A Coupled Cosserat Two-Phase Double Porosity Flow Model

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EXTENDED ABSTRACT

Coal production in Australia will increasingly come from deeper underground mines in the future particularly with longwall mining methods as near surface resources, amenable to open cut or shallow underground mining, become exhausted.

Recent experience of some underground coalmines and measurements from the deeper seams indicates that gas contents, rock and coal stress levels tend to increase with depth.

Reliable mine water and gas prediction is not only essential for improving mine safety and reduction of coal production costs, but also important for the assessment of environmental impact of mining.

Rock strata in a coal mining environment are essentially bedded in nature and hence exhibit specific load-deformation characteristics. Mining may induce shearing as well as separation along the bedding planes which may result in bending and subsequent fracturing of the rock layer. This on the other hand may substantially change the in situ fluid flow properties of the rock mass, such as permeability and porosity. Thus a proper coupling of mine induced deformation, fluid flow properties and the process of fluid flow itself is a must for any reliable prediction of rock mass deformation, water and gas flow into a mine.

Simulation of mining induced rock deformation, rock fracture enhanced permeability and fluid and gas flow into a mine working is a complex task. There are a number of computer codes which handles either the mechanical load deformation process alone or the fluid and gas flow process alone. Only a few commercially available codes couple the mechanical and fluid flow processes.

There is also no consensus on how to formulate permeability changes due to rock mass deformation.

A new three dimensional coupled mechanical two-phase double porosity finite element code called COSFLOW has been recently developed by CSIRO Exploration and Mining as a result of a major joint project between CSIRO and NEDO and JCOAL of Japan. A unique feature of COSFLOW is the incorporation of Cosserat continuum theory in its formulation. In the Cosserat model, inter-layer interfaces (joints, bedding planes) are considered to be smeared across the mass, i.e. the effects of interfaces are incorporated implicitly in the choice of stress-strain model formulation. An important feature of the Cosserat model is that it incorporates bending rigidity of individual layers in its formulation and this makes it different from other conventional implicit models.

The Cosserat continuum formulation has a major advantage over conventional continuum models in that it can efficiently simulate rock breakage and slip as well as separation along the bedding planes. Any opening/closure along a bedding plane may introduce a strong anisotropy in fluid flow properties of the porous medium. This, in turn, will impact on the fluid/gas flow behaviour of the porous medium.

This paper will briefly describe the Cosserat continuum theory, the treatment of permeability changes with rock deformation and the coupling of the two-phase dual porosity (with desorption/adsorption formulation) fluid flow model.

During longwall mining, the overburden will cave into the mine void inducing extensive fractures deep into the overburden. This will enhance the rock mass permeability facilitating increased flow of gas and water from the surrounding rock mass into the mine panel. An example highlighting the capability of COSFLOW in simulating gas emission from multiple coal seams into a longwall panel during mining is presented.

1. INTRODUCTION

Coal production in Australia will increasingly come from deeper underground mines in the future particularly with longwall mining methods as near surface resources, amenable to open cut or shallow underground mining, become exhausted.

Recent experience of some underground coalmines and measurements from the deeper seams indicates that gas contents, rock and coal stress levels tend to increase with depth. In recent years a number of new and existing Australian mines have encountered unexpected gas and water management issues which have seriously impacted on operations and even threatened the viability of mining. With increased coal seam gas content with depth, gas liberation during mining is expected to increase.

Future deep coal mining with those conditions may face significant economic, technical and environmental challenges. The potential impact of these difficult conditions is that the mining risks and costs with current mining technology might increase for future deep coal reserves.

Reliable prediction of rock mass deformation, mine stability, mine water inflow and mine gas emission is not only essential for improving mine safety and reduction of coal production costs, but also important for the assessment of environmental impact of mining.

This paper will briefly describe the Cosserat continuum theory, the treatment of permeability changes with rock deformation and the coupling of the two-phase dual porosity (with desorption/adsorption formulation) fluid flow model.

2. SIMULATION OF ROCK MASS AND WATER/GAS BEHAVIOUR WITH COSFLOW

Rock mass deformation and water/gas flow processes interact dynamically during underground mining of coal by the longwall mining method (Figure 1). To be able to predict rock mass behaviour and associated mine water inflow and mine gas emission during longwall mining, any reliable simulation method needs to have the capability to accurately determine mining induced rock mass deformation, fractures and resulting changes in fluid flow parameters.

