Multi-scale discontinuum simulation of ground support design for large deformations

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ABSTRACT

Large deformations in deep mines occur due to the exposure of extensively damaged rock mass adjacent to an excavation. In order to properly simulate the support response in such conditions, the ground deformation must be captured accurately. The mechanisms of rock mass damage, dilation and deterioration must first be correctly simulated to produce a realistic tunnel deformation in three dimensions. Furthermore, the physical response of the support elements must be realistic.

In this paper, a multi-scale, discontinuum approach to mine deformation modelling has been described to improve the simulation reliability of ground support capacity and demand. Case studies were used to demonstrate the behaviour of several heavy support systems using this approach. Some support designs for squeezing ground were tested and the limitations and vulnerabilities of the support systems described. The modelling methods used to simulate the mine deformation, drive behaviour and support system response were discussed and some sufficiency requirements for similar analysis were highlighted.

1 INTRODUCTION

The purpose of ground support is to ensure that excavations remain safe and open for their intended life span. The effectiveness of a ground support strategy is important for two main reasons, namely safety to personnel and equipment and to achieve the most economical access to extract ore. Ground support consists of rock support and rock reinforcement (Windsor & Thompson, 1993) which is installed into a deformed, discontinuous rock mass. The loads that develop in the support system are a function of displacements in the rock mass and the resultant forces generated by blocks and wedges that would otherwise be kinematically free to fall or slide into the excavation.

To evaluate the performance of a support system, one must sufficiently capture the evolution and timing of the discontinuous deformation within a rock mass. The ground support schemes also interact with the rock mass in a complex way and they represent a complex, three dimensional assembly of elements interconnected by other elements or the rock mass. The analysis of a rock mass-ground support scheme interaction is further complicated if the performance is to be simulated beyond the point of failure of some of the elements, as the problem becomes significantly non-linear; the failure of one part of the system could lead to failure of another and another and so on.

Put simply, the simulation of ground support is a complex problem demanding the highest level of realism. If the simulated 'loading system' displacements, or the simulated support system load-displacement response is incorrect, the evaluation will not be sufficient.

2 REALISTIC DISPLACEMENT MODELLING

Apart from the quality of input data for the model variables (material properties, boundary conditions etc), several model fundamentals that limit the ability of a model to simulate realistic displacements exist. These things are fundamental, meaning that even if the model variables are otherwise correct, the model would be incapable of simulating deformation realistically.

The main categories of these 'fundamental' model characteristics are: dimensionality, geometry, constitutive behavior and scale; these categories are very broad and cover most decisions made when developing a model. It is beyond the scope of this paper to cover all of these aspects in detail, but in the mining context, it is possible to specify some broadly applicable requirements for realistic and sufficient displacement modelling:

- Generally, realistic displacement models will usually be three dimensional in nature. Although specific situations, in a specific location for some stage of the life of an excavation, can be approximated using a two dimensional model, the demand from a reasonable range of outcomes that need to be considered for a particular ground support scheme will span too many situations in which the complete three dimensional stress path, including the intermediate stages of the stress path, is critical to the outcome. Even monolithic forms such as universal beam sets discussed in more detail below, are likely to fail via a mechanism which is not able to be simplified to a two dimensional problem.
- Geometrically, just as almost all deformation problems require a three dimensional model, almost all rock related problems in mining are significantly geometric. Capturing the geometry of a problem is essential to simulate the stress path and this means not only representing the shape of excavations and structure, but also simulating the timing and the excavation process. The process of forming the geometry - the intermediate geometries - will shape the extent and magnitude of damage and the deformation field. If the intermediate excavation stages are too far apart in a model, the effects cannot usually be unraveled using experience alone.
- The effective constitutive response of a model is a function of the governing physics that a model *can* capture. This accounts for the constitutive material model that is adopted, the element type and density or any other inherent characteristic that limits or constrains the behavior of a simulated material. Assuming a sufficient type and density of elements is used and the analytical framework can solve for the physical response that needs to be captured, the practical challenge for ground support problems is to simulate the continuous and discontinuous parts of the deformation field around an excavation.

