Prediction of Water Ingress into Underground Excavations Using Plasticity Based Rock Mass Permeability Formulation

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Abstract

Reliable prediction of rock mass deformation and associated water inflow is important for the stability and safety of underground excavations. This prediction requires the accurate simulation of complex, highly non-linear and irreversible processes including the mechanics of rock deformation and failure due to excavation and the consequent water flow.

This paper describes a three-dimensional numerical code, called COSFLOW. It uses a Cosserat continuum approach for the efficient description of mechanical stress changes and deformation in weak layered rock, typical of coal measures. This mechanical model is coupled with a two-phase dual porosity fluid flow model to describe flow of water and gas through porous rock, desorption/adsorption of gas from the matrix and subsequent flow of water and gas through the fracture network. The coupling includes simulation of permeability and porosity changes with rock deformation.

As an example, a simulation of water inflow in an Australian mine is presented. The model is calibrated using existing extensive mine water inflow measurements and used to make predictions for future longwall panels. Comparisons of numerical predictions with mine measurements of water inflow demonstrate the suitability of COSFLOW in accurately predicting mine water inflow and gas emission into a coal mine.

Introduction

Reliable water inflow prediction is important for the stability and safety of underground mines. In addition, in Australia, the ability to accurately predict the behaviour of water in longwall operations has become a pressing issue due to environmental reasons. While higher capacity longwall mines are putting pressure on dewatering requirements, environmental concerns about loss of water supply overshadow many mines. In the future, environmental water issues, associated with major aquifers, could affect a mine's ability to gain mining approval.

This paper describes a three dimensional finite element code, called COSFLOW, developed to simulate longwall mining water inflow problems. A COSFLOW simulation of water inflow at an Australian longwall mine is presented.

Rock strata in a coal mining environment are essentially bedded and this has a large impact on 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/gas 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 (Figure 1) is a must for any reliable prediction of rock mass deformation, water and gas flow into a coal mine. However, there is no consensus in the literature on how to formulate permeability changes due to rock mass deformation.

COSFLOW incorporates a loosely coupled mechanical and two-phase fluid flow

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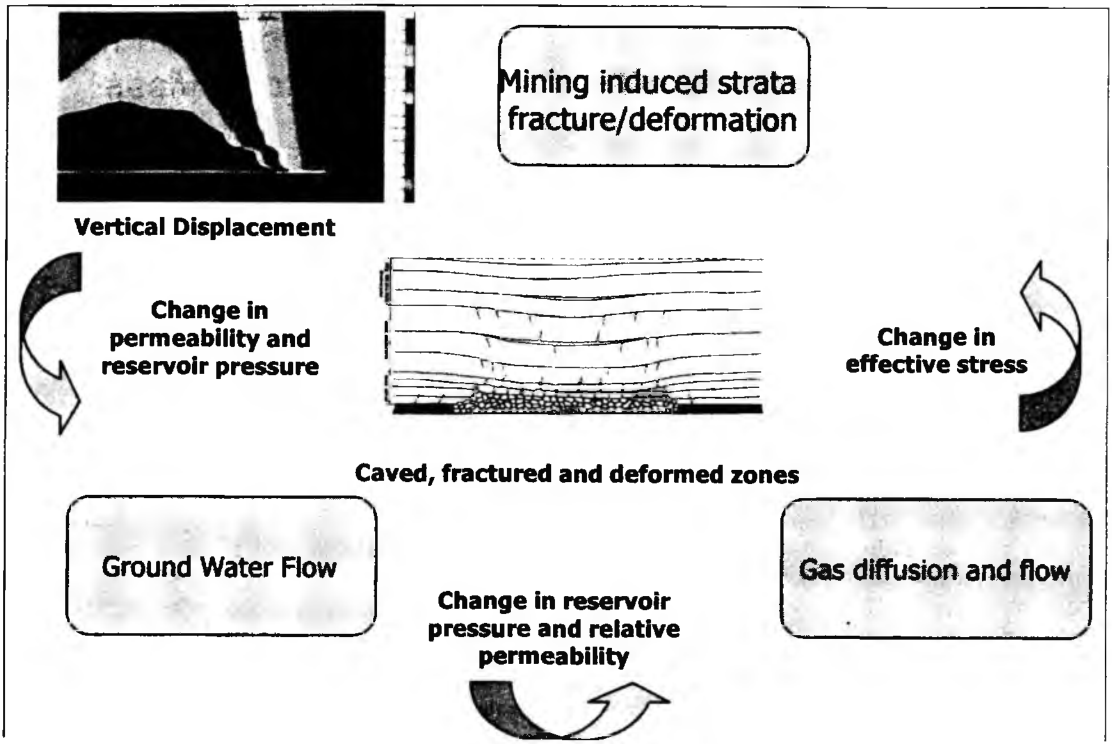