A three-dimensional finite element computer code called "COSFLOW" has been developed at CSIRO Exploration and Mining for modelling rock mass deformation, desorption, and two-phase flow (gas and water) problems arising in underground coal mines. The flow of either phase of fluid is controlled by the permeability of the porous medium, which remains a highly non-linear function of mining induced stress and resulting fractures. Thus, in order to be able to correctly estimate gas emission, it is not only important to estimate the initial permeability correctly, but equally important to compute its variation during mining. In this code, permeability change during mining is computed as a function of the mining induced strain. Key features of COSFLOW are described in the following sections.

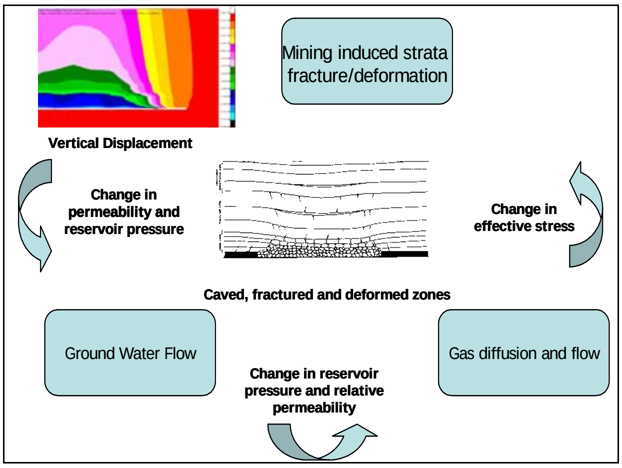

Figure 1. Complex interaction between rock mass deformation and water/gas flow during longwall mining

2.1 Mechanical (Cosserat) Model

Since stratified rock masses exhibit highly anisotropic strength and deformation characteristics, it is necessary to include effects of stratification into the mathematical formulations describing the load-deformation behaviour of such rock masses.

For the case of rock layers with bending stiffness, such a model can be formulated successfully on the basis of Cosserat theory (Adhikary & Guo, 2000; Adhikay and Dyskin, 1997 & 1998). This provides a large-scale (average) description of a layered medium. In this model, inter-layer interfaces (joints) are considered to be smeared across the mass, i.e. the effects of joints are incorporated implicitly in the choice of stress-strain model formulation. An important feature of the Cosserat model is that it incorporates bending rigidity of individual layers in its formulation and this makes it different from other conventional implicit models. In comparison to the conventional model which has six independent stresses in a three dimensional case, the Cosserat model for the stratified material will have ten independent stresses.

2.1.1 2D Cosserat Formulation

For simplicity a 2D Cosserat formulation will be presented in this paper. Using the Cartesian coordinates (x_1,x_2) in two dimensions, the material point displacement can be defined by a translational vector (u_1,u_2) and by a rotation Ω_3. Here, x_3 is aligned to the out of plane direction and x_2 is perpendicular to the layers.

The two-dimensional Cosserat model has 4 non-symmetric stress components $\sigma_{11}, \sigma_{22}, \sigma_{21}, \sigma_{12}$ and two couple stresses m_{31}, m_{32}. When the rock layers are aligned in the x_1 direction, the moment stress term m_{32} vanishes. The four stresses are conjugate to four deformation $\gamma_{11}, \gamma_{22}, \gamma_{21}, \gamma_{12}$ measures defined by:

$$\gamma_{ij} = \frac{\partial u_j}{\partial x_i} - \varepsilon_{3ij}\Omega_3 \quad (1)$$

and the couple stress m_{31} is conjugate to the respective curvature κ_1 defined by:

$$\kappa_1 = \frac{\partial \Omega_3}{\partial x_1} \quad (2)$$

The elastic stress strain relationships are described by:

$$\boldsymbol{\sigma} = [D_e]\boldsymbol{e}_e \quad (3)$$

where

$$\begin{aligned} \boldsymbol{\sigma} &= \{\sigma_{11}, \sigma_{22}, \sigma_{21}, \sigma_{12}, \mathrm{m}_{31}\} \\ \boldsymbol{e} &= \{\gamma_{11}, \gamma_{22}, \gamma_{21}, \gamma_{12}, \kappa_1\} \end{aligned} \quad (4)$$

