Numerical Models Currently Being Developed for Use in Mining Industry

Saba Gharehdash and Milad Barzegar

Mining and Metallurgy Department, Amirkabir University of Technology, Tehran, Iran

Abstract. The computer programs MINSIM and MAP3D are widely used in the analysis of stress distributions in the vicinity of tabular mine openings. MINSIM is a boundary element code, based originally on Salamon's "Face Element Principle". MAP3D (*Wiles, 2000*) has a number of more general features than are catered for in the MINSIM code, including the ability to model cavities, multiple material zones, and limited volumetric plasticity. Numerical modelling of rock-mass response to underground excavations is of vital importance for the decision-making process in designing and running a mine. Likewise, seismic monitoring with state-of the art local seismic systems is indispensable as a means for quantifying hazard and as an indicator for potential instabilities in the rock-mass due to mining activities, geological structures and other hazard enhancing factors. The statistical processing of long local seismicity records can throw light on the correlations between the character of the mining activity, the existing geological structures and could even highlight some general trends in the seismic activity. It is precisely the answers to this type of question that is vital for planning and organising the mining process for maximum safety and efficiency.

Keywords: numerical modeling, MAP3D, MINSIM, seismic activity, mining.

1 Introduction

The behaviour of the rockmass under specified loading conditions is governed by the laws of continuum mechanics, thermodynamics, material damage evolution and damage-driven rheology. In addition there are the very important and yet poorly understood processes of energy dissipation and friction on material discontinuities. The problem is of such complexity that even the formulation of it as a mathematical system of equations is not possible without massive simplifications. Even when such simplifications are made and a corresponding mathematical problem is correctly set, its solution is, as a rule, inaccessible by analytical means and has to be sought numerically. *Hazzard* (*1998*) presented a detailed study on the ways in which seismicity could be obtained from discrete element methods, in particular the Particle Flow Code. This work indicated that there were five methods of determining the event size in order to present the frequency magnitude plots [1]. The IDRM (Integrated Damage Rheology Model)

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[2,3] software is an integrated system for numerical modeling of damage evolution, elastic and plastic deformations as well as the occurrence of sudden material failure leading to the formation, localisation and propagation of cracks within solids subject to some prescribed external loading. A box counting method was applied, but not described in detail by *Wilson et al.* (*1996*) to obtain frequency magnitude plots from cellular automata [4].

Seismic monitoring provides the volume and spatial distribution of information on the rock mass response that can be obtained in no other way at reasonable cost. Map3D provides a mechanism to directly use this information for model calibration. In this paper by applications of Map3D to the modeling of PFC3D could result in improved accuracy of prediction of spatial seismic hazards.

2 Numerical Models Using in Mining Industry

2.1 MINSIM/MAP3D

The computer programs MINSIM and MAP3D are widely used for the analysis of stress distributions in the vicinity of tabular mine openings. MINSIM is a boundary element code, based originally on Salamon's "Face Element Principle" [5] which uses the displacement discontinuity method to solve tabular excavation and fault slip interaction problems. MAP3D [6] has a number of more general features than are catered for in the MINSIM code, including the ability to model cavities, multiple material zones, and limited volumetric plasticity. In addition to MINSIM and MAP3D, a number of generically similar computer tools have been employed for the analysis of stress patterns near deep level openings. These include, specifically, the programs MINAP and MSCALC developed by Crouch; the basic principles are described in detail by *Crouch and Starfield* [7]. In the context of exploring the integration of seismic monitoring with numerical modelling, it is important to highlight certain broad attributes of these computer programs rather than attempting a detailed comparison between each particular code.

Map3D is an advancement of the standard MAP3d programme that permits the superposition of external field loading effects onto a standard Map3D model. The field loading can arise from thermal heating, fluid pressure, non-linear behaviour, etc. In addition, the magnitudes of the external effects can be determined from many forms of in situ monitoring including for example fluid pressures (e.g. well drawdown, dams, hydrofracturing), heating (e.g. natural heating, nuclear waste storage), and deformations (e.g. monitored with extensometers). Another important source of in situ field loading information arises from seismic activity. By definition, the presence of seismicity indicates that the rock mass is yielding to load and hence deforming in some way. The seismicity could indicate shearing on a fault plane or 3D material non-linearity possibly resulting from a weak lithological feature. The deformations indicated by the seismicity can be superimposed onto the Map3D mine model, thereby redistributing the stresses to accommodate the deformations. The field loading information is specified as ride and dilation components on a segment of a slip plane, and/or deformation of a 3D zone. Slip or dilation on a fault plane would be applied by subdividing the known extent of the fault into small planar zones and then specifying the slip or dilation components in each zone. If the seismic observations suggest that entire volumes of the rock mass are deforming and other parts are not, the whole rock mass can be divided into up into small 3D zones with the deformation components specified in each zone based on the observed seismic strain deformations. The overall stress state is then updated to accommodate the contribution of the integrated field loading. Note that the Map3D model can contain all of the regular features including excavations, stiff dykes, faults etc. The effects of the field loading and all of these other features will be superimposed to provide a final composite prediction of the stresses, strains and displacements throughout the rock mass. The wealth of information that comes from seismic monitoring is enormous. Seismic monitoring provides the volume and spatial distribution of information on the rock mass response that can be obtained in no other way at reasonable cost. Map3D provides a mechanism to directly use this information for model calibration and assists in applying Terzaghi's Observational Approach to Design. Owing to the real-time nature of seismicity, it becomes practical to traverse the mine/monitor/redesign loop for every increment of mining. Thus, instead of spending years making visual observations to develop a history of rock mass response, there is potential to calibrate the model much more quickly. Perhaps the most important part of this is that it provides the possibility of adapting to changing rock mass conditions. In this paper by applications of Map3D to the modelling of seismicity in mines could result in improved accuracy of prediction of spatial seismic hazards. The calculation of the redistribution of stresses due to the occurrence of large events allows the assessment of the extent that a large event might diminish the seismic hazard and should improve the temporal prediction of seismic hazard as a result of the superimposition of measured displacement onto modelled displacement for both historic and planned mining steps.

