2010

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MINE-SCALE NUMERICAL MODELLING OF LONGWALL OPERATIONS

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ABSTRACT: Elastic three dimensional Boundary Element (BE) codes are commonly used in the coal industry to model the induced stresses and rock mass response to longwall mining. While these models are often easy to build and quick to run, it is questionable whether these elastic models are capable of accurately simulating the highly non-linear rock mass response observed in longwall operations, in particular the complex caving and goaf behaviour of the overlying strata and resulting surface subsidence.

This study presents a comparison between modelling results obtained from the finite difference (FD) code FLAC^{3D} and elastic BE code Map3D for a generic longwall extraction sequence. These models are compared with regard to the extent of surface subsidence and associated stability of pillars.

INTRODUCTION

Abutment stability, cavability and surface subsidence are important geotechnical issues that need to be considered for most longwall operations. These issues involve significant rock mass yield and deformation, which may necessitate the use of inelastic numerical models to analyse these complex problems. While three dimensional (3D) mine-scale inelastic numerical modelling is now being routinely conducting in hard rock mines, the application of these models in the coal industry is limited, usually only conducted for research purposes and not for operational design.

Reluctance to use mine-scale inelastic 3D models by the industry has largely been due to hardware limitations, long processing times and difficulties in constructing accurate mine geometries. However, most of these limitations have been resolved through recent hardware advancements and the use of CAD software to speed up model construction times.

This paper discusses the aspects of mine-scale numerical modelling for longwall operations and presents a comparative study between elastic and inelastic codes, for a generic longwall extraction sequence.

In this study the modelling results from the finite difference (FD) code FLAC^{3D} and elastic BE code Map3D for a generic longwall extraction sequence are compared. The accuracy of each model is compared with regard to the extent of surface subsidence and pillar stresses modelled. The ease of construction, skills required, computing efficiency and cost effectiveness of each method are also discussed.

FLAC^{3D} MODELLING

FLAC^{3D} (Itasca, 2006) is a three-dimensional explicit finite-difference program. Finite-difference is a domain method where the problem domain (or rock mass) is divided into geometrically simple sub-domains or elements.

FLAC^{3D} has been commonly used for the longwall research purposes. Examples of recent studies using FLAC^{3D} for longwall modelling include Badr et al. (2003), Yasitili and Unver (2005), and Tarrant (2006).

AMC Consultants Pty Ltd has developed a new approach for mine-scale modelling which involves the use of both Abaqus/CAE (Dassault Systèmes, 2008) and FLAC^{3D} programs. In this approach, ABAQUS/CAE is used for geometry construction and meshing, and also for visualization of results. The numerical analysis is conducting using FLAC^{3D}.

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The modelled generic longwall layout is shown in Figure 1-a. This model comprises six different material properties (Figure 1-b).