$$D = \begin{bmatrix} A_{11} & A_{12} & 0 & 0 & 0 \\ & A_{22} & 0 & 0 & 0 \\ & & G_{11} & G_{12} & 0 \\ & symm & & G_{22} & 0 \\ & & & & B_1 \end{bmatrix} \quad (5)$$

where,

$$A_{11} = \frac{E}{1-\nu^2 - \dfrac{\nu^2(1+\nu)^2}{1-\nu^2 + \dfrac{E}{hk_n}}} \quad (6)$$

$$A_{22} = \frac{1}{\dfrac{1-\nu-2\nu^2}{E(1-\nu)} + \dfrac{1}{hk_n}} \quad (7)$$

$$A_{12} = \frac{\nu}{1-\nu}A_{22} \quad (8)$$

$$\frac{1}{G_{11}} = \frac{1}{G} + \frac{1}{hk_s} \quad (9)$$

$$G_{11} = G_{12} = G_{21} \quad (10)$$

$$G_{22} = G_{11} + G \quad (11)$$

$$B_1 = \frac{Eh^2}{12(1-\nu^2)}\left(\frac{G - G_{11}}{G + G_{11}}\right) \quad (12)$$

where E is the Young's modulus of the intact layer, ν is the Poisson's ratio, h is the layer thickness, G is the shear modulus of the intact layer, k_n and k_s are the joint normal and shear stiffnesses.

The layer interfaces can exhibit three different modes of behaviour: (a) elastically connected with the interface normal and shear stiffness, (b) plastic with frictional sliding and (c) disconnected with tensile opening. Similarly the rock layer may either deform elastically or may sustain some plastic deformation as well. A full elasto-plastic Cosserat formulation is provided in (Adhikary & Guo, 2000).

2.2 Flow Model

In COSFLOW formulation, a porous medium is simulated as an entity having two porosities; one representing a continuum porous rock (primary porosity) and the other representing a fracture network (secondary porosity). Thus, the flow behaviour is mainly described by the interaction of the basic components, namely the porous matrix and the surrounding fracture system. The fractures provide rapid hydraulic connection but little fluid mass storage, whereas the porous matrix represents high storage but low hydraulic connection. The developed flow model is very similar to the conventional flow model; the flow in the fracture (cleat) system is controlled by the pressure gradient and is described using Darcy's law, whereas, the desorption (flow in the matrix) is controlled by the concentration gradient and is described using Fick's law. The relationship between gas concentration and pressure is a non-linear function and is described using Langmuir equations.

The flow model adopted in this study can be briefly described in the following manner. By assuming the flow of fluid (gas/water) to obey Darcy's law, the continuity requirement of each fluid phase can be expressed through the following sets of equations:

$$\nabla \cdot q_m + Q_m + \frac{\partial}{\partial t}\left(\frac{\eta S_m}{B_m}\right) = 0 \quad (13)$$

$$q_m = -\frac{k_{rm}}{B_m \mu_m} k \left(\nabla P_m - \gamma_m \nabla d\right) \tag{14}$$

where $\nabla \cdot$ is divergence operator, q is volumetric flux or flow rate, η is porosity, *Q* is source or sink term which for the gas phase represents mass transport between the secondary and primary porosity systems , *S* is fluid saturation, *B* is formation volume factor, *k* is the absolute permeability, k_r is relative permeability factor, *P* is fluid pore pressure, γ is fluid density, *t* is time, μ is viscosity, d is distance from a given datum and subscript *m* refers to each of the fluid phases.

In this formulation, the pore volume is assumed to be fully occupied by the combination of the two fluids, i.e.

$$S_w + S_{nw} = 1 \tag{15}$$

where the subscripts *w* represents the wetting phase and *nw* represents the non-wetting phase. The wetting phase and non-wetting phase fluid pressures are assumed to be related as follows:

$$P_{nw} - P_w = P_c \tag{16}$$

where P_c is the capillary pressure.