Fig. 1. Complex interaction between rock mass deformation and water/gas flow during longwall mining

formulation, where the mechanical equations and fluid flow equations are solved sequentially. Such an approach of solving a coupled mechanical and two-phase fluid flow problem is widely used in the scientific community (e.g. Rutqvist et. al, 2002). In such an approach mechanical effects are assumed to occur almost instantaneously when compared to diffusion effects. In COSFLOW, sequential cycling between fluid flow steps and mechanical steps is controlled through a limiting parameter that would switch off the fluid flow steps and start the mechanical steps once the maximum change in average porepressure within the model exceeds the value set by the limiting parameter.

A unique feature of COSFLOW is the incorporation of Cosserat continuum theory (Cosserat and Cosserat, 1909) 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 finite element implementation of Cosserat theory is presented in Adhikary and Guo (2002), and Adhikary and Dyskin (1997 & 1998). Adhikary and Dyskin (1997) provide a thorough analysis and comparison between the conventional equivalent continuum and the Cosserat continuum models.

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 water inflow or 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.

In COSFLOW, a porous medium is simulated as a region 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 flow model incorporated in COSFLOW is similar to the conventional flow model; i.e. 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.

Mine Water Inflow Simulation

This mine was concerned with the increasing amount of water inflow into the underground workings and for the past three years, CSIRO has conducted site monitoring planning, data interpretation, hydrogeological assessment, and numerical modelling work. On the basis of local geology and 26 piezometers installed in 8 boreholes at different horizons CSIRO developed a conceptual hydrogeological