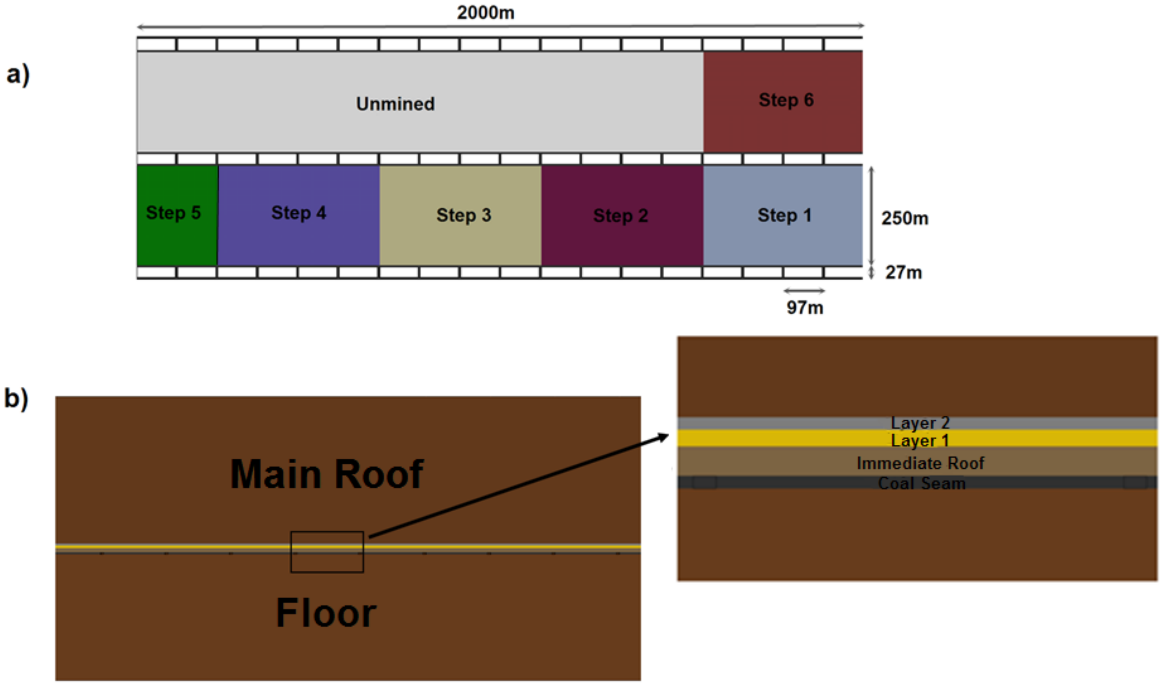

Figure 1 - Overall layout of the modelled longwall panel

One of the main difficulties involved in longwall modelling is the modelling of cave and goaf behaviour. In order to study the large-scale longwall caving behaviour, a computer model must be able to effectively simulate *large order strain* and the correct induced stresses caused by the compaction of the goaf material. This requires a thorough understanding of the post-peak behaviour of the rock mass and a representative *constitutive material model*. However, in small-scale and more detailed studies, there are many other factors that need to be modelled in order to effectively evaluate the caving behaviour. These factors include: detachment/rotation of blocks, frequency and pattern of discontinuities and bending/rotation of roof layers. For more detailed study on small-scale caving behaviour refer to Vakili et al, (2007,2008 and 2009).

The numerical formulation in FLAC^{3D} allows the use of small-strain and large-strain modes. In small-strain mode —unlike the large-strain mode— small displacements, displacement gradients and rotations are assumed. In that mode, node coordinates are not updated, and stress rotation corrections are not taken into consideration (Itasca, 2006). As the caving process in longwall operations involves large strain (including block rotation), the use of small-strain mode may not be realistic.

For this paper, the sensitivity of the model to different constitutive models and strain modes (small or large) are investigated. Elastic, perfectly-plastic and strain-softening constitutive models are compared. The post-peak response of the rock mass, in the strain-softening model, is taken from Badr et al. (2003). The extent of the yield zone for each mining step in the strain-softening model is shown in Figure 2.

The extent of the caving zone at step 6 is shown in Figure 3 for three material models used. Both perfectly-plastic and elastic models show a more or less symmetrical goaf formation. However, for the strain-softening model the caving zone forms asymmetrically, reflecting the effect of the stress redistribution around the longwall panel after each step.

One of the main difficulties with the elastic longwall modelling is associated with modelling of two neighbouring panels. As can be seen in Figure 3, unlike the inelastic models, in the elastic model a symmetrical interaction takes place between two panels. This is due to the reversible nature of the elastic deformation.

