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TECHNICAL NOTE

Deficiencies in 2D Simulation: A Comparative Study of 2D Versus 3D Simulation of Multi-seam Longwall Mining

Deepak Adhikary[1] · **Manoj Khanal**[1] · **Chandana Jayasundara**[1] · **Rao Balusu**[1]

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1 Introduction

The reliable prediction and management of mining-induced surface subsidence is one of the environmentally challenging issues for the coal mining industry. Because coal mining companies operate under strict environmental accountability, the absence of robust and reliable analysis tools may significantly affect the industry's ability to gain approval and licenses when significant surface subsidence issues are involved. This issue becomes even more critical in multi-seam mining conditions, where high-stress concentration and large amounts of surface subsidence are expected to generate during multi-seam mining, hence could affect the feasibility and safety of all seams being mined. To obtain mining approval, it is, therefore, imperative to understand the geomechanical effect of mining in one seam on the mining of the underlying/overlying seams, and to accurately predict the magnitude and profile of surface subsidence.

Various computer programs using empirical or numerical approaches have been developed to estimate the stresses at pillars and coal seams during multi-seam mining (Bigby et al. 2007; Ellenberger et al. 2003; Mark et al. 2007; SCT 2010; Sears and Heasley 2013). However, empirical-based models have severe limitations, which often make them inapplicable for assessing the feasibility of multi-seam mining at green field sites. Instead, numerical simulations are widely employed for this purpose. Due to the complexity of the problems and the computational times, researchers and engineers generally resort to two-dimensional (2D) simulations.

The present study assesses the performance of 2D and 3D numerical simulations and presents comparisons of subsidence profiles and stresses in pillars obtained during multi-seam mining. We modeled two different seams, each with four mining panels, using an in-house, 3D, finite element code called COSFLOW (Adhikary et al. 1996; Adhikary and Guo 2002). A unique feature of COSFLOW is the incorporation of Cosserat continuum theory in its formulation (Cosserat and Cosserat 1909). In the Cosserat model, interlayer interfaces (i.e., joints, bedding planes) are considered to be smeared across the mass. In other words, the effects of the interfaces are incorporated implicitly in the choice of stress–strain model formulation. The Cosserat model incorporates the bending rigidity of individual layers in its formulation, unlike other conventional implicit models. COSFLOW produced very accurate results when simulating surface subsidence due to longwall mining at Appin Colliery in New South Wales in Australia (Guo et al. 2004).

2 Model Development

We selected a model with data obtained from a mine site in India, as described in Khanal et al. (2011, 2014) to investigate parameters related to multi-seam mining under various scenarios. Figure 1 shows the plan view, oblique view and the location of the panels from the side of the 3D

✉ Manoj Khanal
Manoj.Khanal@csiro.au

[1] CSIRO Coal Mining Research Program, Queensland Centre for Advanced Technologies, 1 Technology Court, Pullenvale, QLD 4300, Australia

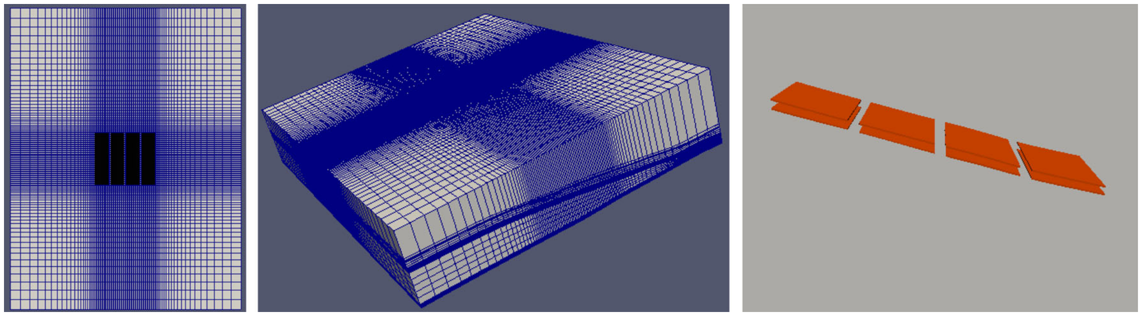

Fig. 1 Plan view (*left*), oblique view (*centre*) and panel location seen in a view down the length of the longwall panels represented in the 3D model and *right picture* shows the *upper* and *lower* mining panels (*note* that the panels are not off-set)

model. In addition to the model described in Khanal et al. (2011), we incorporated two panels on either side of the existing panels. Each longwall panel is assumed to be 1 km long. The panels are 260 m wide with 40 m wide chain pillars between them. In the plan view, model spans an area bounded by 4.6 and 6 km to minimize boundary effects.