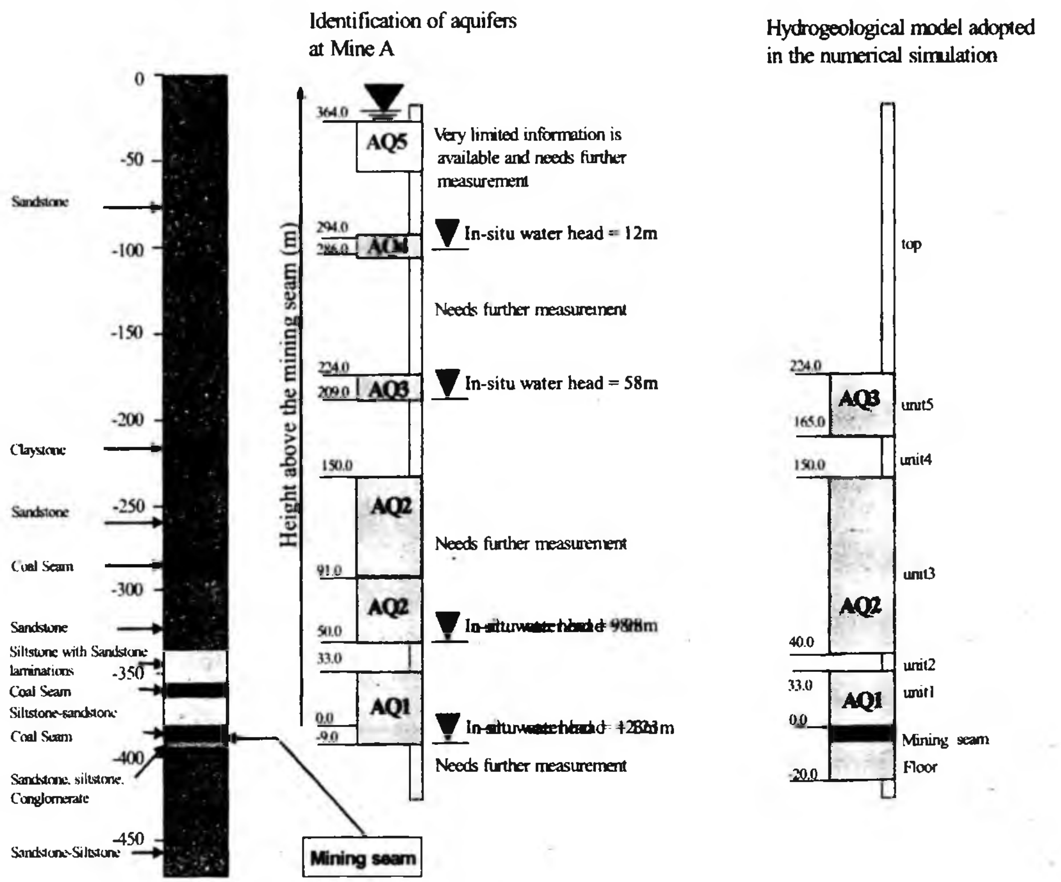

Fig. 2. A conceptual hydrogeological model of the mine

model of the mine (Figure 2). Five distinctive aquifers separated by low permeability layers (aquitards) were identified.

The numerical model consisted of about 500,000 finite elements and simulated a region 7.5 km long in the East-West direction and 9.3 km long in the North South direction, thus covering an area of approximately 71 km2. Figure 3 presents the plan view of the finite element mesh adopted in the study respectively. Piezometers installed in the AQ4 horizon appeared to be unaffected by the mining underneath, hence, for simplicity, AQ4 and AQ5 were not included in the numerical simulation.

Tables 1 and 2 present the rock mechanical and hydraulic properties obtained from direct or indirect field testing and used in the simulation after slight modifications as a result of model calibration. The mine had supplied the water inflow records during the excavation of panels LW0 to LW5 and LW1b to LW9b. Once the close match between the model predictions and the mine water inflow measurements were obtained the model parameters were fixed and used in the simulation of the extractions of subsequent longwall panels. The mine water inflow results obtained for panels LW6 and beyond are real predictions.

In Table 1 no bedding implies that the material is modelled as conventional elasto-plastic solid whereas the rock units with the specified joint properties are modelled as elasto-plastic Cosserat solids.

Table 1: Geomechanical parameters used in the numerical simulation

Rock units	Young's Modulus (GPa)	Cohesion (MPa)	Friction Angle (degrees)	Tensile Strength (MPa)	Remarks
Base	18.0	8.0	35.0	3.7	No-bedding
Floor	10.0	2.5	35.0	0.96	No-bedding
Mining Seam	3.5	1.3	40.0	0.5	No-bedding
Unit 1	10.0	3.0	35.0	1.15	0.5m bed spacing, joint cohesion = 0.5 MPa, joint friction angle=25°
Unit 2	10.0	3.0	30.0	1.0	0.25m bed spacing, joint cohesion = 0.3 MPa, joint friction angle=25°
Unit 3	10.0	3.0	35.0	1.15	0.5m bed spacing, joint cohesion = 0.5 MPa, joint friction angle=35°
Unit 4	10.0	3.0	30.0	1.0	0.25m bed spacing, joint cohesion = 0.3 MPa, joint friction angle=25°
Unit 5	10.0	3.0	35.0	1.15	0.5m bed spacing, joint cohesion = 0.5 MPa, joint friction angle=25°
top	5.0	2.0	35.0	0.77	No-bedding

