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A NUMERICAL SIMULATOR OF OUTBURSTS OF COAL AND GAS

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*ABSTRACT: A*n outburst of coal and gas in underground coal mines may occur when stress condition and coal failure combine with rapid gas desorption. A mechanical and fluid coupled numerical simulator, SimBurst, has been developed to simulate the initiation process of the outburst, as a first step to model the whole process of the outburst. This paper describes the simulator and a simple model set up with the simulator to model the initiation of an outburst in roadway excavation to illustrate the methodology and approach with the SimBurst. The model simulated the basic features of an outburst initiation process, including coal deformation, pore pressure and principal stress vector redistribution, and yield and tensile failure zone of coal.

INTRODUCTION

An outburst of coal and gas is a major hazard in underground coal mining. It could cause dangers of asphyxiation due to oxygen deficiency, of poisoning y noxious gases, and explosion by inadvertent ignition of the resultant explosive mixtures and of injury due to violence.

A number of theories have been proposed to explain the mechanism of the outburst. These include; cavity theory and the pocket theory (Shepherd *et al*, 1981), the dynamic theory (Farmer and Pooley, 1967; Shepherd *et al*, 1981), and the spherical shell destabilization theory (Jiang, 1995). It is generally accepted that mining-induced changes in strata stress and gas pressure cause deformation and failure of coal and the interaction between gas and coal results to a dynamic type of failure or outbursting. More specifically, there are two conditions which must be met for an outburst to occur: coal must be failed under an effective stress; gas must be able to desorp rapidly from the coal and the gas pressure must be large enough to push the failed coal into the mining opening instantaneously. In other words, the occurrence of an outburst is the result of combined effects of stress redistribution, gas desorption, coal property and time. Despite the generalized understanding of the outburst mechanism, quantitative prediction of the outburst is still a challenging issue as current outburst prediction methods are largely based on past practical experiences and empirical data.

Some attempts have been made to numerically model the process of the outburst. These include mainly a phase transformation model (Litwiniszyn, 1985), a gas desorption and flow model (Paterson,1986), a boundary element model (Barron and Kullmann, 1990), an airway gas flow model (Otuonye and Sheng, 1994), a fracture mechanics model (Odintsev's,1997), a simple finite element model (Xu *et al*., 2006) and a plasticity model (Wold *et al*., 2008). Despite these great efforts there is still no single numerical model to simulate the whole process of the outburst. It has proven to be difficult because the outburst is in fact a two-step process (initiation and development) and each step has its own characteristics and requires different approaches. As a first step, a numerical simulator, SimBurst, is developed to model the initiation process of the outburst.

SIMBURST DESCRIPTIONS

SimBurst is a three-dimensional numerical simulator developed by CSIRO Earth Science and Resource Engineering. With this simulator, the process of mining-induced stress redistribution, changes of coal/rock permeability and pore pressure, and coal/rock failure (initiation of the outburst) can be simulated to gain a better understanding of outburst mechanism. It can also be used to understand the relative importance of the key contributing factors in the outburst initiation through parametric studies and help determine the threshold values for outburst risk.

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There are two important processes in outburst initiation: coal deformation and failure, and gas desorption and flow. The deformation and failure of coal are modelled with a widely used commercial code for geotechnical analysis of rocks (FLAC3D), and the gas desorption and flow are simulated with a well-established code for fluid flow and gas desorption modelling (COMET3). These two codes are coupled to model the outburst initiation.

Modeling of the deformation and failure of coal

Coal is treated as a continuous medium and its mechanical behaviour is numerically modelled as it reaches equilibrium or steady plastic flow. Application of the continuum form of the momentum principle yields the following equations of motion:

$$\sigma_{ij,j} + \rho b_i = \rho \frac{dv_i}{dt} \tag{1}$$

Where ρ is mass per unit volume of the medium; b_i is body force per unit mass; and dv_i / dt is material derivative of the velocity.