A typical lithological log used in the model is shown in Fig. 2. From practical point of view, it is not easy to incorporate all the field lithologies in the model; thus similar field lithological layers have been assigned aggregate properties reducing the number of model layers. Two seams considered in the investigations are I_BOT (top seam) and II (bottom seam). The seams are separated by 15.6 m. The I_BOT seam has a uniform extraction thickness of 3 m, whereas the extraction thickness of the II seam varies at different locations.

The varying depth and thicknesses of the seams are shown in Table 1 (measured at the centre of the panels). Panels a, b, c and d are extracted in the top seam, while panels e, f, g and h are extracted in the bottom seam. The constitutive models employed for the rock blocks and the joints are the elastic, perfectly plastic Mohr–Coulomb model (Adhikary and Guo 2002). In the model, the major and minor principal horizontal stresses were assigned values of 1.3 and 1.1 times the vertical stress, respectively, measured in the field. Table 2 provides the strength

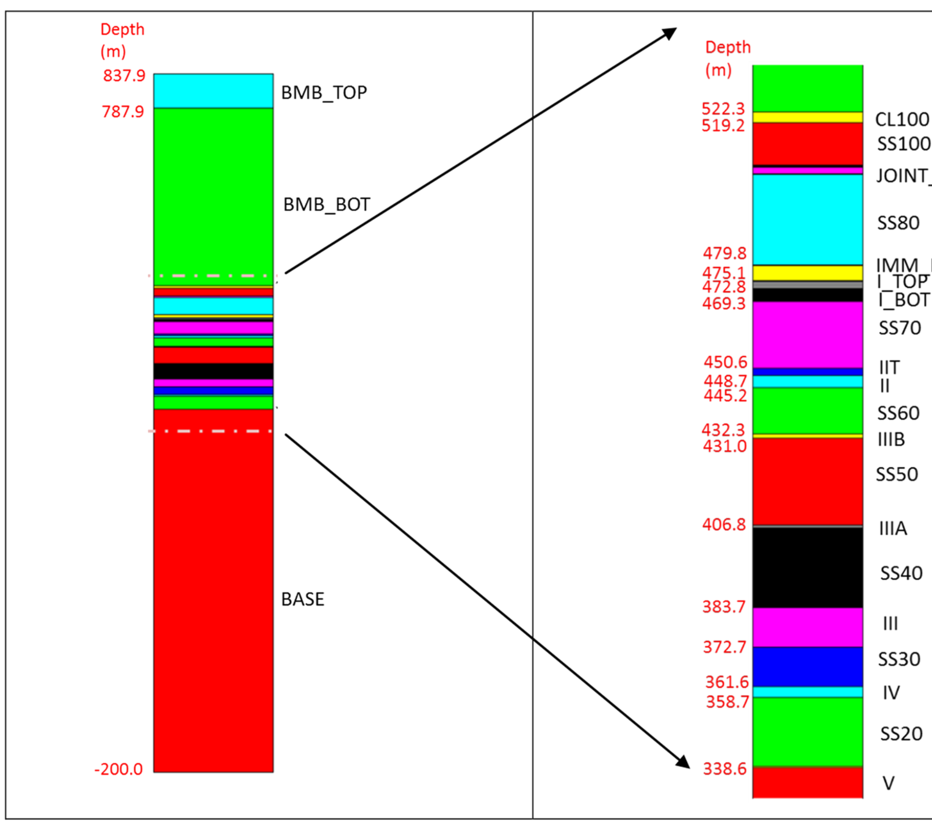

Fig. 2 A typical core log of the geology used in the model showing the elevation above the mean sea level

deformation parameters used in the numerical simulation. These values were calibrated from the real mine site model as described in Khanal et al. (2011, 2014). A 10-m slice at the centre of the model was selected for the 2D modeling to understand the effect of 3D and 2D simulations (Fig. 3). During this study, the material properties and appropriate in situ stresses remain unchanged.

Table 1 Panel width, depth and thickness

Panel	Depth (m)	Thickness (m)	Width (m)
a	328.14	3	260
b	377.68	3	260
c	415.88	3	260
d	447.45	3	260
e	Varying	2.6	260
f	Varying	1.8	260
g	Varying	3.1	260
h	Varying	2.8	260

3 Results and Discussion

The geotechnical field data described in this paper is obtained from a 4-year study conducted at a Greenfield site in India, where the longwall panel is not started yet. 3D COSFLOW simulation results have been validated against the observed surface subsidence at a number of mine sites in Australia and China; for example Guo et al. (2014) describe a comprehensive study conducted at Blakefield South Mine in New South Wales in Australia and present comparisons between the observed surface subsidence during multi-seam mining and those obtained using 3D COSFLOW simulations. 3D COSFLOW simulation results are found to agree remarkably well with the measured values both in terms of magnitude and subsidence profile.