  This implies that the model will capture the stress-strain behavior well enough to model the extent and magnitude of damage around the excavation (for example with a strain-softening, dilatant, large strain model), but also incorporate sufficiently small scale structure, so that the discontinuous deformation and kinematics of the problem are captured.
- The different length scales are interconnected: The stability and deformation at a mine scale is connected to behavior at a precinct scale, which drives pillars and drives the response of the smaller excavations. The interconnectedness also works in the opposite direction: Small scale rock mass behavior is the nucleus of stability of larger parts of the mine, and sum to affect global scale deformation. In practice, the 'length scales' are not discrete and no distinct boundaries exist. Nevertheless, it is helpful to explain the concept of scale in a mine problem in this way.

  Multi-scale modeling is any modeling where there is defined precision for deformation and distortion of the rock mass at multiple length scales, and this requires that excavations and discontinuities are represented across the length scales (or at least sufficiently bracketing the length scale of interest). Generally, the behavior at each length scale is built upon to simulate successively larger length scales and this could be achieved by incorporating geometry and sequencing details at a resolution and complexity suiting the smallest length scale of interest in the problem, but inside a model with similar complexity at longer length scales or using appropriate sub modeling techniques (see for example Beck 2008 and Beck et al 2009).
- Displacement in a rock mass are almost always significantly discontinuous, more so close to excavations and at large strains where support is relied upon or support capacity is likely to be challenged. Simulating realistic displacement close to an excavation almost always will require a discontinuum approach.

3 AN EXAMPLE PROCEDURE

At this time, it is not efficient to build a single mine-scale model with all scales of necessary structure/discontinuities from development (drive) scale to global (mine scale). Instead, a multi-scale sub-modelling approach can be adopted, using larger scale models to provide boundary displacements for smaller scale models, each with successively smaller scale structure. All scales of model have different purposes and incorporate different details:

- The purpose of a *donor* model is not to replicate the drive scale displacements. A donor model must produce sufficiently correct displacements to drive the boundary of the smaller scale models (the *sub*-models).

  Small scale structure in the donor models is *smeared* into a continuum representation. The Representative Elementary Volume (REV or RVE) is used as a guide to the length scale below which this smearing, or homogenisation should occur. A procedure for identifying the REV is outlined in Beck et al 2009. For most problems (not all), the REV in the donor model is the smallest volume needed to homogenise the effects of joint sets on rock mass scale properties. Heterogeneities larger than joints, such as faults or shears may need to be considered explicitly.

- The ground support scale sub model has the purpose of producing displacements at a wall, or support element scale, including the nature and magnitude of the discontinuous deformation around a tunnel and at a tunnel surface. This means that smaller structures that can dislocate in the area of influence of a tunnel need to be explicitly represented.

A simple example of donor and sub models is shown in Figure 1. The purpose of this model was to evaluate the capacities of the steel arches and steel sets for block caving drawpoint support. A global model of the entire mine was used to drive the boundaries of a 1/10 footprint sub model spanning from below the extraction level to above the undercut. Because many support designs needed to be tested, the drives within the 1/10 footprint sub model were only filled with supporting 'filler' elements approximating the pre-failure stiffness of the systems that were being studied. The displacements at the drive surface could then be applied to the explicit models of the support elements or directly compared to published load-displacement data (Villaescusa, et al, 1992). In more detailed studies, the support can be included directly in the 1/10 footprint model, in order to achieve the required resolution of discontinuities.

In this particular example, the 1/10 footprint models incorporate Discrete Fracture Networks (DFN) to represent drive scale structure. The included discontinuities are shown in the sub model plots. The DFN are based on a statistical representation of the discontinuity spatial distribution. The procedure for developing these Finite Elements (FE) DFN models was as follows:

- Geotechnical line mapping recorded the dip, dip direction, trace length and set number of discontinuities in several locations.
- The scan lines were de-surveyed to establish the distribution of discontinuity spacing and persistence along typical drives.
- DFN were constructed that match these distributions and applied to FE models of as-built excavations as shown in the Figure.
- The FE DFN models were numerically inspected to ensure that the same tunnel scale discontinuity distribution was achieved in the model, and the persistence of the joints was adjusted iteratively to achieve a best qualitative match. Note only tunnel scale or larger discontinuities were included; smaller scale (i.e. ~<1m persistence) discontinuities were homogenised.