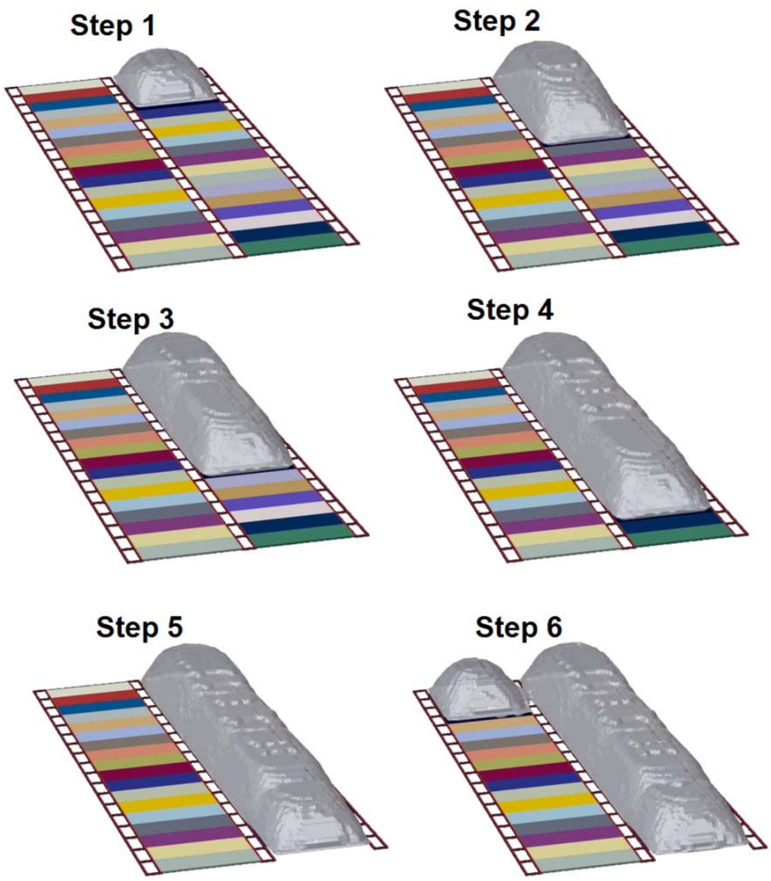

Figure 2 - Extent of yield zone (goaf) in strain-softening model

Figure 4 and Figure 5 show the extent of subsidence at the end of model steps 5 and 6. The strain-softening model shows the most non-linear subsidence behaviour. The non-linearity of this model is more obvious in Figure 4, where it can be compared with the linear subsidence profile of the elastic model. This correlates well with observed subsidence monitoring results. Compared with the perfectly-plastic case, the strain-softening model predicts less subsidence. This can be explained by the fact that goaf compaction and reloading is better represented in this model and therefore the compacted goaf act as an additional support in the system, which inhibits excessive subsidence.

Figure 6 shows the total volume of the caved material for the different material models. As expected, the strain-softening model has the maximum volume of caved material.

The assessment of abutment conditions (i.e. chain pillar stability) can be highly influenced by the choice of constitutive model, element discretisation and face advance interval. As shown in Figure 7, the strain-softening model is the only material model that can represent the true effect of goaf compaction/reloading and its associated influence on pillar stability. All of the other models underestimate the stress distribution in the pillar.

MAP3D MODELLING

Map3D (Mine Modelling Pty Ltd) is a three-dimensional Boundary-Element (BE) program. The BE is an integral method. In integral methods only the boundaries of the problem domain are divided and the domains are considered to be an infinite medium. BE programs are best suited for linear (elastic) and homogenous materials (Brady and Brown, 2004).

Map3D program is commonly used to address operational requirements in longwall mining. Examples of recent studies where Map3D was used for longwall geomechanics include Hatherly et al (2003) and Klenowski (2000).