Table 2 Rock properties

Unit	Density (kg/m^3)	Modulus (GPa)	Poisson ratio	Rock tension cutoff (MPa)	Rock cohesion (MPa)	Rock friction angle (°)	Rock dilation angle (°)
BMB_TOP	2045	1.5	0.3	0.2	0.7	31.4	5.0
BMB_BOT_U	2045	3.0	0.2	0.5	1.4	31.4	5.0
BMB_BOT_M	2045	3.0	0.2	0.5	1.4	31.4	5.0
BMB_BOT_L	2045	3.0	0.2	0.5	1.4	31.4	5.0
CL100	2206	5.0	0.3	1.4	3.8	35.0	5.0
SS100	2172	7.1	0.2	2.5	5.7	40.7	5.0
IAT	1701	3.0	0.1	1.4	1.3	40.0	7.5
IB90	2229	5.0	0.3	1.1	2.7	37.0	5.0
IA	1720	3.0	0.1	1.3	1.2	40.0	7.5
SS80	2125	6.0	0.1	2.5	5.7	41.5	5.0
IMM_ROOF	1779	3.0	0.1	0.8	3.3	31.8	5.0
I_TOP	1497	3.0	0.3	0.6	1.3	40.0	7.5
I_BOT	1497	3.0	0.3	0.6	1.3	40.0	7.5
SS70	2247	7.4	0.2	0.2	5.7	40.4	5.0
IIT	1721	3.0	0.1	1.1	1.2	40.0	7.5
II	1510	3.0	0.3	1.0	0.9	40.0	7.5
SS60	2192	7.2	0.1	0.2	1.9	35.5	5.0
IIIB	2080	3.0	0.3	0.4	0.4	40.0	7.5
SS50	2234	6.6	0.1	0.1	1.8	39.8	5.0
IIIA	2290	3.0	0.3	1.0	0.9	40.0	7.5
SS40	2187	5.7	0.1	0.1	1.4	39.3	5.0
III	1529	3.0	0.3	1.1	2.8	40.0	7.5
SS30	2249	7.9	0.2	0.2	1.7	45.5	5.0
IV	1472	3.0	0.3	0.7	0.9	40.0	7.5
SS20	2197	8.9	0.2	0.2	1.8	42.7	5.0
V	1502	3.0	0.3	1.1	1.2	40.0	7.5
BASE	1957	5.3	0.1	0.9	4.7	39.5	6.2

Joint dilation angle of 3°, joint tension cutoff of 0 MPa and joint friction angle of 25° are used for the layered units

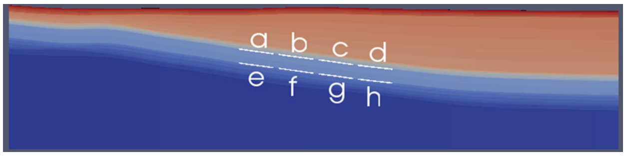

Fig. 3 A cross-sectional view at the *centre* of the model showing inclined seams and panel naming sequence

4 Comparison between 2D and 3D models

In the 2D model, each longwall was extracted in a single step, whereas in the 3D model, each longwall was extracted in multiple steps along the longwall retreat direction. In the 3D model, four different extraction steps were used for each longwall (i.e., a single step of 1000 m, 10 steps of 100 m each, 20 steps of 50 m each and 80 steps and 12.5 m each) to study the effect of the number of extraction steps in longwall mining simulations. An additional model with 3-km-long longwall panels was simulated with the same geological conditions and extracted in a single step to mimic the pseudo plain strain scenario and compare it with the plain strain 2D simulation. The mining was performed in a descending sequence (i.e., panels are extracted in the following order: a, b, c, d, e, f, g and h).

Figure 4 shows the predicted surface subsidence for 2D and 3D models at various extraction steps. Subsidence was measured along a line at the centre of the model across the width of the panels. The thickness of the second panel was thinner than the thickness of the other panels of the bottom seam (see Table 1); hence, the measured subsidence is lower at this location (right figure). The simulations suggest that:

- 2D models overpredict subsidence compared with 3D models with multiple extraction steps.
- 3-km-long panels (pseudo plane strain) extracted in a single step yield results similar to 2D plain strain models.