Equation (1) is solved with a stress-strain law. The incremental stress and strain during a time step is governed by various elastic or elasto-plastic constitutive laws, which can be written in a general form as follows:

$$\Delta\sigma^{'} = H(\sigma^{'}, \dot{\varepsilon}\Delta t) \tag{2}$$

Where H is a given material functions; $\sigma^{'}$ is the effective stress; $\dot{\varepsilon}$ is infinitesimal strain-rate tensor and Δt is a time increment.

The effective stress in Equation (2) is related to the total stress in Equation (1) by

$$\sigma^{'} = \sigma + I\alpha P \tag{3}$$

Where α is Biot's effective stress parameter; I is the unit tensor; and P is pore pressure.

Simulating gas desorption and flow

Coal is considered as dual-porosity/single-permeability system. Gas diffuses from the discontinuous coal matrix blocks into the continuous cleat system in coal. The basic equations governing fluid flow in the coal cleats (fractures) are mass conservation for gas and water:

$$\nabla \cdot \left[b_g M_g \left(\nabla p_g + \gamma_g \nabla Z \right) + R_{sw} b_w M_w \left(\nabla p_w + \gamma_w \nabla Z \right) \right] + q_m + q_g = \left(d/dt \right) \left(\phi b_g S_g + R_{sw} \phi b_w M_w \right) \tag{4}$$

$$\nabla \cdot \left[b_w M_w \left(\nabla p_w + \gamma_w \nabla Z \right) \right] + q_w = \left(d/dt \right) \left(\phi b_w S_w \right) \tag{5}$$

Where ∇ is gradient operator; $\nabla \cdot$ is divergence operator; subscript g and w stand for gas phase and water phase respectively; $M_n = kk_{rn} / \mu_n$ is phase mobility, where k, k_{rn}, μ_n are absolute permeability, relative permeability and viscosity respectively, μ_n is viscosity; $\gamma_n = \rho_n g$ is gas or water gravity gradient, where ρ_n is phase mass density and g is gravitational acceleration; S_n is degree of saturation; $b_n = 1/B_n$ is gas or water shrinkage factor, where B_n is formation volume factor; t is time; Z is elevation; ϕ is effective fracture porosity; q_g and q_w are the normal well source terms; R_{sw} is gas solubility in water.

Gas phase pressure P_g and water phase pressure P_w are related by capillary pressure P_c:

$$P_c = p_g - p_w \tag{6}$$

Water and gas saturation satisfy:

$$S_w + S_g = 1 \tag{7}$$

Equations (4)-(7) make up four equations and contain four unknown variables P_g, P_w, S_g and S_w, hence it is a solvable system. The volume of adsorbed gas in the coal matrix is described by the Langmuir adsorption isotherms:

$$\frac{V}{V_L} = \frac{p_g}{P_L + p_g} \tag{8}$$

Where V is volume of gas adsorbed at pressure P_g; V_L is Langmuir volume; P_L is Langmuir pressure.

The gas flow (rate) through the matrix is described mathematically by Fick's first law of diffusion expressed in the form:

$$q_m = \left(\frac{V_m}{\tau}\right)\left[C - C(p)\right] \tag{9}$$

Where C is average matrix gas concentration; V_m is bulk volume of a matrix element; p is gas pressure; and τ is gas sorption time.

Coupling

Because FLAC3D and COMET3 are two separate codes, when coupled together, the resulted equations cannot be solved simultaneously; instead they are solved sequentially with coupling parameters passed to each equation at specific intervals. In the SimBurst, the FLAC3D and COMET3 codes are executed sequentially on compatible numerical grids and coupled through user-defined modules which serve to pass relevant information between the equations that are solved in the respective codes. The basic ideas of the coupling process are shown in Figure 1.