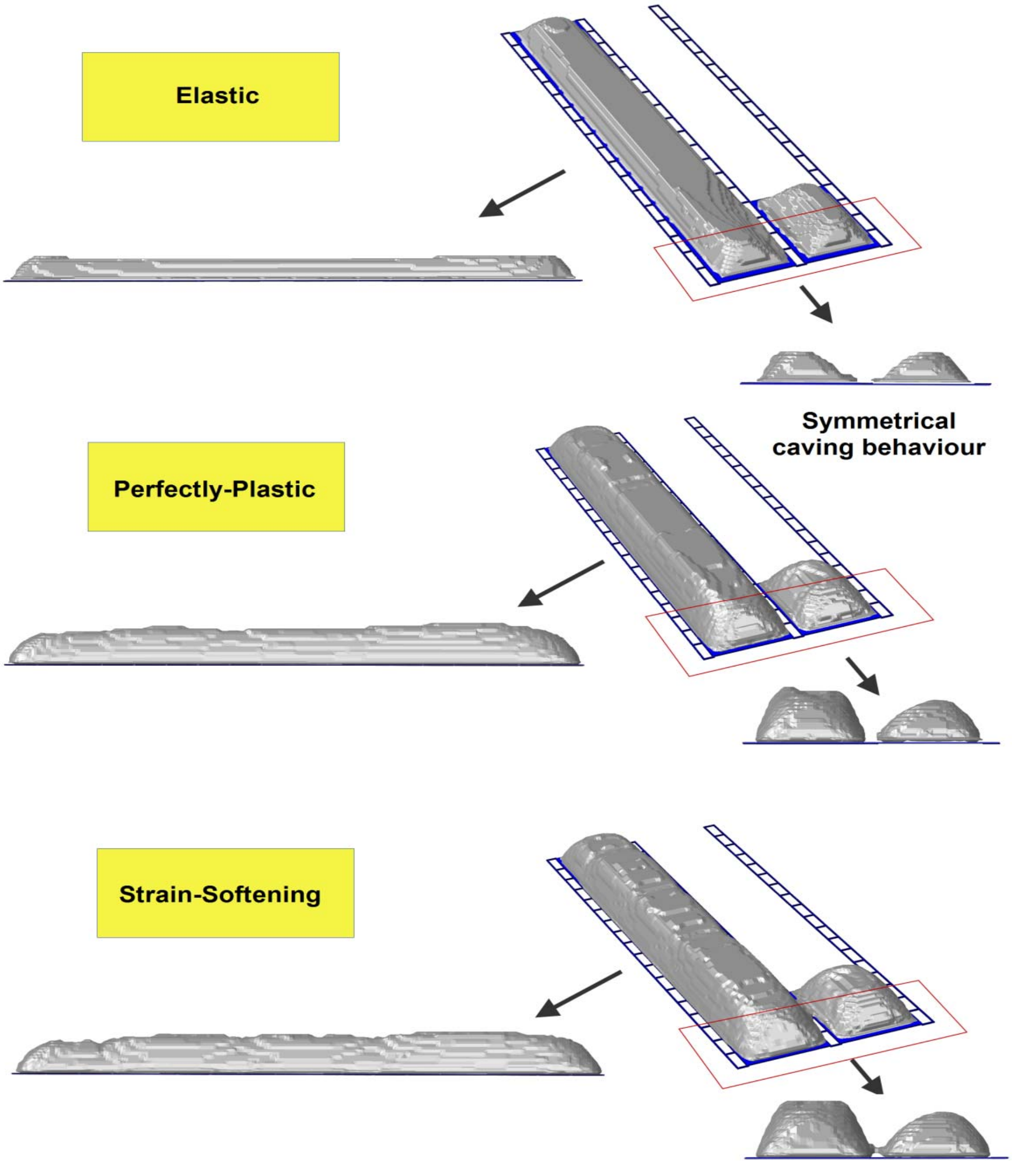

Figure 3 - Interaction between two longwall panels in different constitutive models

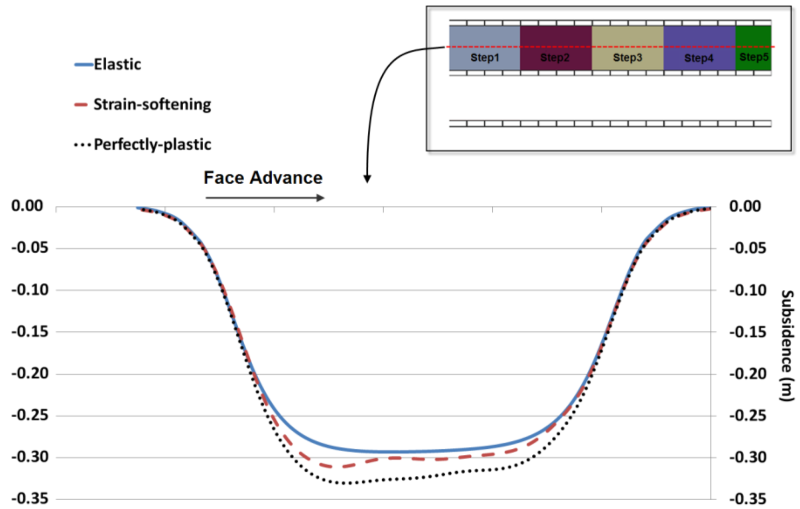

Figure 4 - Subsidence after completion of first panel (step 5)

