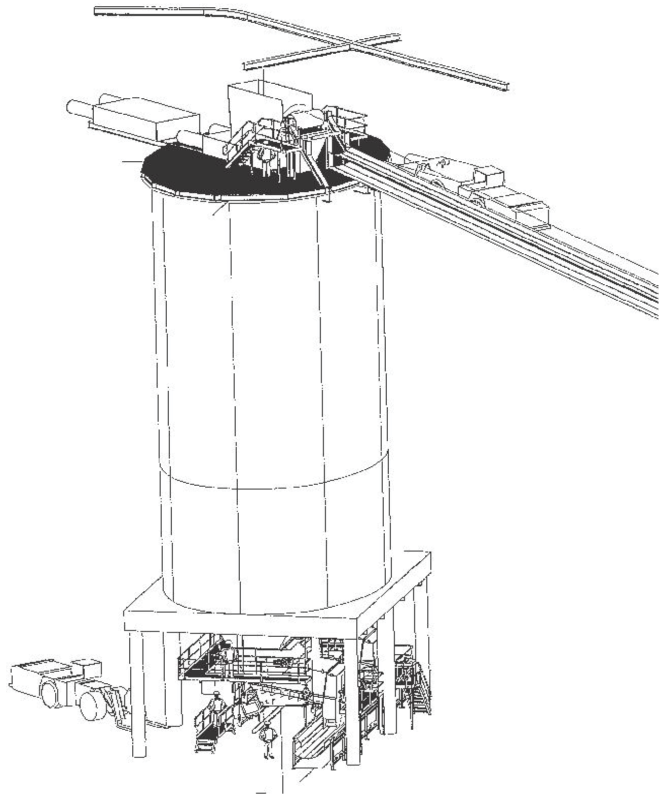

Figure 1. 3D diagram of underground coal storage bin arrangement. (Courtesy of Arkhill Engineers.).

Drift and Roadway Vertical Separation Assessment

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

SCT recommended a minimum separation of 20 m of rock head between the seam roadway roof and the drift floor, based on the original model outcomes. 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 C, B, and A headings of 12.5 m, 16.5 m and 21.5 m, respectively. 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.

Pogo sticks in the first 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 monitoring.

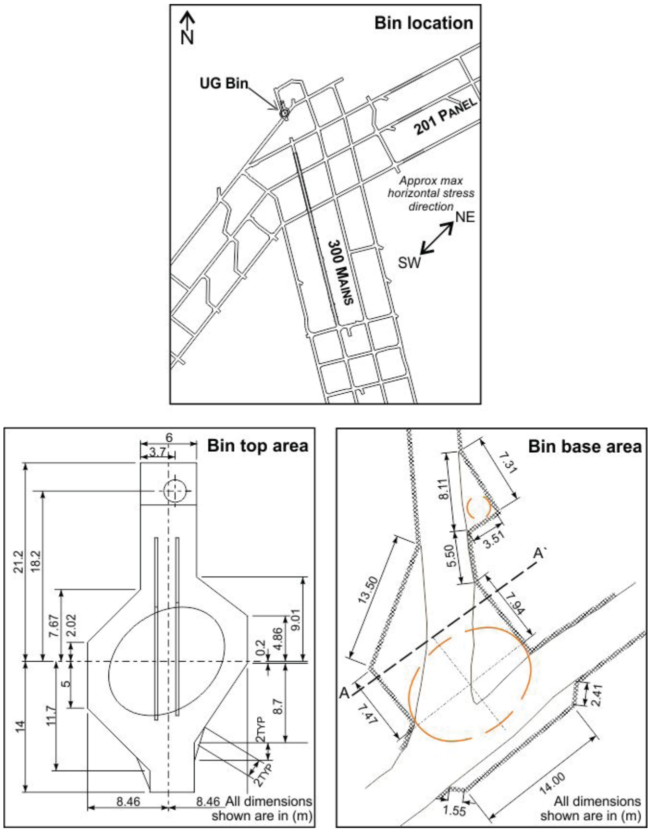

Figure 2. Bin location with bin top and bin base area dimensions.

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 was observed to connect for a 12.5 m separation while no connection was observed for the deformation in the 21.5 m separation model. The 16.5m separation model was observed to connect at the higher range of expected stress but not for the lower range of expected stress.

The model results for vertical displacement between the roadway and drift are presented in Figure 3. Displacements are comprised of downward displacements, related to the roof of the coal seam intersection, and upward displacements, due to floor heave and failure in the floor of the drift. Figure 3 shows the vertical displacement relative to the seam roadway roof in order to compare the GEL and Tell-Tale extensometer data. The monitoring data is consistent with the model data. The GELs and Tell-Tales 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.