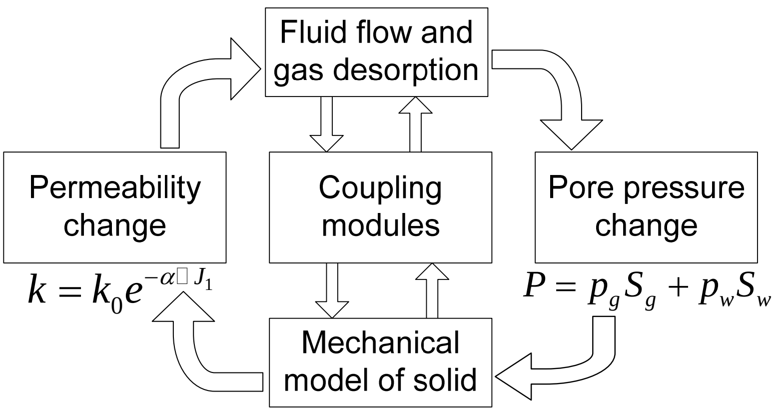

Figure 1 - Basic process of coupling mechanical model with fluid model

AN EXAMPLE WITH SIMBURST

A simple model is set up with the SimBurst to simulate the initiation of an outburst in roadway development to illustrate the methodology and approach (Figure 2). The model is 150m long in x-direction, 105m wide in y-direction and 4m in z-direction (Figure 3).

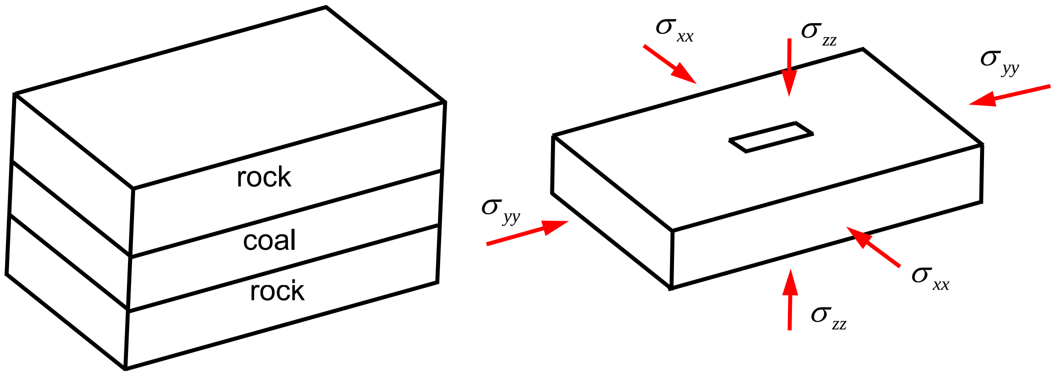

Figure 2 - A computational model in roadway development

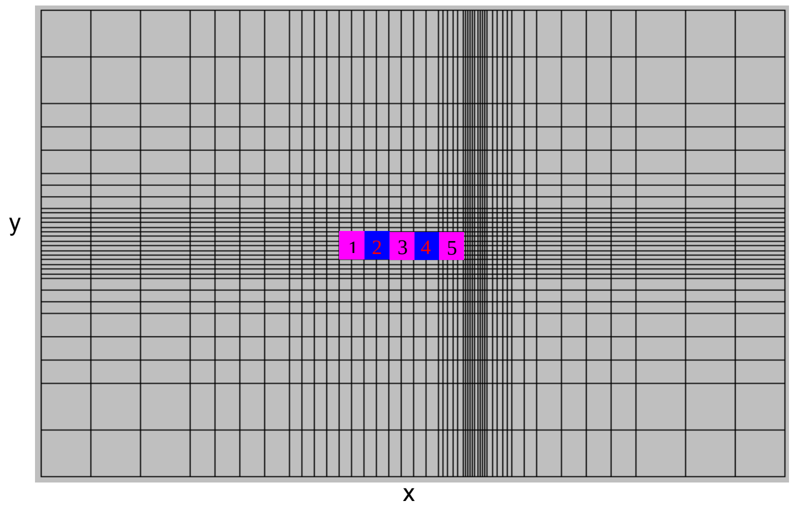

Figure 3 - A plain view of the model

The roadway is 5 m in width and a total of five excavation steps (from 1 to 5) with 5m in each step are simulated with the model. The development rate is 13.75m/shift. Table 1 lists other major parameters used in the model.

