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Monitoring and modelling of gas dynamics in multi-level longwall top coal caving of ultra-thick coal seams, Part II: Numerical modelling

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ABSTRACT

The longwall top coal caving method, which enables the most productive exploitation of thick/ultra-thick coal seams, may result in a distinct geomechanical response of strata and associated gas emission patterns around longwall layouts. A two-way sequential coupling of a geomechanical and a reservoir simulator for the modelling of gas emissions around a longwall top coal caving (LTCC) panels was developed building on the understanding established from the analysis of in-situ gas pressure and concentration measurements carried out at Coal Mine Velenje in Slovenia. Model findings have shown that the modelling method implemented can reproduce the dynamic changes of stresses and gas pressure around a LTCC face and predict the total gas emissions and mixed gas concentrations accurately. It was found that, in LTCC panels, although the rate of gas emission from mined coal depends highly on the coal face advance, floor coal and roof goaf act as a constant and steady gas source accounting for a considerable part of the overall gas emission. Research has shown that, at first and/or second mining levels of multi-level LTCC mining, a notable stress relief and pore pressure drop induced by fracturing of the mined and roof coal can be experienced within 40 m ahead of the face-line. In the floor coal, on the other hand, the pore pressure change was found to extend to 20 m below the mining horizon. Model results have clearly shown the permeability enhancement and gas mobilisation zones around the LTCC panel, which can be the target zones for gas drainage boreholes.

1. Introduction

Gas emissions, which occur along with coal extraction activities, have long been recognised as one of the main hazards affecting production and safety in coal mining. Recent advances in computational methods have provided cost-effective solutions to investigate the mechanisms of gas emissions induced by coal mining. Geomechanical response of the strata to coal extraction and the associated gas flow around a longwall coal face can be realistically reproduced by geomechanical and fluid flow simulators.

Over the past 40 years significant progress has been made in modelling gas emissions from longwall panels and the surround strata. Kidybinski (1973) used finite element method to study stress redistribution and fracturing within the roof rocks of a longwall face. Researchers at Nottingham University conducted numerical modelling studies on gas emissions in longwall mining (Keen, 1977; O'Shaughnessy, 1980). Durucan (1981) combined numerical modelling and laboratory investigations into stress-permeability relationship of coals and derived models for permeability distribution and associated gas flow around an advancing longwall coal face. Based on these studies Ren and Edwards (2000) developed a three-dimensional methane flow model using computational fluid dynamics, with permeability values ranging from 10^{-14} to 10^{-8} m^2 assigned to different regions in the flow model. However, in most of these early studies, the mechanical impact of coal extraction on gas flow was neglected or over simplified.

More recently, Whittles et al. (2006) presented a methodology to derive dynamic permeability changes in coal measure rocks from the results of geomechanical modelling of a longwall face for fluid flow simulation. A one-way explicit coupling approach was developed by Esterhuizen and Karacan (2005) to investigate gas migration from surrounding rocks towards longwall working faces. In their models, a geomechanical simulator was used to simulate the continuous advance of a longwall face and provide dynamic permeabilities for gas emission modelling in a reservoir simulator. The advance of a longwall face was modelled as a moving boundary problem and restart models were run sequentially representing different mining steps and corresponding strata responses. Based on this approach, the performance of in-seam degasification boreholes and goaf gas ventholes was evaluated by the authors (Karacan et al., 2007a,b).

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Although significant improvements have been made in modelling gas flow around coal faces by applying a one-way coupled approach, this coupling methodology does not provide feedback from the output of the flow simulator back to the geomechanical simulator to update the pore pressure distribution for computing the changes in the effective stresses. This missing link may incorrectly estimate the dynamic permeability, especially where significant changes in the pore pressure are expected in the fractured zone around a producing longwall face. On the other hand, experience in coalbed methane industry suggests that two-way coupled modelling between geomechanics and fluid flow can improve the model predictions significantly (Connell, 2009; Gu and Chalaturnyk, 2010; Shi and Durucan, 2005).

Although gas emissions during mechanised conventional longwall mining have been extensively studied in the past few decades (Karacan et al., 2011; Lunarzewski, 1998; Noack, 1998), gas emission patterns around longwall top coal caving (LTCC) panels used in mining thick/ultra-thick coal seams are not very well understood. The application of multi-level LTCC mining method, which yields the most productive exploitation of thick/ultra-thick coal seams, may result in a distinct geomechanical response of the strata and associated gas emission patterns around thick seam layouts. This is because the LTCC faces are fully surrounded by solid coal, and gas may migrate into the mine openings from coal at the mining horizon, the lower mining levels, and even the previously mined goaf.