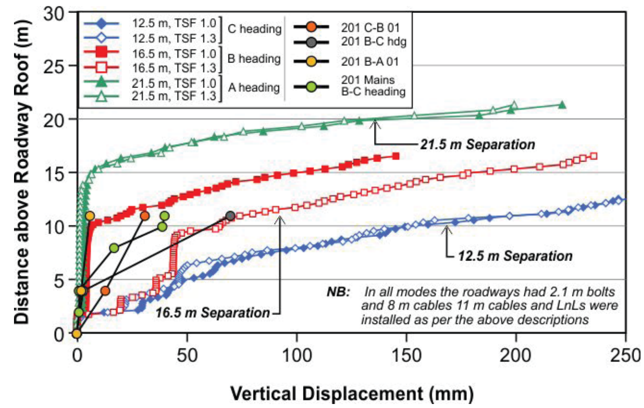

Figure 3. Modelled and observed roof displacement for roadway and drift vertical separation.

For validation of the modelling process, the mining outcomes after implementing the design recommendations are as follows:

- Monitoring of roof displacements and roadway convergence was within the range of the model results.
- The monitoring was consistent with the lower stress in the range of modelled expected stresses, confirming the stress environment for future assessments.

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. Numerical modelling of the 14 m and 20 m roof expanses was conducted using FLAC 2D to assess the deformation in the roof and to determine appropriate support recommendations. Although the bin top area is a three-dimensional problem, due to time constraints, the approach was limited to two-dimensional representation while taking into account the limitations of the two-dimensional model.

The two-dimensional models show the height of softening for the bin top roof at approximately 7–10 m for the 14 m and 20 m roof expanses. Height of softening to this extent is problematic due to cables of similar lengths not being able to pin back into intact strata. Figure 4 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. For the arched roof model, 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 4 where the secondary support is observed to extend into competent ground.

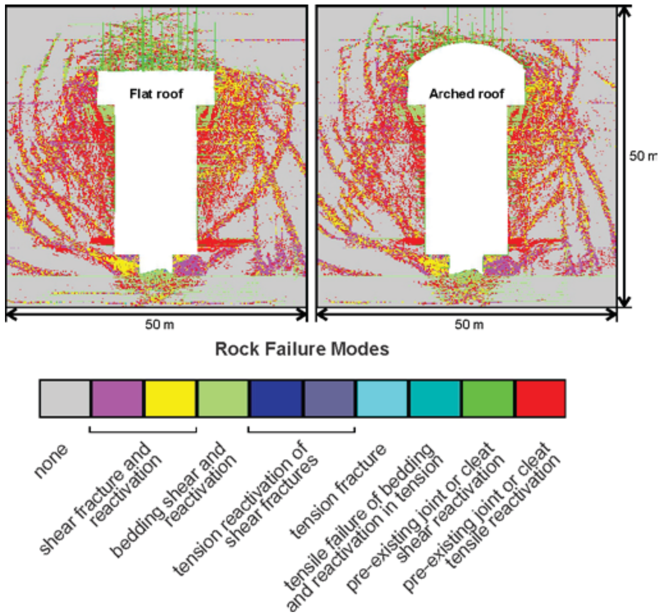

Figure 4. Mode of deformation for a 20m wide bin top section for a 14m wide bin.

Elastic models were run in FLAC 2D and FLAC 3D to compare the horizontal stress concentration in a flat roof, shown in Figure 5. Although elastic models do not simulate stress transfer due to rock failure, they do 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 is likely to be less than observed in the two-dimensional models. The excavation is also expected to be controlled by its minimum width (such as an infinite roadway is). Therefore, the deformation in the 14 m model is expected to be more indicative of the three-dimensional deformation than the 20 m model.

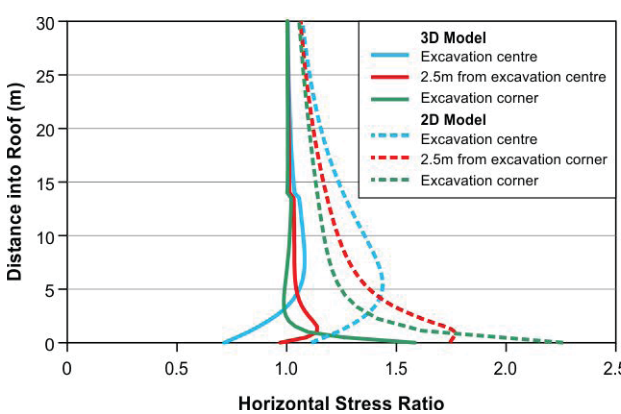

Figure 5. Horizontal stress profiles for the roof of the bin top excavation.