The developed code can handle both two-phase flow and single-phase flow. In the case of a single-phase flow, the pore volume is allowed to be partially filled by the wetting phase fluid, in which case the fluid pore pressure is expressed as:

$$P_w = -P_c \tag{17}$$

The volume of the adsorbed gas in the coal matrix can be described by the Langmuir adsorption isotherms

$$V = \frac{V_L P_g}{P_L + P_g} \tag{18}$$

Where *V* is the volume of gas adsorbed at pressure P_g, V_L is Langmuir volume, which is the maximum volume of gas that can be adsorbed, and P_L is the pressure at which the volume of the adsorbed gas is half V_L.

The mass transport can be described by Fick's law:

$$\frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial c}{\partial r}\right) = \frac{\partial c}{\partial t} \tag{19}$$

Where *D* is the micropore diffusion coefficient, *c* is gas concentration, and *r* is radial distance from the centre of the sphere.

2.3 Dynamic Coupling

The dynamic interaction between mechanical deformation and fluid flow processes can be described through a set of coupled non-linear partial differential equations. The presence of a fluid in the mechanical model is considered by utilising the concept of effective stress such that such a stress field and the pore-fluid pressure satisfies the following force equilibrium conditions:

$$\frac{\partial \sigma'_{ij}}{\partial x_j} - \alpha \frac{\partial P}{\partial x_j} = F_j \tag{20}$$

Here, σ' is effective stress, α is Biot coefficient, *P* is pore pressure and *F* is body force density, *x* is spatial coordinate and *i*, *j* are the components of the vector and tensor variables in Cartesian space.

The incremental stress changes are related to changes in incremental strain and pore pressure either through linear (elasticity) stiffness terms prior to yielding or through non-linear (plasticity) stiffness terms after yielding.

Similarly change in pore volume is used to compute the associated changes in fluid pressures and saturations by solving the following sets of equations:

$$\frac{\eta_0 S_m^0}{B_m^0} = \frac{\eta_1 S_m^1}{B_m^1} \tag{21}$$

where *0* and *1* refers to initial and final conditions.

The flow of either phase of fluid is controlled by the permeability of the porous medium, which is either derived by field measurements or through theoretical/empirical formulations. There are different formulae proposed in the literature for estimating the permeability of porous medium depending upon whether the porous medium is intact or contains a network of fractures. The permeability of a porous rock remains a highly non-linear dynamic function of mining induced stress and subsequent fractures. Thus, it is not only important to estimate the initial permeability correctly, but equally important to compute its possible variation induced by mining.

A number of researchers in the past have attempted to establish a relationship between permeability and stress field. In this study, change in rock mass permeability is formulated on the basis of the mine induced strain (Liu and Elsworth, 1997). Such a derivation posses a definitive appeal as far as mine induced stress-flow simulation is concerned.

The absolute permeability is assumed to be controlled by the fracture network. For a fractured rock with fracture spacing Fs_i (i = 1, 2, 3) and fracture apertures Fa_i (i = 1, 2, 3), the relationships between the absolute initial permeability and the fracture parameters can be expressed as:

$$k_{11}^{ini} = \frac{Fa_2}{12Fs_2} + \frac{Fa_3}{12Fs_3} \tag{22}$$

$$k_{22}^{ini} = \frac{Fa_3}{12Fs_3} + \frac{Fa_1}{12Fs_1} \tag{23}$$

$$k_{33}^{ini} = \frac{Fa_1}{12Fs_1} + \frac{Fa_2}{12Fs_2} \tag{24}$$

The effect of mining induced strain on permeability is introduced through the use of the following expression:

$$k_{11} = \frac{1}{2} k_{11}^{ini} \left[(1 + \beta_2 \Delta\varepsilon_{22})^3 + (1 + \beta_3 \Delta\varepsilon_{33})^3 \right] \tag{25}$$

$$k_{22} = \frac{1}{2} k_{22}^{ini} \left[(1 + \beta_1 \Delta\varepsilon_{11})^3 + (1 + \beta_3 \Delta\varepsilon_{33})^3 \right] \tag{26}$$

$$k_{33} = \frac{1}{2} k_{33}^{ini} \left[(1 + \beta_1 \Delta\varepsilon_{11})^3 + (1 + \beta_2 \Delta\varepsilon_{22})^3 \right] \tag{27}$$