Although extensive research has been carried out on gas emissions from longwall panels operated in relatively thin coal seams, only a very few studies have been reported on multi-level or LTCC operations, which mainly focused on strata geomechanics. Yasitli and Unver (2005) developed a three-dimensional numerical model to study top coal caving mechanism in a longwall panel at the Omerler underground mine in Tuncbilek, Turkey. Later, they applied this approach to study the strata movement induced by LTCC in thick seam coal mining (Unver and Yasitli, 2006). Using discrete element method to model the particle flow during the process of top coal caving, the application of vibration technique to improve the recovery ratio of top coal was studied by Xie and Zhao (2009). Likar et al. (2006) carried out a geomechanical analysis of top coal caving process at Coal Mine Velenje using laboratory physical, analytical and numerical models. A 3D numerical model was developed based on the actual geological conditions at the mine. Stress distribution around a LTCC face was simulated using FLAC3D and the results compared with stress monitoring data from the face (Jeromel et al., 2010). More recently, dynamic stress response of the coal seam to coal production at different levels of the coal seam was monitored and compared with the numerical modelling results (Likar et al., 2012).

As the second part of a two-part series, this paper focuses on numerical modelling of gas emission mechanisms around LTCC faces during the mining of ultra-thick coal seams. In Part One, a conceptual model for gas emissions in multi-level LTCC mining of ultra-thick coal seams has been proposed based on extensive in-situ measurements of in-seam gas pressure, gas composition, and ventilation environment. It was found that, coal within the near face fracturing zone 40 m ahead of a LTCC face plays a significant role in contributing to longwall gas emissions. It was also confirmed that the gas emission into the LTCC face is very sensitive to the rate of fracturing experienced due to stress relief and the size of fractured zone in the floor coal. In addition, gas inflow from the roof goaf may also take a considerable share of overall gas emissions in LTCC panels operating at lower mining levels.

In this paper, a two-way sequential coupling of a geomechanical and a reservoir simulator for the modelling of gas emissions around a longwall top coal caving panels was developed building on the understanding established from the analysis of field investigations carried out at Coal Mine Velenje in Slovenia. Mining geomechanics and gas flow were linked by two coupling parameters, namely the permeability and pore pressure. Anisotropic and stress dependent permeability for intact and fractured coal and rock were considered. The proposed methodology was successfully applied to history match the dynamic changes of stress and gas pressures around the K.-50/C LTCC panel.

2. Methodology

2.1. Two-way coupling model workflow

Modelling of gas emissions in a longwall panel can be carried out through either one-way or two-way coupling of a geomechanical and flow simulator. With one-way coupling, mining induced dynamic stress changes are first solved using the geomechanical simulator assuming a constant pore pressure field in the model domain. The computed (effective) stress profiles, which evolve with the advance of the face, are used to estimate corresponding permeability changes in the mined coal seam and the surrounding strata. The prevailing permeabilities around the mining opening at each excavation step are then used in the flow simulator to obtain the pressure field and compute the gas emission rates. In this way, the impact of mining induced stress changes on gas flow around the mine openings and gas emission rates are accounted for. This coupling approach is justified since stress wave propagation is normally several orders of magnitude faster than pressure propagation (ITASCA, 2012), and thus stress equilibrium can be considered to be established almost instantly after each excavation step.

The main drawback of this simplified coupling approach is that there is no feedback from the output of the flow simulator back to the geomechanical simulator at the end of each excavation step to update the pore pressure distribution for computing the changes in the effective stresses in the next excavation step. This missing feedback is included in the two-way explicit sequential coupling workflow adopted in this work, as illustrated schematically in Fig. 1.

The two-way coupling achieved in this paper is between $FLAC^{3D}$, a widely used commercial software package for conducting advanced geomechanical analysis encountered in geotechnical engineering applications, and ECLIPSE 300 (Schlumberger, 2010), an industry standard compositional reservoir simulator which has a coalbed methane module. As shown in the workflow, pore pressure field (p^{n-1}) arrived at the previous excavation step ($n-1$) by ECLIPSE 300 is passed on to $FLAC^{3D}$ to compute a provisional total stress ($\sigma^{n'}$) after coal extraction in the first instance of current excavation step n, using the pore pressure field (p^{n-1}). Then, the permeability field k^n, which is computed based on the provisional total stress $\sigma^{n'}$ and pore pressure p^{n-1}, is sent to ECLIPSE 300 as the input to derive the pressure field (p^n) after coal extraction. The simulated fluid time from t^{n-1} to t^n represents the actual time spent in coal extraction activity at step n. The updated pore pressure field p^n is then fed back to $FLAC^{3D}$ to re-equilibrate the disturbance caused by pressure change within step n. The final stress field σ^n at pore pressure p^n is then produced as the input for the next excavation step $n+1$. A special script was written in Matlab to facilitate seamless exchange of parameters between the two software packages. Since the permeability of coal is controlled by the effective stress, two-way coupling allows a more accurate representation of the dynamic permeability where significant changes in the pore pressure are expected, e.g. in the fractured zone around a longwall face.

During the study, a comparison between two-way coupling and one-way coupling without considering the feedback of pore pressure from gas flow modelling to geomechanical modelling was also conducted. Model set-up and procedure followed were exactly the same as above, except that pore pressure has not been involved in the geomechanical simulations. It was found that, compared to the field measured values, mining induced fractured zone ahead of the face was significantly underestimated by the one-way coupling approach.

2.2. Geomechanical and gas flow modelling of coal excavation in a LTCC panel

As with mechanised conventional longwall mining, face advance at a LTCC face in a given period of time (e.g. one weekday) is modelled as a