An issue that arises is that the global scale models in both cases represent geotechnical domains using rock mass scale properties (the joints are smeared into a continuum representation for each rock type), whereas the FE DFN models contains the smeared joints. This means that different material properties are needed for the DFN models than for the global models. Generally, as the global scale model would be calibrated, or else material properties at that scale already determined and agreed upon, the joint and continuum mass properties in the DFN are usually iteratively adjusted until the response at the REV scale is the same in both scales of models.

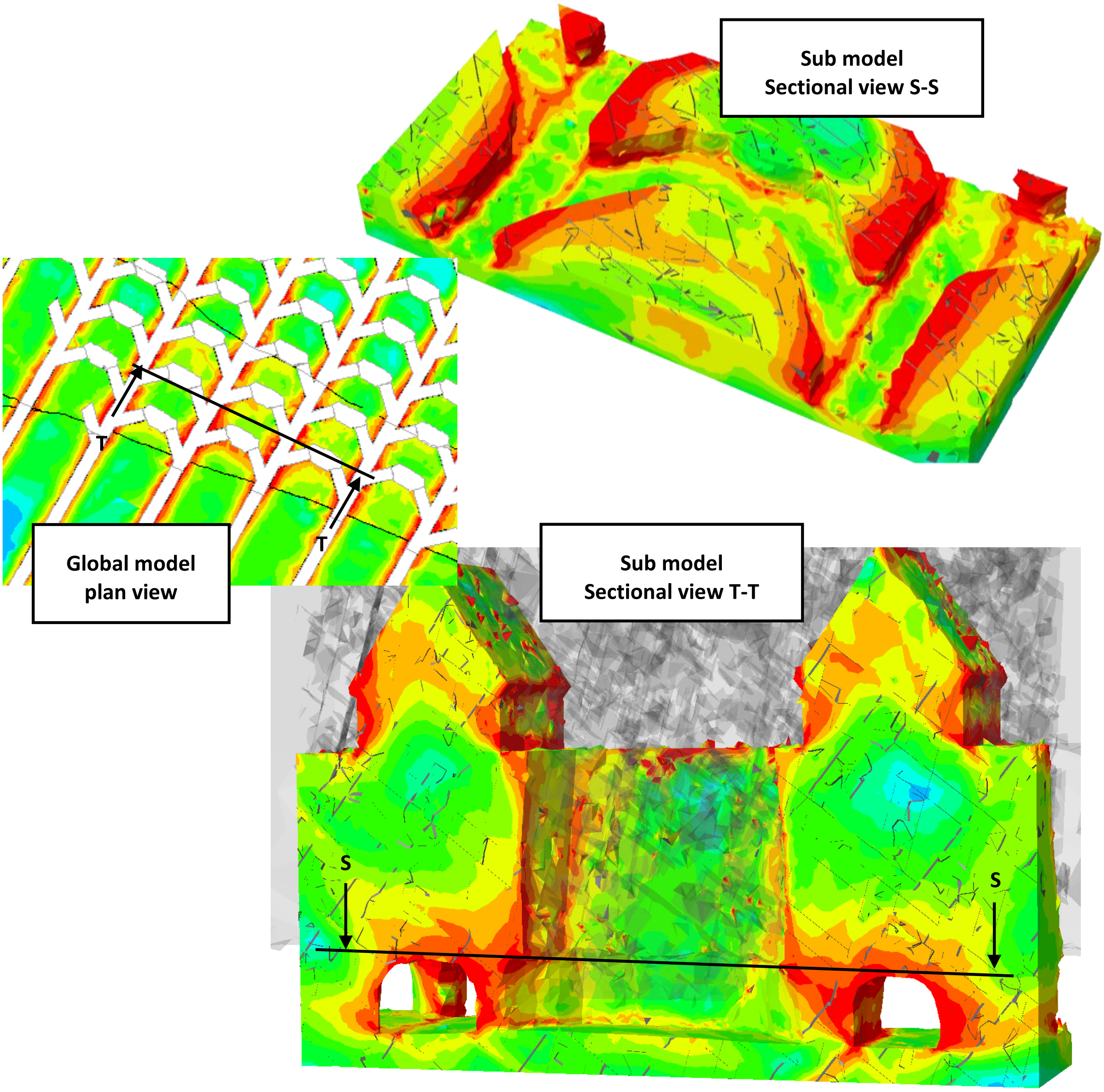


Figure 1. Example sections through a 1/10 footprint DFN and global donor model used to produce drive surface displacements to test steel arch and steel set support. Only part of the model is shown