Table 2 Permeability values used in the simulation

Rock units	Horizontal hydraulic conductivity (m/sec) x 10^{-8}	Vertical hydraulic conductivity (m/sec) x 10^{-8}	Porosity
Floor	1.0	0.25	0.15
Mining Seam	10.0	10.0	0.10
Unit 1	2.5	1.0	0.15
Unit 2	0.05	0.05	0.10
Unit 3	1.0	0.25	0.15
Unit 4	0.1	0.1	0.10
Unit 5	1.0	0.25	0.15

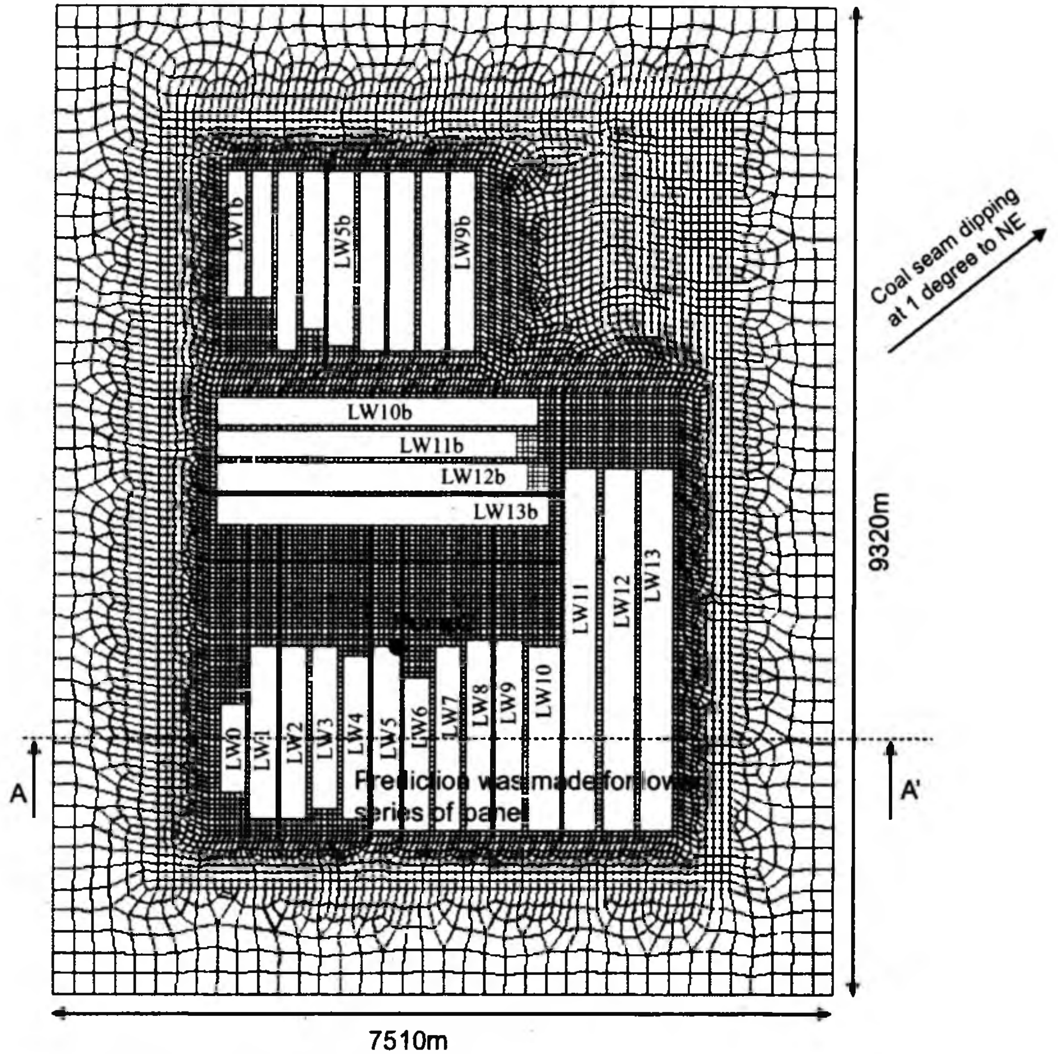

Fig. 3. A plan view of the numerical grid with the longwall panels numbered according to the order of mining