Table 1 - Key parameters used in the model

Parameter	Value	Unit
Mining depth	500	m
Coal UCS	10	MPa
Permeability in x-direction	0.4	mD
Permeability in y-direction	1.3	mD
Permeability in z-direction	0.2	mD
Langmuir constant V_L	21	m^3/t
Langmuir constant P_L	900	kPa

The modelled results presented here include mesh deformations, pore pressure contours, principal stress vectors and yielded and tensile failure zones around the excavated roadway.

The mesh deformation for each exaction step is shown in Figure 5. It indicates that marginal deformation occurs in the 4th step, and a large deformation occurs at the 5th step, indicating an initiation of an outburst. It should be noted that the deformation at the 5th step as shown in the Figure is taken at an instant when the outburst is initiated.

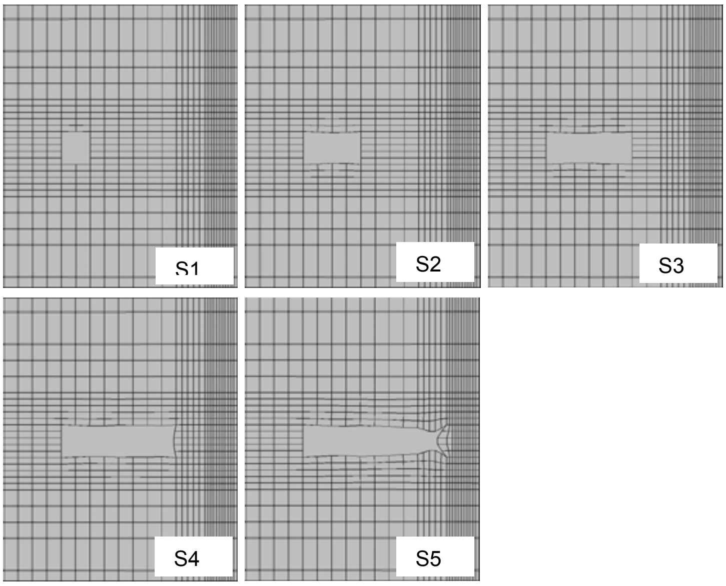

Figure 5 - Mesh deformations with roadway development

Figure 6 shows contours of the pore pressure distribution at the 5th step. The elliptical shape of the pore pressure distribution is caused by anisotropic permeability. The maximum pore pressure gradient occurs in the direction of minimum permeability at the face.

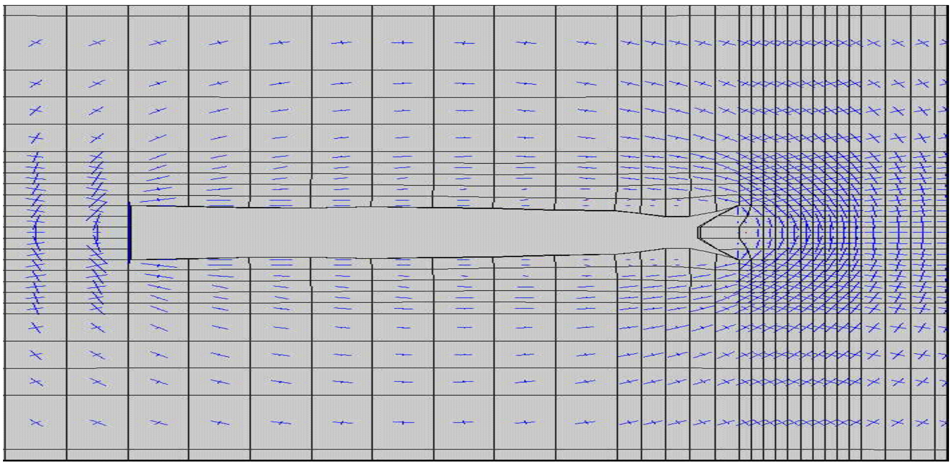

Figure 6 - Pore pressure changes with mining advance

Figure 7 shows the principal stress distribution when an outburst occurs. It indicates that a stress arch is formed about 4 to 5 m ahead of the face. Due to yield and tensile failure of coal failure, a destressed zone is formed around the excavated roadway, as shown in Figure 8.