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 long cables in a 2 m by 2 m grid), followed by a secondary support pattern (11 m long infill cables creating a 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. This also allows 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. Figure 6 shows a photograph of the completed bin top excavation with the arched roof. The bin top deformation shows greater displacement in the modelling than observed. This prompted a review of the rock model properties, including a new borehole drilled at the bin site for rock properties. Model rock properties were changed to be consistent with the local rock test data, with a higher Modulus to UCS ratio, and less tectonic stress for higher strength lensing units. A 1 m x 1 m constitutive Mohr-Coulomb Failure Model, to check the differences in rock properties, shows significantly less failure around 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 6. Panoramic photograph of the 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 a combination of the following:
  - Overestimating the stress concentration in the roof due to the two-dimensional model not redistributing the stress in three dimensions
  - 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.

For validation of the modelling process, the mining outcomes after implementing the design recommendations are as follows:

- Less than 10 mm roof displacement was measured, confirming the arch roof shape is a stable shape.
- The additional recommended support was not required, which prompted a review of rock properties.
- It was found that the strata at the bin site differed from original modelled strata.
- A model was run to compare original and updated rock properties. The updated properties showed significantly less deformation, consistent with observations.

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 the 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-softening ubiquitous joint model in FLAC 3D. The reduction of 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 7 shows a slice of the stress distribution at 1 m from the edge of the bin. At 5 m from the bin, a similar stress distribution is observed where the stress is also near zero.

Two-dimensional modelling 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, in reality, the roof span is confined on one side and open on the other where it meets the bin. The appearance of shear failure in the roof is reduced by the residual rock properties and stresses input into the seam roof prior to the widening of the bin base. 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-Coulomb failure model was run in the horizontal plane to observe the stress vectors about the bin excavation. Figure 8 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 forming vertical fractures about the bin.

Parallel horizontal 8 m long cables extending from the bin wall at 3 m spacing per 1.5 m bench were recommended to provide seam roof confinement. 10 m long cables angled away from the bin, at a 15-degree angle from vertical, were recommended to be installed in the seam roof at a 2 m by 2 m grid. The three-dimensional bilinear strain-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, 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 bin.
- The models show that, although primary support yields, secondary cables do not yield, creating the required confinement in the seam roof strata.

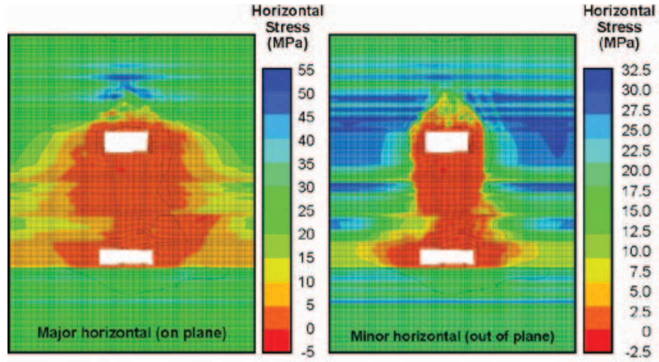

Figure 7.Stress redistribution about bin on vertical plane A-A' (See Figure 2).

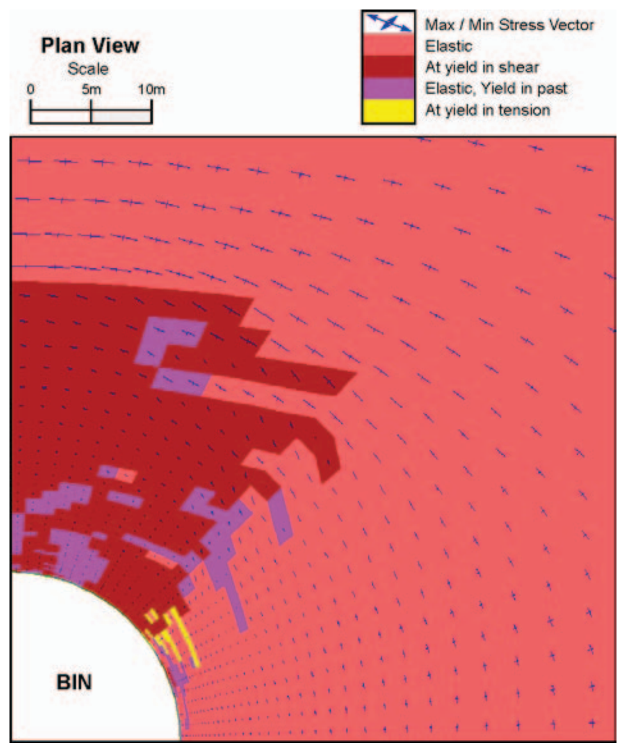

Figure 8. Mohr failure model with stress vectors around bin excavation.