where , $\Delta\varepsilon_{ii}$ are the normal strain components and β_i are expressed as:

$$\beta_i = 1 + \frac{1 - R_m}{\left(\frac{Fa_i}{Fs_i} \right)^n} \qquad i=1,2,3 \tag{28}$$

here, R_m is the modulus reduction ratio (ratio of rock mass modulus to rock matrix modulus), the term Fa_i/Fs_i may be defined as a function of equivalent fracture porosity and n is a constant (in Liu and Elsworth (1997), n is assumed to be equal to 1.0). Both R_m and n are considered to be a fitting parameter and hence needs to be calibrated properly against well-documented field data. β_i equals to 1.0 for R_m of 1.0 resulting in minimal strain induced permeability changes. When R_m tends to 0.0 (i.e. the case of highly fractured rock), β_i will attain the maximum value and hence will induce large change in permeability.

3. NUMERICAL SIMULATION

For the last 3 years CSIRO exploration and mining has been actively involved in predictive simulation of mine subsidence, mine water inflow and mine methane emission.

One example of numerical simulation of methane emission from multiple seams into the longwall panel in a mine in Australia is presented. Here we consider the extraction of two adjacent panels; denoted Panel A and Panel B, (see Figure 2), where Panel A is excavated before Panel B. The emphasis on gas emission estimates is for Panel B and Panel A is included in the simulation simply to provide accurate initial conditions for mining of Panel B. Panel B could represent any longwall panel with similar pre-drainage conditions and retreat rate in a similar geological regime where emission and post-drainage production data are available. Thus the predictions from numerical simulations should be equally valid for comparison with measurements obtained from any similar longwall panels.

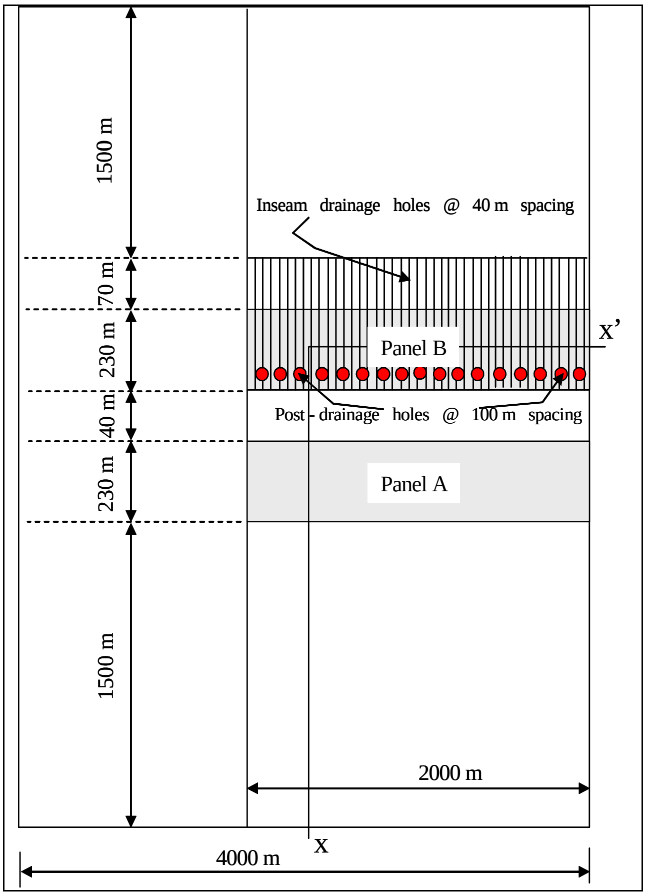

Figure 2. A sketch showing simulation layout

Figure 3 shows a simplified geology used in the simulation. It is representative of the geology around panel A and B. The mining seam and two other seams were included in the simulation. The geomechanical properties used for the various rock layers are listed in Table 1 and Table 2. The mining panels are 230m wide and 2.6m high and are at a depth of about 390 m. The three-dimensional finite element mesh used in this simulation is shown in Figure 4.