2.2 Boundary Element Basics

All boundary element methods rest on the assumption that any solution can be expressed as a linear superposition of fundamental solutions. The fundamental solution provides the response to a local excitation, at a given time and position in space, at all other points in space and at all succeeding times. By using such a fundamental solution and classic results from vector analysis, a boundary integral representation can be established in terms of the values of key variables defined on the surfaces surrounding the medium and on any special surfaces (such as fractures) within the problem region. The computational advantages of such a surface representation are clearly manifest in the analysis of steady state, three-dimensional problems. These advantages are reduced as the controlling surface area is increased relative to the volume and if transient problems are to be solved. In addition, the fundamental solutions may only be known for simplified approximations to the actual medium behaviour (such as linear isotropic elasticity). Despite these shortcomings, the boundary integral method provides a very useful tool in the analysis of stress distribution problems in solid mechanics. The particular approach, referred to as the displacement discontinuity method (DDM), is ideally suited to the analysis of tabular excavation and fault interaction problems although detailed numerical difficulties may arise in its implementation and efficient solution, particularly with regard to intersecting or acutely angled discontinuities. The implementation of the DDM for the solution of tabular excavation or fault sliding problems requires that the excavation or fault surface be divided into discrete areas termed "elements". Each element is assigned a "shape function" which controls the variation of the displacement discontinuity density within the element. Boundary conditions must be matched at one or more "collocation" points within each element or must be satisfied in some average sense over the element area. In the simplest approximation, the discontinuity vector is assumed to be constant over a flat polygonal element and the boundary condition is enforced at a single representative point within the element. In the solution of tabular mine problems, it is often assumed that each element has a square shape and that the boundary condition is matched at the center of the element. This scheme is used by the current versions of the MAP3D, MINSIM codes in the solution of discontinuity problems. In order to highlight some of the properties of the constant element assumption, consider the expression for the normal stress, τ_{zz}, induced by a single square element of side *2a*, centred at the origin of the *x-y* plane. This is given by the formula

$$\tau_{zz}(x,y) = \frac{G}{4\pi(1-\nu)} I_{,zz} D_Z^0 \tag{1}$$

where G is the shear modulus and ν is the Poisson's ratio of the assumed isotropic rockmass. D_Z^0 is the value of the normal (z direction) displacement discontinuity component across the element. (This is interpreted as the stope closure in tabular mining problems). The quantity I is the Newtonian potential, integrated over the surface area of the element:

$$I = \int_{-a}^{a}\int_{-a}^{a} \frac{d\xi d\eta}{r} \tag{2}$$

Where $r^2 = (x-\xi)^2 + (y-\eta)^2 + Z^2,\ I_{,zz} = \partial^2 I/\partial z^2$ represents the second derivative of this function, evaluated in the limit $z \to 0$, and is given by:

$$I_{,zz} = \frac{\sqrt{(x+a)^2+(y+a)^2}}{(x+a)(y+a)} - \frac{\sqrt{(x+a)^2+(y-a)^2}}{(x+a)(y-a)} - \frac{\sqrt{(x-a)^2+(y+a)^2}}{(x-a)(y+a)} - \frac{\sqrt{(x-a)^2+(y-a)^2}}{(x-a)(y-a)} \tag{3}$$