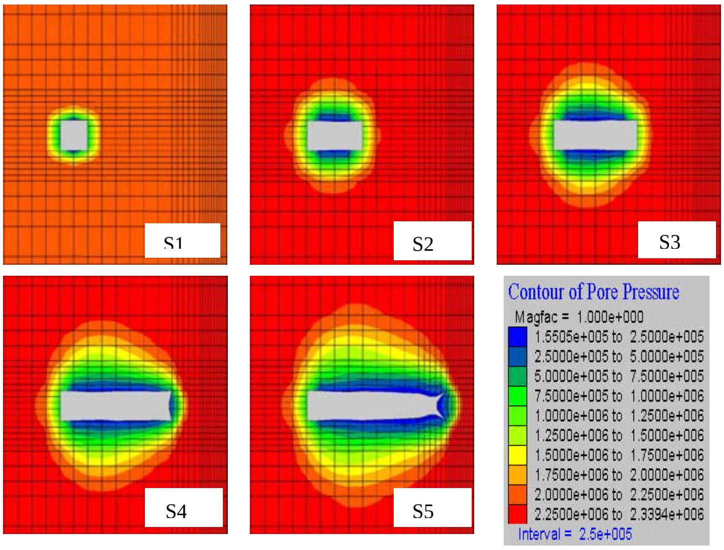

Figure 7 - Principal stress distributions

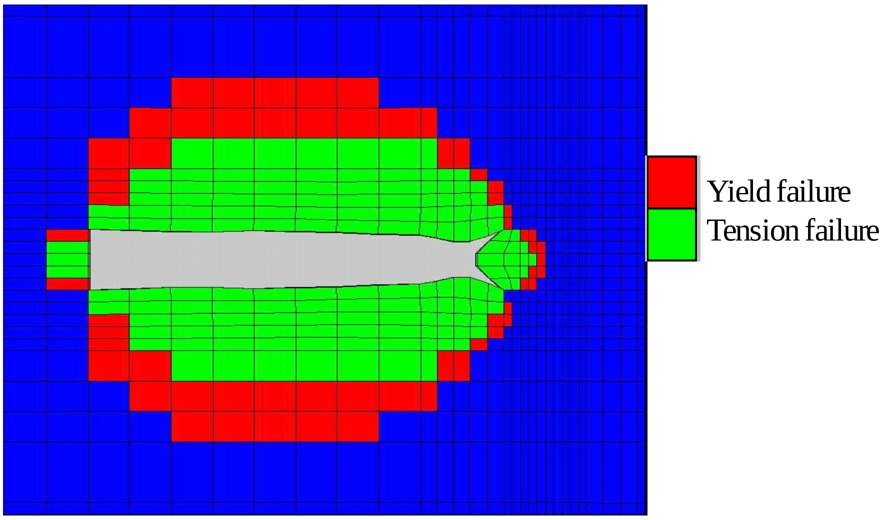

Figure 8 - Coal failure zones around the excavated roadway

SUMMARY

A numerical simulator, SimBurst, has been developed by coupling a geotechnical analysis code and a fluid flow and gas desorption model to simulate the initiation process of the outburst, as a first step to model the whole process of the outburst.

A simple model is set up with the SimBurst to simulate the initiation of an outburst in roadway excavation to illustrate the methodology and approach of the SimBurst. The model simulated the basic features of an outburst initiation process, including coal deformation, pore pressure and principal stress vectors redistribution, and yield and tensile failure zone of coal.

It should be noted that the current version of the SimBurst is limited to simulate the process of the outburst initiation mainly because it is based on continuum media and no explicit mechanisms of fracture and fragmentation of coal is included. The CSIRO outburst research team is currently developing a new version of SimBurst which will overcome some of the limitations of the current SimBurst. For example, coal will be considered as a non-continuum medium and two-way coupling between gas and fractured coal will also be taken into considerations.

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