In the 2D model, each panel was extracted in a single step to represent the extraction of infinitely long panels in one extraction step. The 2D simulation results are comparable to those of the 3D simulation, in which 3-km-long longwall panels were extracted in one extraction step. However, in reality, a longwall retreats gradually as the shearer slices around 0.3 m of coal from the longwall face in each pass. Thus, it is desirable to simulate coal extraction in multiple excavation steps. As the extraction steps become smaller and smaller, the results would be expected to match realistic mining scenarios. The figures also suggest that once the extraction step is around 100 m or less (1 km extraction in 10 steps), the surface subsidence predictions are very similar. Figure 5 shows the comparison of 2D and 3D normalized subsidence above the panel a after completion of panel d. The surface subsidence predictions are very similar with the finer steps.

5 Conclusions

This paper presents the results of numerical simulation of surface subsidence induced by longwall mining obtained using a 2D and 3D Cosserat continuum-based, finite element code called COSFLOW and highlights the deficiencies associated with 2D simulations:

- 2D models overpredict the magnitude of surface subsidence and stresses in chain pillars.
- 3D models produce results comparable with 2D models when longwalls are extracted in large steps (e.g., one step).

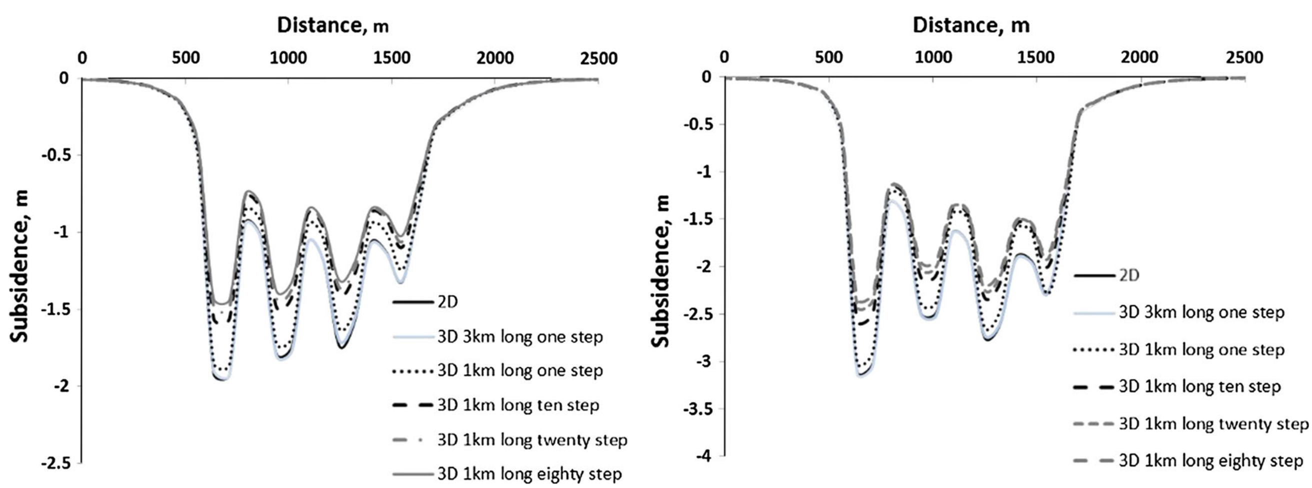

Fig. 4 Subsidence observed in 2D and 3D simulations after the extraction of four panels in the upper seam (*left*) and additional four panels in the lower seam (*right*). Subsidence was measured at the centre of the model across the panel width

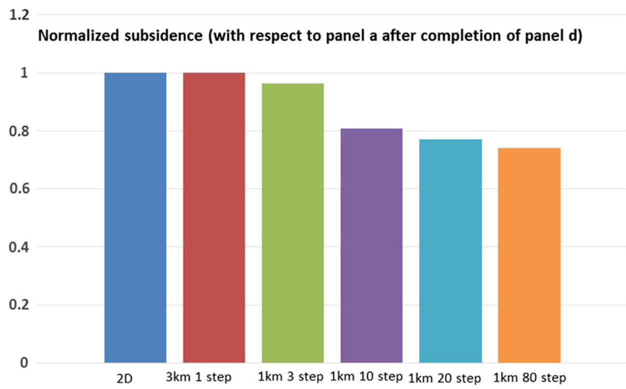

Fig. 5 Comparison of 2D and 3D normalized subsidence above the panel a after completion of panel d

- When the longwall is extracted in smaller steps to approximate reality, the 3D models yield lower values for subsidence and chain pillar stress.
- Extraction steps of <100 m in the 3D models are found to produce consistent predictions for subsidence and chain pillar stress.

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