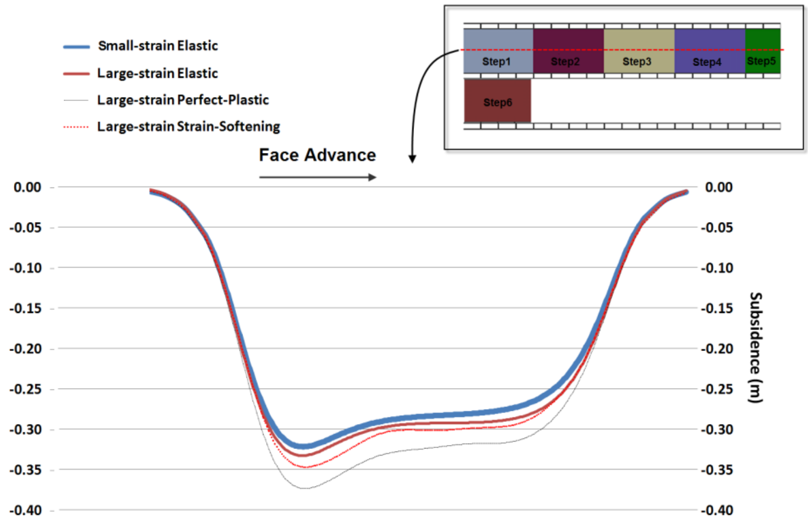

Figure 5 - Subsidence after completion of step 6

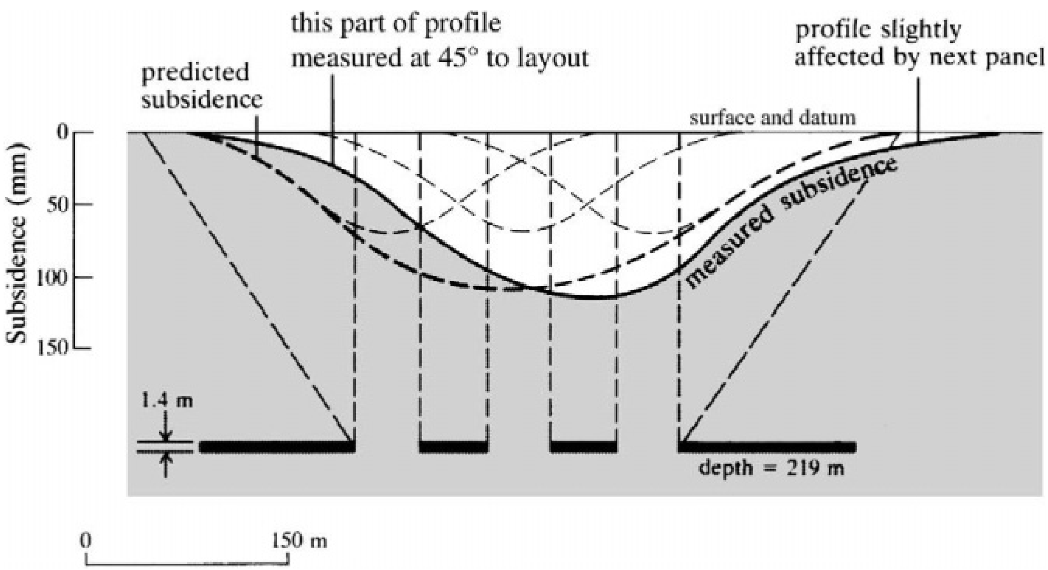

Figure 6 - Predicted and measured subsidence profiles (after Orchard and Allen, 1970)