In Figure 3 the longwall panels are numbered according to the order of mining. In the figure the location of Pump2 used to dewater from LW0 to LW5 is also shown. Comparisons of numerical simulation results and the actual measurements of both the total flow and the Pump2 flow will be presented later.

The actual overburden sequence has been simplified, combining lithological layers to represent rock characteristics of primary importance to obtain an average response and a reasonable fit with the measurements. This simplification was necessary so that the model could be run in a practical time.

Initial vertical stress was assumed to be proportional to the overburden weight. The water bearing units (i.e. from Floor upward to Unit5) were assumed to be fully saturated with water and were assigned initial porewater pressure distributions corresponding to water heads presented in Figure 2.

The pore water pressure distribution in the coal seam after mining panel LW8 as obtained from the numerical simulation is shown in Figure 4. The location of a piezometer installed in a borehole B31 is marked on the plot. The pore water pressure at that location is about 0.4MPa (i.e water head is about 41m), the piezometer readings were fluctuating around 43m after the completion of LW8.

Figure 5 presents the numerical predictions of water inflow into the lower series of panels from LW6 to LW13. The water inflow rate into the mine up to LW6 was much smaller with total flow averaging around 55l/s. However the measured water inflow rate after mining LW7 onwards increased substantially yielding a rate of about 88l/s after mining LW7.

Figure 6 shows the predicted changes in vertical and overall average permeability of the rock strata lying above the LW11 panel horizon. These are the values of change in permeability averaged over the length of the panel LW11. The changes in permeability predicted by COSFLOW seem to fluctuate, reflecting the uneven response of different rock units present in the overburden. The longwalls are predicted to induce increases of up to 35 times in vertical permeability and 1000 to 2000 times in overall average permeability $\left(K_{avg} = \sqrt[3]{\left(K_x \times K_y \times K_z\right)}\right)$ near the mining horizon up to a distance of about 50m above the mining horizon. These numbers compares favourably with those measured in the field by other researchers. No direct measurements of permeability changes due to mining at the mine were made.