The results for excavation closure from this model at an isolated location in which large deformation leads to high drive closure are plotted in Figure 2. This shows representative, underlying inwards wall movement versus model step in the 1/10 footprint sub model at 3 key locations in the sub model; a drawpoint, crosscut and drawpoint intersection. Note that the specific location was selected in the basis of expected large deformation and that the model is calibrated using measured drive closure. Almost all of the rest of the footprint shows much lower expected drive closure. The model indicates that at this selected location, with effective TH or universal beam support, up to 275-300mm of closure is eventually expected after propagation of the cave.

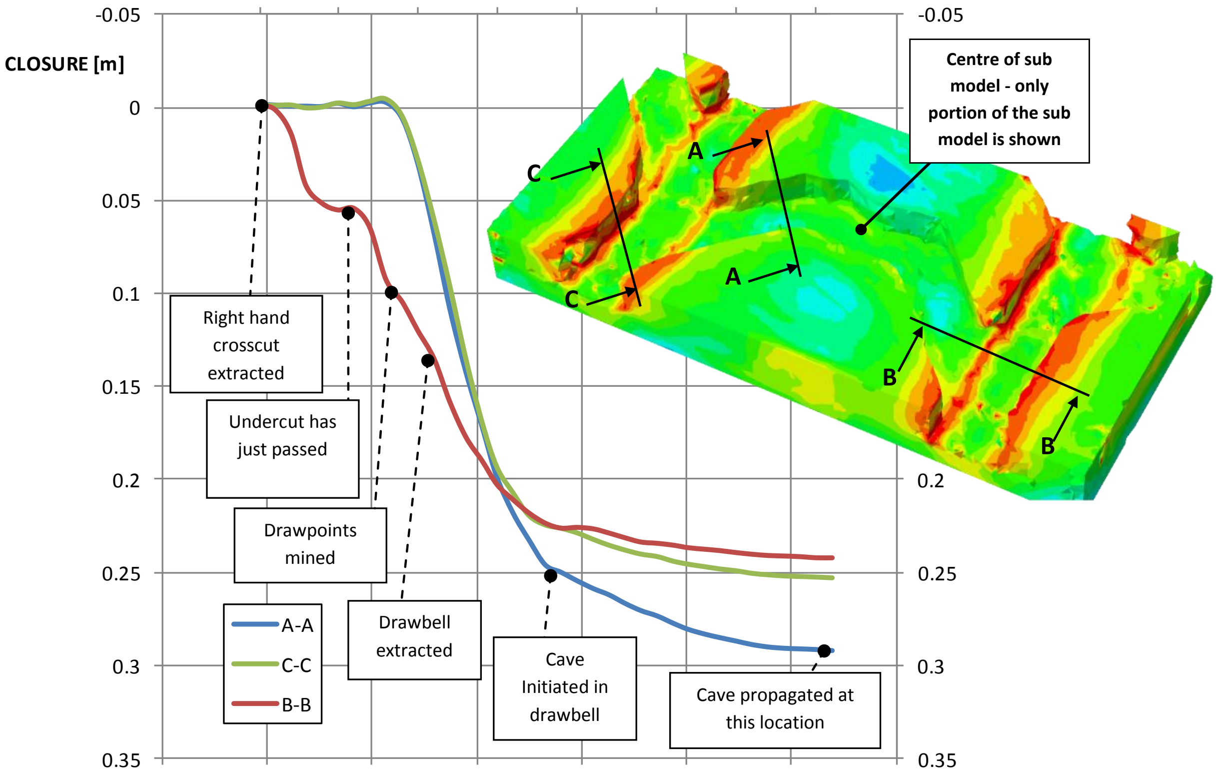
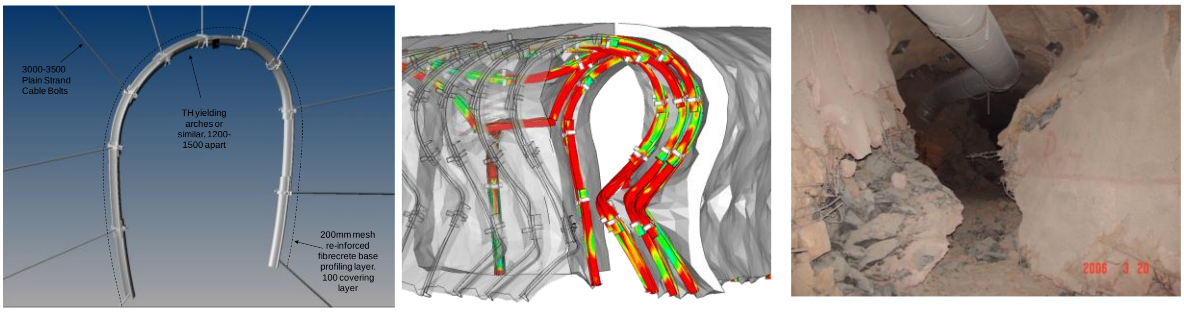