For validation of the modelling process, the mining outcomes after implementing the design recommendations are as follows:

- The seam roof expanse was supported successfully and did not visually show significant deformation. (Monitoring was destroyed during the excavation process, so the roof deformation and bolt loads were visually assessed).

UNNAMED COAL MINE EXAMPLE

Background

This unnamed mine in Australia is a coal mine in Permian strata with a 5-m-thick dipping seam with current workings at 150 m depth. The complex excavation is a conveyor drift and intersection at an acute angle of 25 degrees, with roadway widening and height increase. The geometry of the excavation and sequence of extraction is presented in Figure 9, where the drift is initially mined, then widened. The D heading is then mined, and the floor is removed to increase the final excavation height in both the drift and D heading.

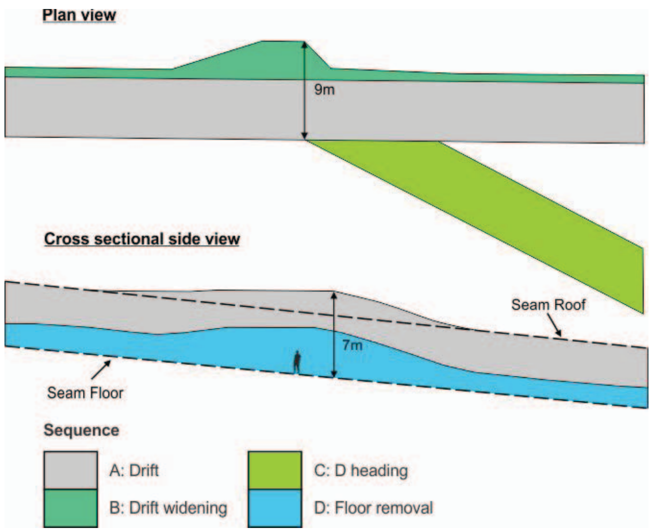

Figure 9. Modelled excavation sequence.

The assessment discussed here is a portion of a broader program of work to assess the stability of all aspects of the excavation. The discussion in this paper has focused on a portion of the larger program of work to show an example of the dynamic changes in complex three-dimensional excavations.

A site-specific characterisation of geotechnical rock properties was conducted to obtain the model geotechnical inputs. The seam roof strata consists of laminated mudstone and siltstone with carbonaceous partings. The laminated strata, with a UCS of less than 25 MPa, forms a weak roof susceptible to shear and deformation.

Assessment of Excavation Stability

The objective is to assess the stability of the drift and D heading during the D heading extraction in order to provide recommendations for adequate roof support. The approach is to understand the key drivers for deformation and to assess the effectiveness of various roof support patterns. Numerical modelling using FLAC 3D constitutive bilinear strain-softening ubiquitous joint model simulated the rock failure and stress distribution about the sequential excavation.

The three-dimensional model was sequentially extracted (Figure 9) and supported with the standard primary roof support design comprised of 6 x 1.8 m long 28 t roof bolts per meter and 2 x 8 m long 52 t cables per 2 meters. Ribs were supported with 2 x 1.2 m long 22 t rib bolts per meter.

The sequence of excavation causes a dynamic shear stress distribution about the drift with the excavation of D heading. The shear stress that developed around the complex excavation is the major cause of the increase in deformation in the roof of the drift. Figure 10 shows the shear stress that developed during the excavation of D heading. The stress redistribution creates additional deformation in the drift roof, as detailed in the shear strain plot in Figure 11. The shear strain contours show areas with significant deformation, where deformation is expected to onset at 0.5% shear strain. The shear strain plot is contoured from 0.7% strain and highlights areas of strain relating to significant deformation.