The mining seam is first pre-drained, using inseam boreholes shown in Figure 2, to give initial conditions for the gas state before the longwall extraction. The extraction of Panel A follows in 10 large steps of 200m and finally 700m of longwall retreat of Panel B is simulated in steps of 40 m. As the simulated extraction progresses, vertical boreholes of 254mm diameter are added to the model on the tailgate side of Panel B at 100m spacing, as shown in Figure 2. Gas may flow into these boreholes or may flow into the excavation. These flows are recorded separately to be compared with post-drainage measurements and flow into the ventilation system respectively.

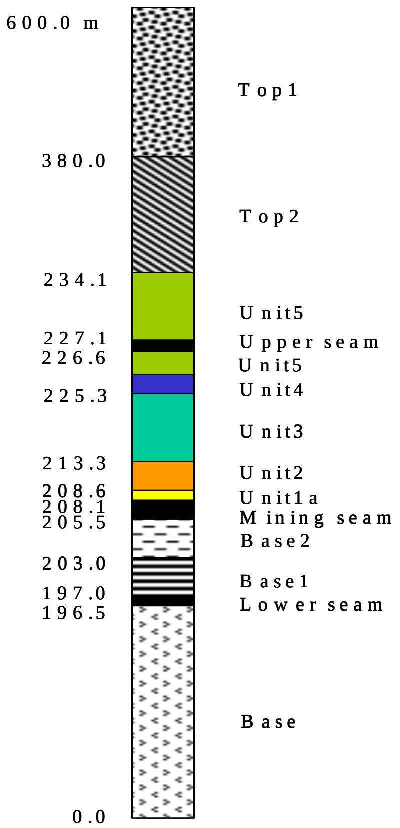

Figure 3. A core log used in the simulation

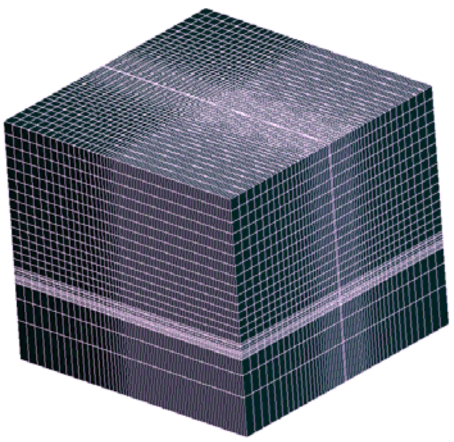

Figure 4. A 3D Finite Element Mesh used in the simulation

Table 1. Rock parameters used in the simulation

Rock units	Young's Modulus (GPa)	UCS (MPa)	Cohesion (MPa)	Friction angle (degrees)	Tensile Strength (MPa)
Base	10.0	14.0	4.0	30.0	1.4
Base1	4.0	7.0	2.0 (0.01)	30.0 (30.0)	0.7 (0.0)
Base2	3.0	4.0	1.15 (0.01)	30.0 (30.0)	0.4
Unit1a	12.	12.0	3.12 (0.01)	35.0 (30.0)	1.2
Unit2	8.0	8.0	2.3 (0.01)	30.0 (30.0)	0.52
Unit3	5.0	5.6	1.7 (0.01)	30.0 (30.0)	0.56
Unit4	7.0	9.6	2.5 (0.01)	35.0 (30.0)	0.96
Unit5	6.0	5.8	1.6 (0.01)	32.5 (30.0)	0.58
Top1	10.0	15.0	3.9 (0.01)	35.0 (30.0)	1.5
Top2	7.0	8.0	2.08 (0.01)	35.0 (30.0)	0.8

Table 2. Flow parameters used in the simulation

Rock permeability in horizontal direction (md)	30.0
Rock permeability in vertical direction (md)	3.0
Coal permeability in horizontal direction (md) - k_h	6.0 - 9.0
Coal permeability in vertical direction (md) - k_v	0.6 - 0.9
Gas content (m^3/t)	13.5
Langmuir volume (m^3./t)	23.8
Langmuir pressure (MPa)	1.5
Coal sorption time (days)	10
Reservoir pressure (MPa)	3 .0

Figure 5 and Figure 6 present comparisons between numerical prediction and actual measurements. In Figure 5, methane emission into the ventilation air in the longwall is compared with the COSFLOW prediction for panel B. It can be seen that COSFLOW provides accurate predictions of average gas emissions into the longwall panel.