Figure 2. Simulated closure at selected locations in the example front cave

For this example, two candidate support designs were considered in detail: TH Arches and steel ("I", or universal beam) sets. In the numerical tests of these support designs, the final loads generated by the donor model can be applied as simulated, or amplified until the support systems fail to assess the ultimate capacity of the support systems. A TH arch design is shown in Figure 3. It is a moderate to high capacity design specified for high levels of drive closure.

Features of the design included ovoid walls and back, but a compromised flat floor. In this case, the model uses drive deformation information from a real scenario observed at a mine where significant tunnel collapses occurred due to pillar failures, but where TH arches were not used. A conclusion from the analysis was that the TH arches helped maintain the drive profile for longer than when bolt, mesh and fibrecrete were used. Nevertheless, when the cores of adjacent pillars failed the TH arches were not a significant constraint on final deformation and appropriate design of pillars to manage loads is ultimately the essential requirement for stability.

The capacity simulation for this support suggested that 200-300mm of closure was the design limit. Better results can be achieved by mining an invert in the floor, but this is currently difficult in a mining environment.



(i) Moderate Capacity TH support design | (ii) Photograph of actual deformation in tunnel used to provide load-deformation scenario for failure analysis | (ii) Failure back analysis

Figure 3. Simulated Shear Zone Support Damage, with 80MPa roadway

Universal beam sets are a more common design for block caving draw point support. Draw points must manage the competing needs of being heavily deformed, as well as resisting wear and impacts from the cave draw. It is also often asserted that the shape of the draw point has a defining impact on flow within the cave, so a 'square' brow is often specified.

The most problematic constraint is the asymmetric deformation that results from the shape of the draw point pillars (typically diamond shaped) which skews the drive along the axis, especially if the pillar core is damaged as shown in Figure 3. While the total closure is similar to that experienced in the adjacent crosscuts, the nature of the deformation can be problematic for stiff monolithic support.

A steel set design for block caves is shown in Figure 4. This design is a modification to a design employed by a number of block caves around the world, employing modified concrete and a circular tunnel shape. The simulated performance of this system is shown in Figure 5 at 325mm of closure. Initially, as the support undertakes passive loads, significant ground movement is required for any substantially load to be taken up. Following this a large disparity in stiffness between the areas of drive affected by the sets and the spans in between is experienced. This effect can be seen in Figure 5(i) which shows the pattern of radial pressure between the wall of the drive and the support system. The support pressures generated are much higher adjacent to the sets than they are in the spans between, suggesting closer spacing is needed for at least this application. The Figure also shows the pressure generated by the sets compared to the deformation at selected locations around the square sets (Figure 5(ii)) i.e. at the shoulder and grade line, immediately adjacent to one of the sets. The sets 'point load' resulting in massive pressures at certain points. It must be noted that the 'point loads' are not representative of the average support pressure. Generally this would be an average of the loads shown in the Figure, probably closer to 1/5-1/6 of the indicated point loads.