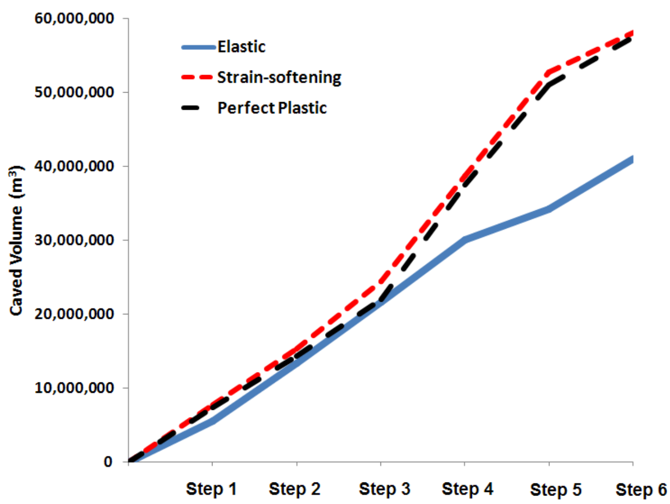

Figure 7 - Volume of caved material in each model

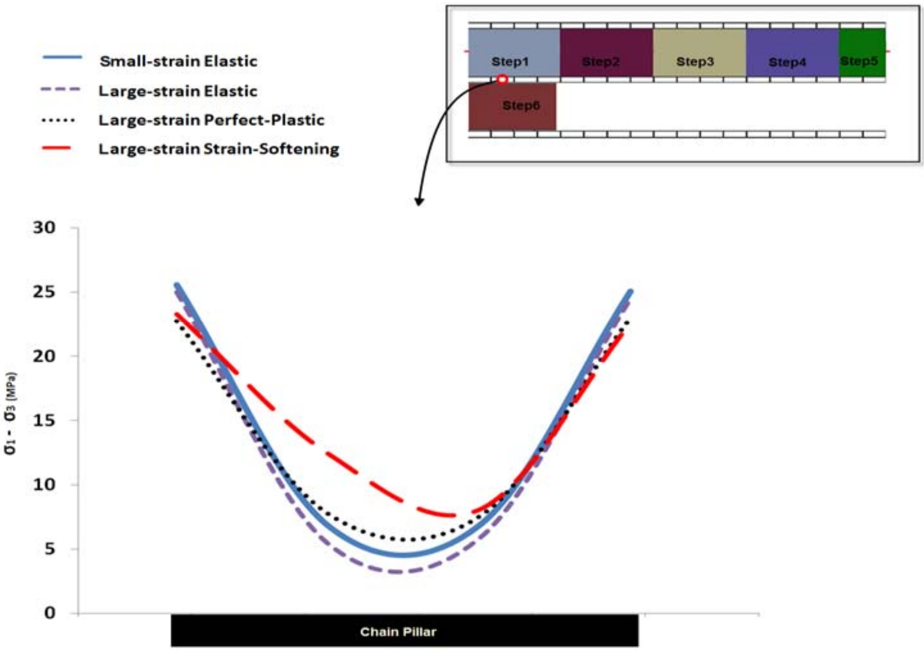

Figure 8 - Stress magnitudes in a chosen chain pillar

In this study, similar longwall layout was modelled with Map3D and FLAC^{3D}. Similar discretisation was used for Map3D model to make both models comparable.

Map3D is generally best suited for linear elastic modelling. However as discussed in the previous section, caving in longwall operations introduces highly non-linear behaviour and this cannot be modelled realistically by an elastic model. In addition, because of the nature of boundary element methods, the effect of large displacements and the associated geometry changes cannot be included in the model. Longwall caving is associated with large deformations and geometry variation, and this has to be considered for a representative modelling study.

To address these problems, it is a general practice, in Map3D models, to include the goaf geometry with a different material property, with gravity load applied to represent the impact of goaf compaction.

To estimate the goaf material properties and goaf compaction characteristics, empirical methods have been generally used by researchers. Example studies include Yavuz (2003), Salamon (1990) and Xie et al. (1999).

For this paper, a 'with goaf' and 'without goaf' case were modelled. For the case with goaf geometry, the goaf dimensions (caving height/angle) were obtained from the FLAC^{3D} modelling results (strain-softening model). The goaf geometry is shown in Figure 9.

A range of goaf material properties and stress conditions were modelled to assess the sensitivity of results. For comparison purposes, the longwall panels were constructed using 'Fictitious Force' (FF) as well as 'Displacement Discontinuity' (DD) elements. The modelling results were compared in terms of pillar stability and overall subsidence.

The stress magnitude (defined using maximum deviator stress) in a selected chain pillar is shown in Figure 10. The modelling results for pillar stability indicate high sensitivity to goaf material properties. Both modulus and vertical stress magnitude can significantly change the state of stress on pillars. As expected, the 'without goaf geometry' model is more or less equivalent to the 'small-strain elastic' FLAC^{3D} model and produces similar results.

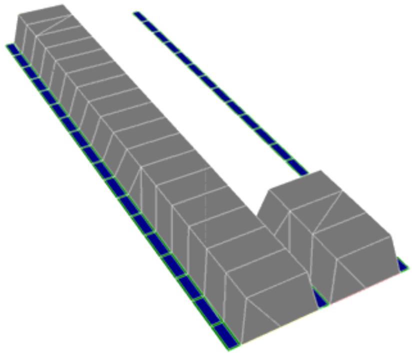

Figure 9 - Assumed goaf geometry for the Map3D model

Based on these results, if the properties of the goaf material are not known, the recommended approach would be to exclude the goaf material and represent the longwall and roadway geometry using FF elements.