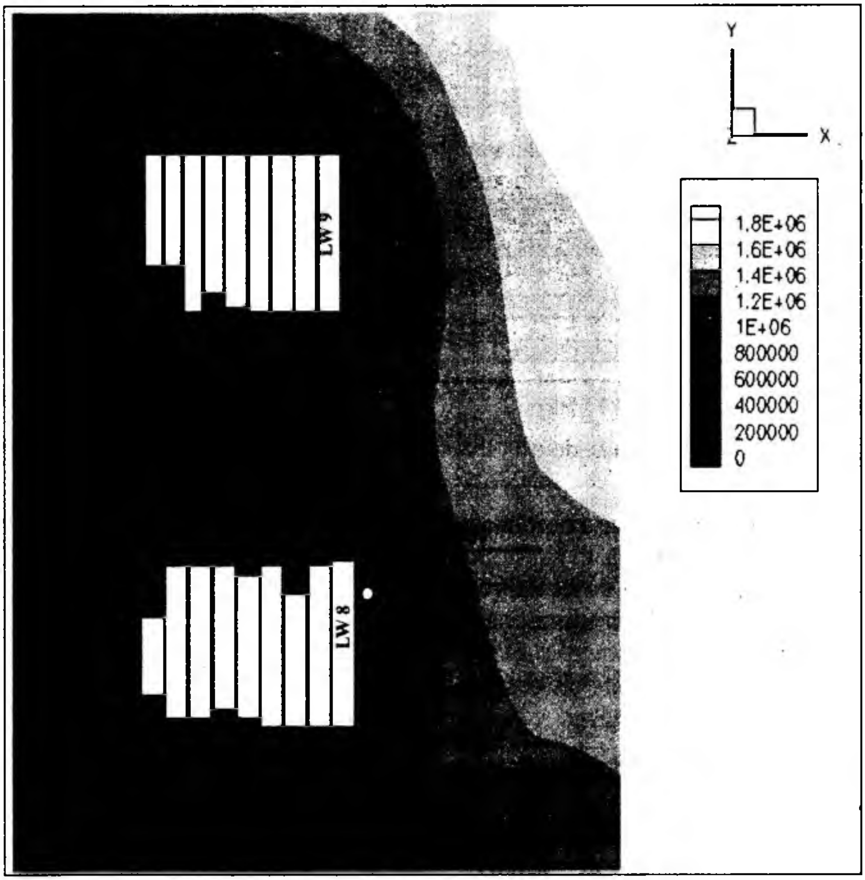

Fig. 4. Porepressure distribution (Pascals) at the mining seam after mining LW8 (Note the position of a piezometer indicated as SPR31)