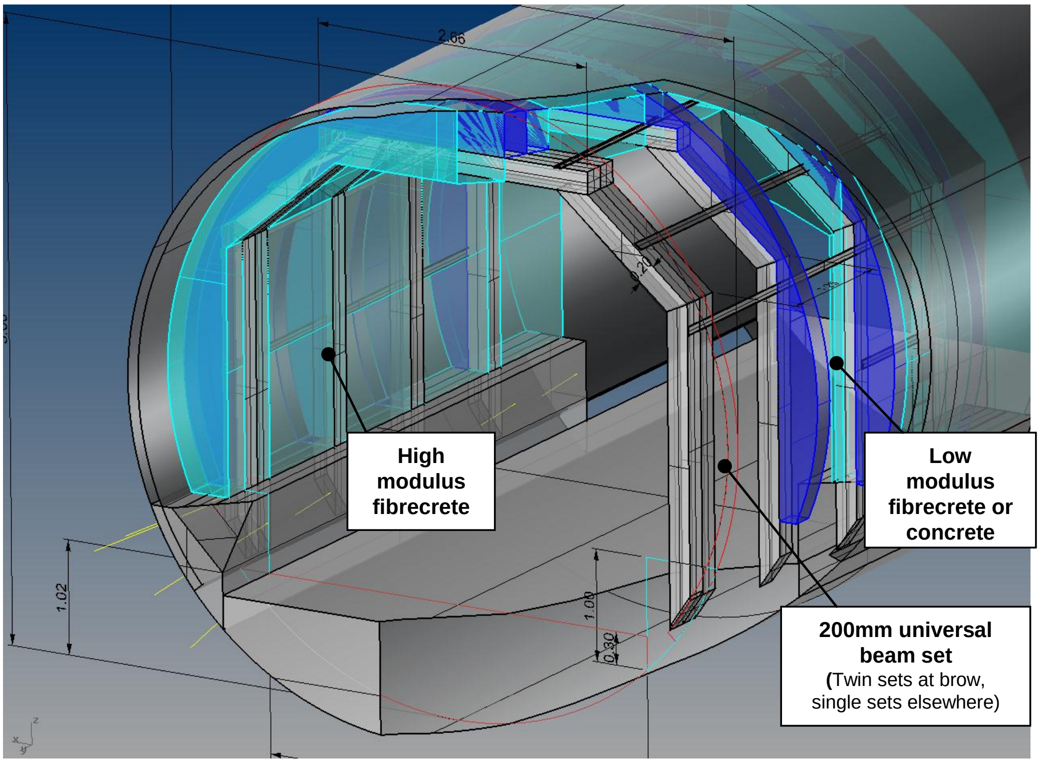
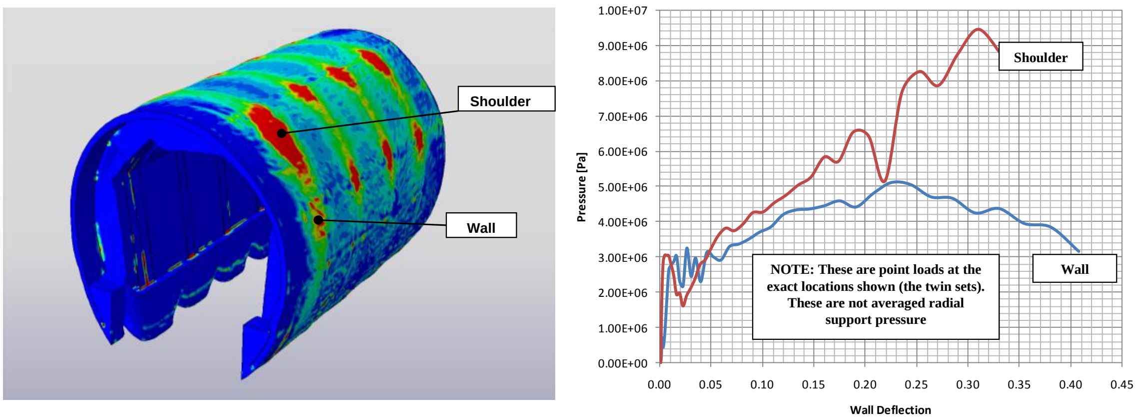


Figure 4. A common steel set design for block cave drawpoints



(i) (ii)

Figure 5. Simulated point loads versus radial deflection for the steel set design. These are not the average radial support pressures.

Between 250mm and 325mm of closure at the brow, the model showed the single steel set starts to buckle by a characteristic mechanism near a shoulder (see Figure 6), but there is significant concrete damage in areas including the apron along the footings of the arch before this. The twin sets at the brow perform better than the single sets, showing no signs of buckling. The type of buckling in this case is driven partly by the mode of drive deformation shown in Figure 5 and anecdotally this torsional failure at the shoulder is a common mechanism for steel set damage. An example comparing set damage from one mine and a close view of the modelled buckling is shown in Figure 6.