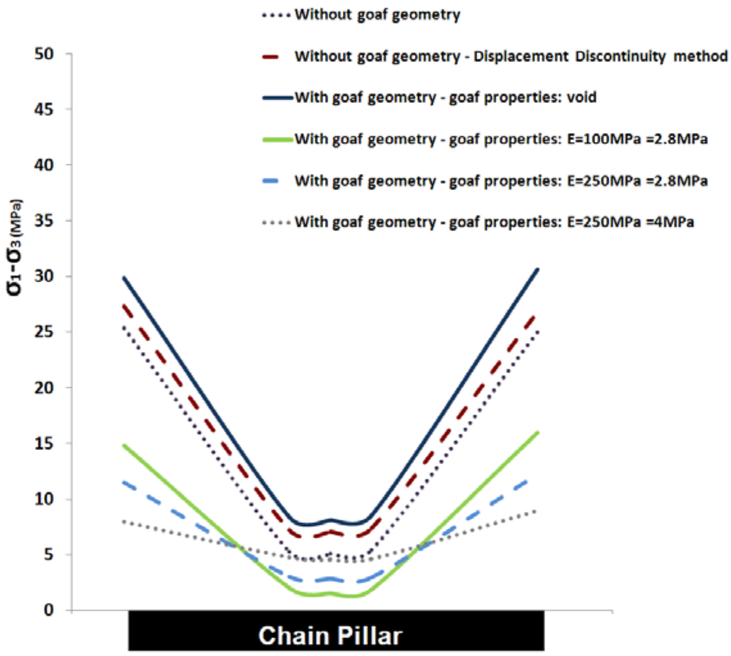

Figure 10 - Stress magnitudes in the selected chain pillar

The subsidence results are shown in Figure 11. The results for cases where the longwall panels are modelled using FF elements are highly erratic. The results for the 'without goaf' geometry model using FF elements show significant ambiguity and are not presented here. This reflects the limitation of using FF elements in the boundary-element method when dealing with thin tabular geometries. This limitation is discussed in more detail in Watson and Cowling (1985).

Figure 11 shows that the use of DD elements results in a more realistic subsidence profile, more closely matching the FLAC^{3D} subsidence profiles.

However, compared with the 'elastic' FLAC^{3D} model, the MAP3D DD model indicates less overall subsidence. This can be associated with the general limitations of boundary-element method, which cannot model large displacements and the associated changes in problem geometry.

COMPARISON BETWEEN FLAC^{3D} AND MAP3D MODELLING APPROACHES

To compare the suitability of the two programs, different aspects of the modelling process must be taken into account. These aspects fall into two main categories, general aspects and technical aspects.

For technical aspects of the modelling, the two programs were compared in terms of their ability to model the surface subsidence and pillar stability. The pillar stability comments are also relevant for the assessment of face and roadway stability.

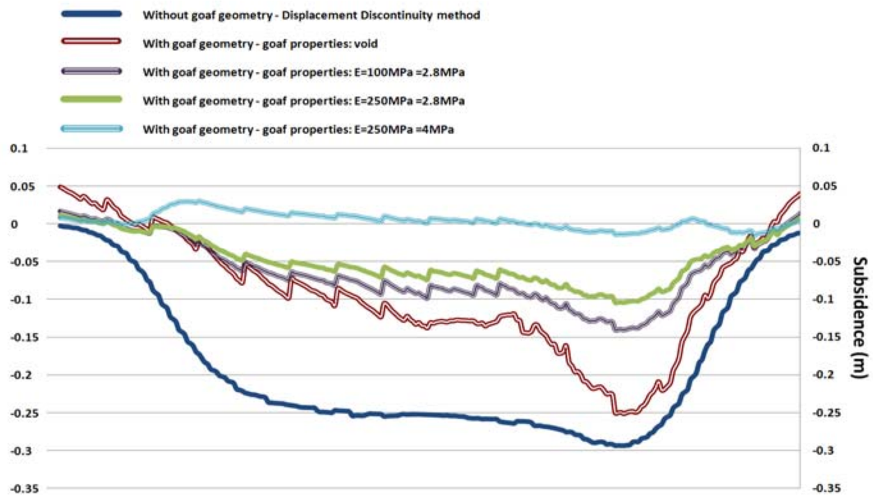

Figure 11 - Overall subsidence predicted by Map3D model

Note that the comments for the FLAC^{3D} modelling only apply to the improved modelling approach, which uses ABAQUS/CAE for model construction and visualization. The comparisons are listed in Table .