The rates of gas emission into longwall panels and gas production from post-drainage holes depend upon a number of factors such as: mining retreat rate, interruption in mining and post-drainage operations, variability of local geology and gas content, effectiveness of pre-drainage schemes etc. Mine gas emissions/productions from longwall panels are not unique and may vary widely within a panel and from one panel to another. Thus for COSFLOW comparison of gas production from post-drainage holes, data from two adjacent panels in the mine are being used. Mine gas production from Panel B (Figure 6) can be seen to drop when the longwall face is at about 300 m, which can be attributed to borehole operational problems. In general, COSFLOW can be seen to provide accurate predictions of average gas productions when compared to the mine data from the two panels.

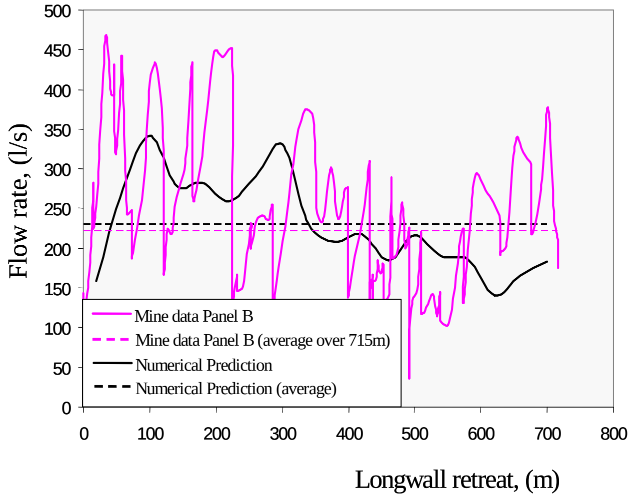

Figure 5. A comparison of gas emission in a longwall panel

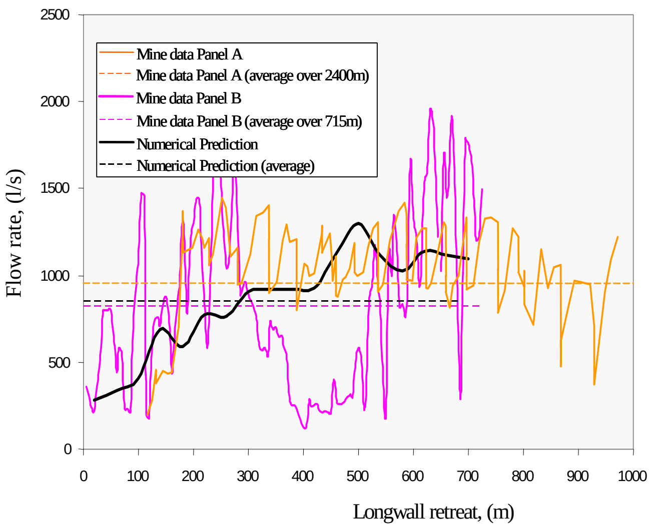

Figure 6. A comparison of gas production from post-drainage

4. CONCLUSIONS

Reliable mine water and gas prediction is not only essential for improving mine safety and reduction of coal production costs, but also important for the assessment of environmental impact of mining.

This paper describes a new three dimensional coupled mechanical two-phase double porosity finite element code called COSFLOW developed by CSIRO Exploration and Mining to service the mining industry's need. A unique feature of COSFLOW is the incorporation of Cosserat continuum theory in its formulation. In the Cosserat model, inter-layer interfaces (joints, bedding planes) are considered to be smeared across the mass, i.e. the effects of interfaces are incorporated implicitly in the choice of stress-strain model formulation. An important feature of the Cosserat model is that it incorporates bending rigidity of individual layers in its formulation and this makes it different from other conventional implicit models.

For the last 3 years CSIRO exploration and mining has been actively involved in predictive simulation of mine subsidence, mine water inflow and mine methane emission. In those work COSFLOW is found to be capable of producing accurate predictions. An example of mine gas emission prediction presented in this paper show the remarkable capability of COSFLOW in simulating the mining induced rock deformation, permeability changes and gas flow into a longwall mine.

5. ACKNOWLEDGEMENTS

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