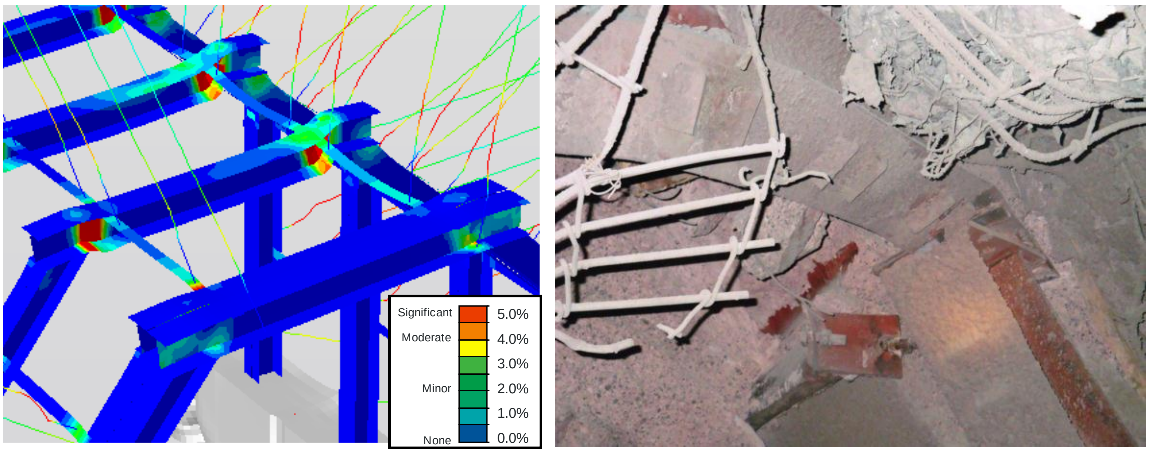


Figure 6. Example of steel set failure, and a close view of steel set failure in the model

Based on the analysis, for the example mines environment it was concluded that as a result of the inherent nature of the support design, the drive may at least require major repair or set replacement beyond 325mm of closure, neglecting effects due to wear or oversize handling.

Another use for the model is to better understand the mechanism for the high levels of damage. Results for rock mass damage - interpreted using plastic strain - through the drawpoint pillars, minor apex and in the walls and back at selected sections of the sub model excavations are shown at 2 milestones in Figure 7: a) minor to moderate pillar core damage b) significant pillar core damage.

The eventual significant closure is correlated with the loss of pillar core stability. Interpreting pillar core conditions using plastic strain is consistent with standard geotechnical practice. Conventional theorems of plastic collapse for limit analysis are well documented (Yu, 2006; Hodge, 1958; Davis, 1968; Lubliner, 1990; Drucker et al., 1952; Hill, 1951).

The detailed modelling correlates drive closure and pillar core stability for the example application. Although the actual level of closure compared to the pillar damage is specific to the rock type and configuration of the excavations, the correlation between stability in general and with levels of plastic strain should be more transferrable:

- Pillar cores with significant damage should be interpreted as failed. The adjacent excavations will also be deformed. From a support perspective these drives are candidates for heavy support and planned rehabilitation.
- Pillar cores with moderate damage should be marginal - some will be interpreted as failed. In these pillars degradation of pillar strength has increased, but the actual deformation is still only moderate. The adjacent drives should not be significantly deformed, though additional load will lead to increased damage and deformation in the pillar and adjacent excavations.
- Pillar cores with minor damage should be expected to be stable. Calibration suggests that at this level of damage, the rock mass is starting to yield, but a significant degradation in strength has not occurred. Also, as the deformation is low, deformation in adjacent excavations will also be low and heavy support is not indicated.