Table 1 - Comparison between MAP3D and FLAC^{3D} programs with respect to general modelling requirements for longwall mine-scale modelling

ADVANTAGES	DISADVANTAGES
Map3D	
• Fast and easy model construction • Minimum modelling expertise are required • Easy post-processing of results • Fast computing • Weakness planes can be modelled implicitly • Generally considered as more cost effective	• Best suited for linear and homogenous materials • The modelling results can generally be presented only in 2D (along grid-planes) • The modelling results can only be obtained in places where a grid-plane is defined • Large displacements and the associated geometrical changes cannot be modelled accurately
FLAC^{3D} (with ABAQUS/CAE)	
• Can model highly non-linear, anisotropic and heterogeneous materials • Bedding separation/slip can be modelled explicitly • Major faults can be modelled explicitly • The modelling results can be presented for all associated geometries in 3D format • All the modelling results can be obtained from one model run	• Well-developed modelling expertise required • Relatively long solution times • Relatively more expensive modelling option

Table 2 - Comparison between MAP3D and FLAC^{3D} programs with respect to pillar-stability modelling requirements

ADVANTAGES	DISADVANTAGES
Map3D	
• Reasonable accuracy can be achieved in a large-scale global model provided sensible input assumptions are made	• Goaf geometry including caving height and caving angle must be known accurately • Goaf material properties including modulus and Poisson's ratio must accurately be known. If not known the goaf geometry should not be included in the model. • Goaf compaction/reloading effect must accurately be known to include the associated vertical stress component.
FLAC^{3D} (with ABAQUS/CAE)	
• The caving behaviour can be accurately modelled subject to application of an appropriate constitutive model • No separate material property or stress condition is required for the caved material • The ground support can be modelled for stability assessment	• Sub-modelling technique might be required if a higher accuracy is required

Table 3 - Comparison between MAP3D and FLAC3D programs with respect to surface subsidence modelling requirements

ADVANTAGES	DISADVANTAGES
Map3D	
• Can provide a quick approximation of the overall subsidence profile, if the longwall panel is constructed using DD elements.	• The predicted subsidence profile can be very inaccurate in cases where high non-linearity is involved • Because of the nature of the program, the subsidence magnitudes are not reliable and must not be taken into account • Visualization of the final subsidence profile can be difficult in cases where complex topography is involved • FF elements should not be used for subsidence prediction
FLAC^{3D} (with ABAQUS/CAE)	
• Very complex and detailed topography can be included into the model • The non-linear subsidence behaviour can accurately be modelled • Given that appropriate constitutive model and material properties are used, the model can predict the subsidence very accurately • The subsidence profile can be visualized very easily in 3D	• Calibration and back analysis may be required to obtain confidence about the material properties and the post-peak response of the rock mass • Small-scale subsidence effects, where detachment and shear slips are involved, cannot be modelled

CONCLUSIONS

In this study the modelling results from the finite difference code FLAC^{3D} and elastic boundary element code Map3D for a generic longwall extraction sequence were compared. These models were compared in terms of the extent of surface subsidence and associated stability of pillars.

In general, Map3D should only be used in cases where high confidence exists about the goaf geometrical characteristics (caving height and caving angle), its properties (modulus and Poisson's ratio) and its compaction/reloading characteristics. This code is generally not suitable for subsidence analyses. Nevertheless the application of this code can be very easy and cost effective where its applicability can be justified.

The FLAC^{3D} program, and in particular its combined application with ABAQUS/CAE, is generally more suitable for cases where less information is available about the caving and goaf behaviour. The program can be effectively used for subsidence prediction. This modelling approach may require higher level of expertise than Map3D and it can sometimes be slightly more expensive. However with recent improvements in hardware and software capabilities, the application of mine-scale 3D inelastic continuum models is becoming easier and more cost effective.

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