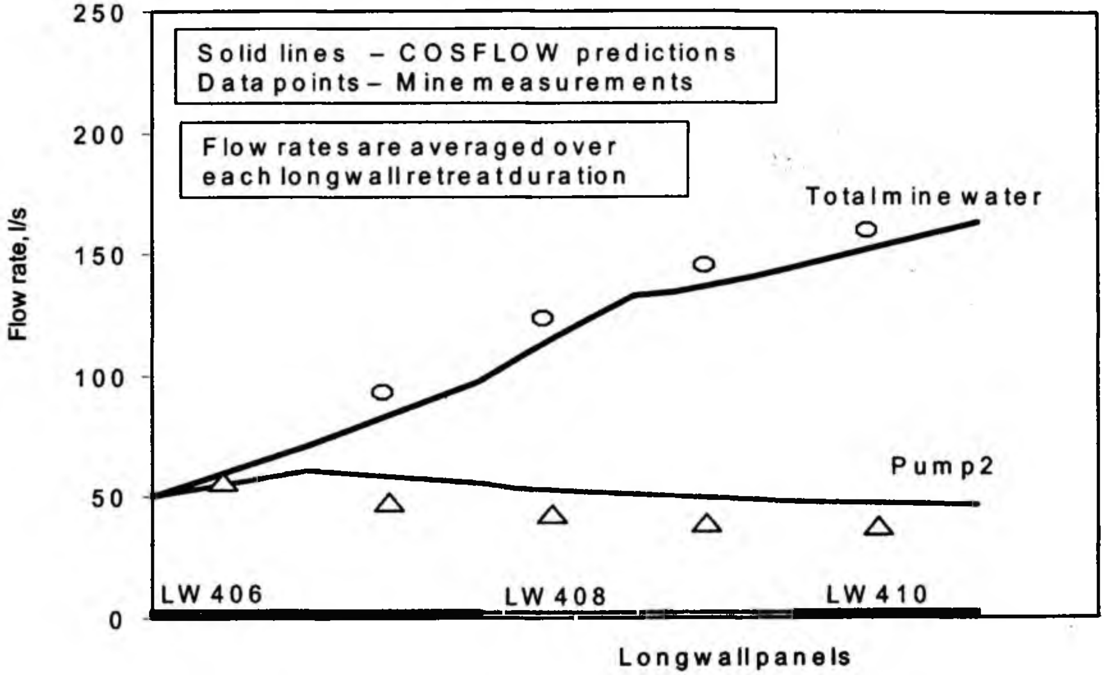

Fig. 5. Comparison of numerical prediction with the mine measurements

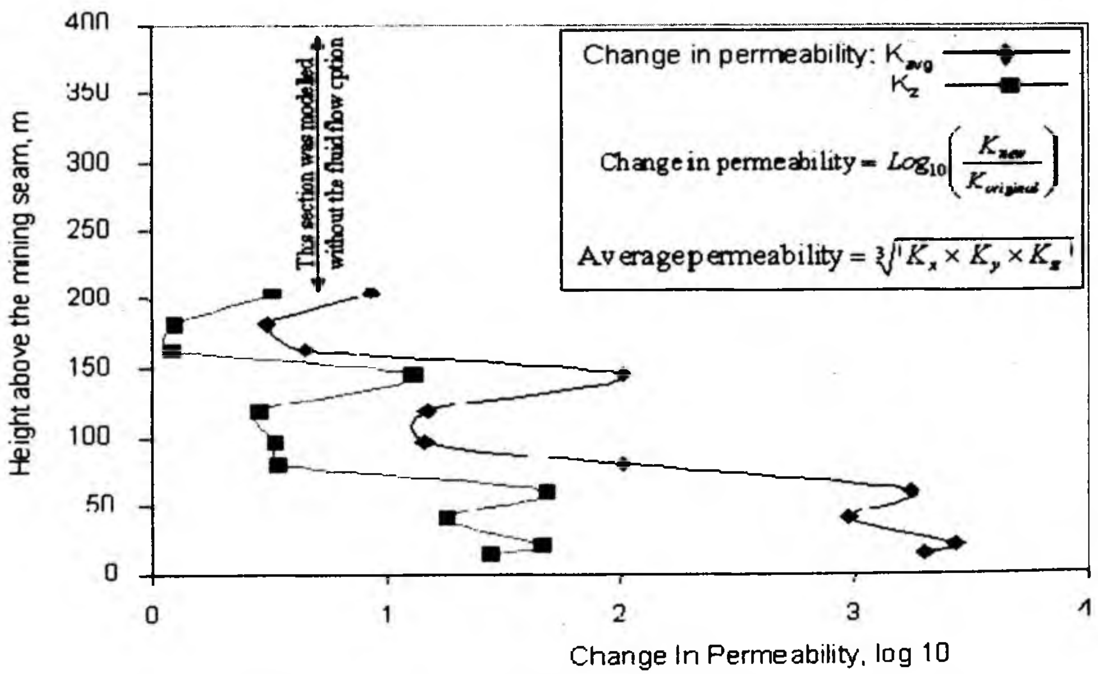

Fig. 6. Change in permeability predicted by COSFLOW above panel LW11 (the values are averaged over entire length along the central line of panel LW11)

Conclusions

Reliable prediction of groundwater flow due to mining is not only essential for improving safety but also important for the assessment of environmental impact of mining.

This paper describes a numerical model that has been successfully used to predict water inflows at an Australian mine. The model uses a new three dimensional coupled mechanical two-phase double porosity finite element code called COSFLOW. A unique and important feature of this code is the incorporation of Cosserat continuum theory in its formulation to efficiently simulate deformation and fracture of weak layered rock. This efficiency is necessary for practical computer run times and achieved by smearing inter-layer interfaces (joints, bedding planes) across the rock mass (i.e. the effects of interfaces are incorporated implicitly in the choice of stress-strain model formulation) and including the effect of layer bending stiffness.

The model at the mine site requires significant geotechnical and hydrogeological data for adequate calibration. Many parameters in the model are not directly measurable and must be inferred by back-analysis of existing deformation, stress and hydrological data obtained during previous mining. The calibrated model is then used to make predictions for future mining panels. Water inflows at Mina A were predicted to increase significantly as mining progressed and this was supported by later measurements. This increase was attributed to wider longwall panels and increased roof rock permeability as more panels are mined.

There is no consensus in the scientific community on how to formulate permeability changes due to rock mass deformation. In this study rock mass permeability is described using an equivalent fracture network approach. Such a formulation is amenable to easy evaluation of permeability changes as a function of stress induced changes in fracture aperture. Although no direct measurements of permeability changes were analysed in this study, the water inflow predictions are sensitive to estimates of permeability change and the accuracy achieved is good justification for this approach.

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