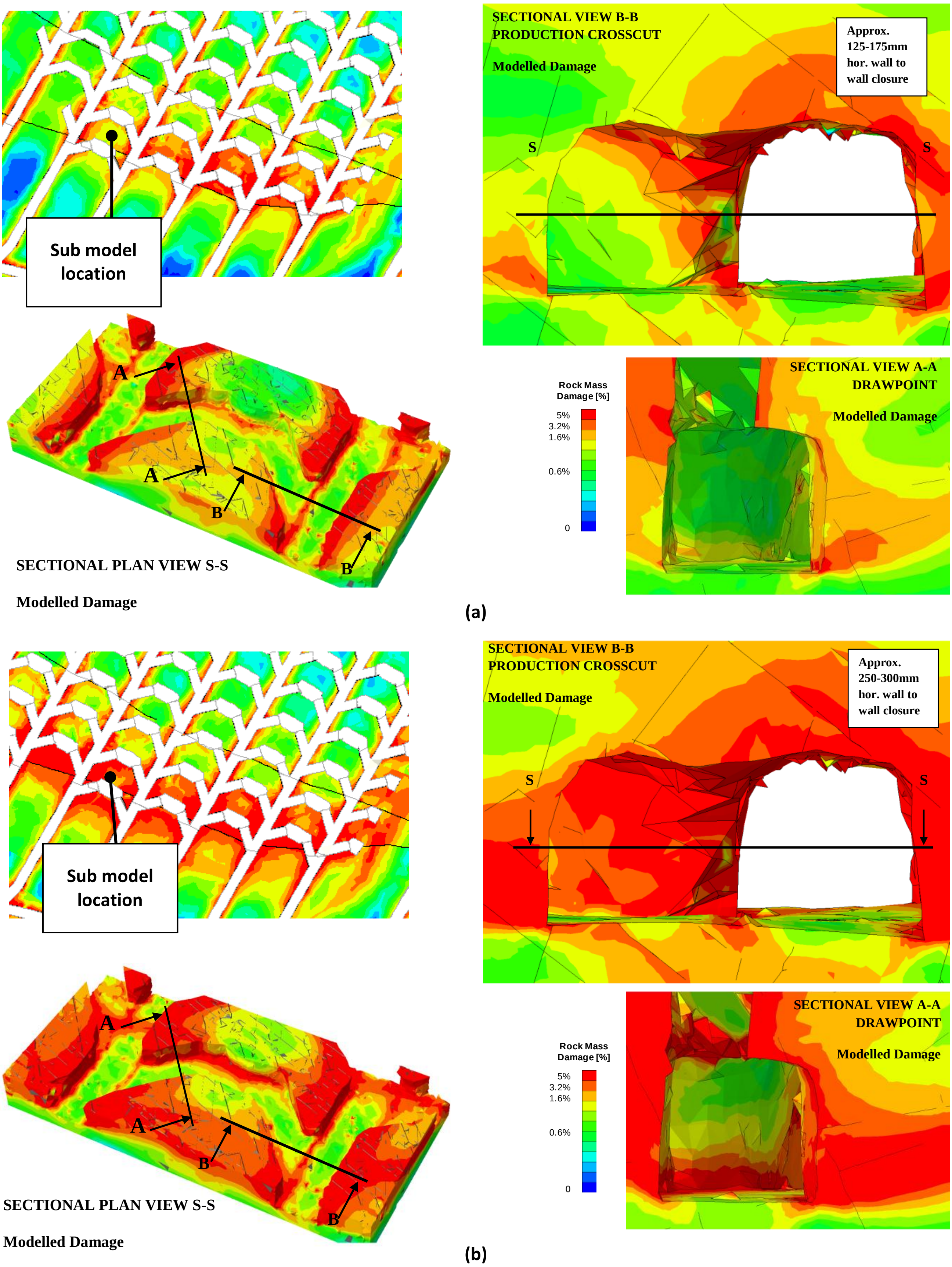


Figure 7. Simulated pillar rock mass damage at selected stages of extraction in an example 1/10 mine scale FE DFN model

4 CONCLUSIONS

A number of different modeling concepts have been brought together in order to simulate support capacity and demand with a very high level of similitude. The intent is to capture the mechanisms of discontinuous deformation around complex geometries with the highest possible level of confidence. The magnitudes and extent of the deformation in the case examples was calibrated using field data, so show that realistic modeling of support is accomplished.

Common to the largest model geometries discussed here are well featured constitutive models, higher order elements and fine meshes, small excavation steps and appropriate boundary conditions. Modern non-linear, strain softening, dilatancy model packages allow for computation of models such as these in sufficiently short time frames and at a cost that makes the analysis feasible.

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