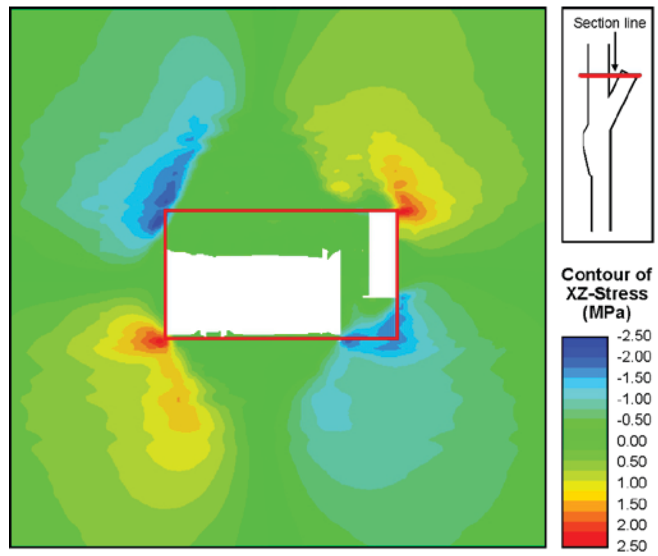

Figure 10. Shear stresses developed on initial excavation of D Heading.

Increased deformation occurred into the roof on the left rib side of the drift, inbye of the intersection. Failure is predominately bedding plane shear and tensile failure, indicating delamination of weak bedding. Deformation initially formed from the stress notch of the initial drift roadway before widening. Subsequently, as D heading was excavated, increased shear stresses developed failure higher into the roof with connection to the initial deformation.

Horizontal and vertical stress distribution shows low stress transfer through the deformed roof, indicating unconfined roof strata in the drift. In comparison, D heading shows significant stress transfer through the roof indicating low levels of deformation.

Another cause for roof instability in this scenario is the location of cables centered around the initial roadway before widening the excavation. The recommendations from this modelling was to infill the standard cable pattern with 2 cables every 2 m with an offset towards the side of the rib to confine the widened roof with shear stress notch. Model extensometer outputs showed that the additional infilled support significantly reduced deformation and height of softening to superficial near roof deformation.

The drift and heading were extracted successfully with minimal deformation in the roof. Roof monitoring showed less than 10 mm

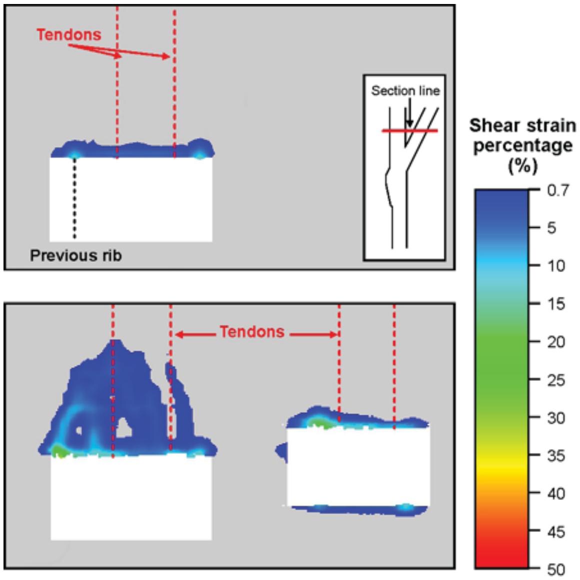

Figure 11. Maximum shear strain contours after D heading extraction (sequence C).

of vertical displacement in the roof after extraction, consistent with the superficial displacements observed in the modelling.

Key outcomes from the drift roof support assessment are as follows:

- The dynamic shear stress notch in the drift roof, produced by the D heading extraction, caused significant displacements and height of softening.
- Vertical cables infilling the standard support pattern, and offset to the widened side of the drift roof, are required to control the roof deformation in the shear stress notch location.
- The timing of secondary infill support is to install before extraction of D heading

For validation of the modelling process, the mining outcomes after implementing the design recommendations are as follows:

- The drift was successfully extracted with monitoring showing less than 10 mm displacement.

CONCLUSIONS

The approach of combined two-dimensional and three-dimensional numerical modelling has been successful in understanding three-dimensional drivers of rock failure and, in turn, has provided adequate roof support recommendations for complex three-dimensional excavations in Australian coal mines.

The examples in this paper show that a combination of two-dimensional and three-dimensional modelling is a valuable tool for understanding rock failure mechanisms and roof stability if used to their strengths and limitations. An interactive approach of monitoring and model review during the excavation process is an important part of model support recommendations to ensure rock failure and deformation in the model are representative of actual conditions, to provide effective and practical controls.

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