Equation (3) determines the normal stress component induced by the element with a normal DD component D_Z^0. General relationships for the full stress tensor, induced by the DD vector (D_x^0, D_y^0, D_Z^0), are documented by *Crouch and Starfield* [7]. Equation (3) reveals a number of interesting properties relating to the DD method that are not always appreciated. Specifically, it can be observed that if $x = \pm a$ *or* $y = \pm a$, the expression contains apparently singular terms. However, on closer inspection it can be seen that these terms cancel in pairs. This in turn implies that some care must be taken in implementing the influence computation procedures in any computer code. Setting $y = 0$ in equation (3) gives the expression for the stress induced by the element along the x-axis:

$$I_{,zz}|_{y=0} = \frac{2\sqrt{(x+a)^2+a^2}}{a(x+a)} - \frac{2\sqrt{(x-a)^2+a^2}}{a(x-a)} \tag{4}$$

Consider a position $x = a + \varepsilon$ close to the edge of the element. For $|\varepsilon| \ll a$, equation (4) tends to

$$I_{,zz}|_{y=0} \to -2/\varepsilon \tag{5}$$

Equation (5) demonstrates that the stress becomes infinite adjacent to the edge of the element and changes sign on each side of the edge. (In the present case a positive value of D_Z^0 represents stope closure). The induced stress component τ_{zz} changes from infinitely positive (tension) to infinitely negative (compression) as x changes from a position just inside the element ($\varepsilon < 0$) to a position just outside the element ($\varepsilon > 0$)). It is important to note that this singularity is much stronger than the $\sqrt{\varepsilon}$ crack tip singularity encountered in fracture mechanics analysis [8]. Furthermore, it is not possible to integrate the expression (1) for τ_{zz} over the area of the element. In fact, the point value τ_{zz} (0,0) should be interpreted as the *average* stress induced over the element. The presence of the strong singularity represented by equation (5) also means that considerable care must be taken in interpreting stress values at points near element edges and displaced normal to the plane of the element. This has particular importance in attempting to perform seismic modelling integration by inserting near-reef strain influences to represent observed seismic activity.

3 Numerical Modeling

To study the response of PFC3D in a model that is more representative of a mining situation, a cubic set of particles of side length 80mm, which contains 71019 balls, was mined with 1 mm face advanced in 40 mining steps. As shown in (Fig.1), mining was at the middle of the cube where finer balls are present. The ball sizes vary from 0.63 mm to 1.2 mm. The balls are finer where the stope is and gradually increased away from the stope both in the hanging wall and the footwall. Four different ways of mining were considered:

1. Excavate the area (since this process is dynamic, excavating the area immediately produces shocking effects in the system).
2. (a) High damping (freeze the system)
   (b) Excavate the area
   (c) Low damping (allows the fracture to occur)
3. Decrease the ball stiffness gradually with time.
4. Decrease the forces gradually on the particles with time around the stope.

The model was loaded up to 80 MPa with a confinement of 40 MPa with the first method explained above.

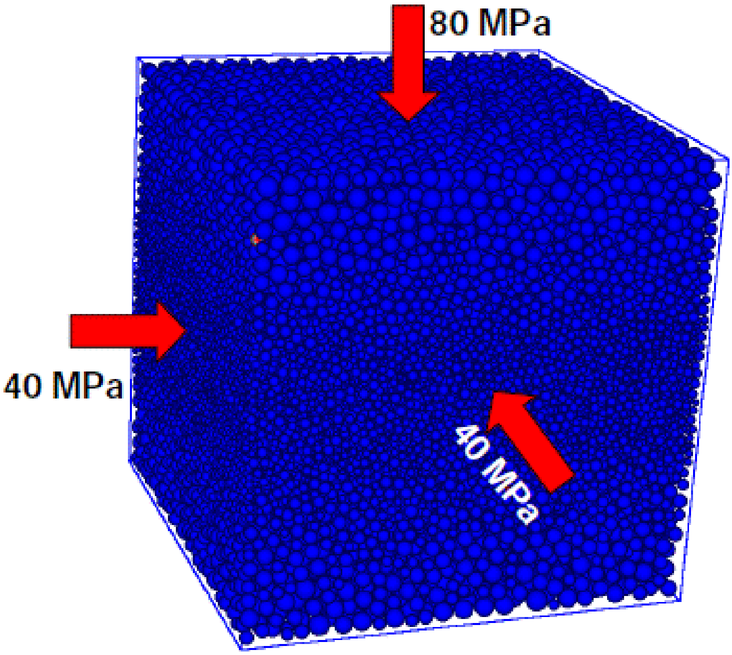


Fig. 1 PFC3D model used for mining model

3.1 Numerical Results

(Fig.2) shows a typical simulated response of the computed off-reef energy release increments when the stope width is 1m and the mining depth is 4000m. Figures 3a and 3b show mining simulations with stope widths of 1m and 0.5m respectively. In each figure, three cases are shown corresponding to mining depths of 3000m,4000m and 5000m. It is also interesting to note that with increasing depth, the slope of these plots becomes less negative indicating an increased probability for larger size energy release to occur. These results appear to be qualitatively satisfactory but rest on many assumptions relating to the shape and dimension of the tessellation mesh, the assumed mechanism of the time relaxation process and, particularly, the mining step excavation procedure.

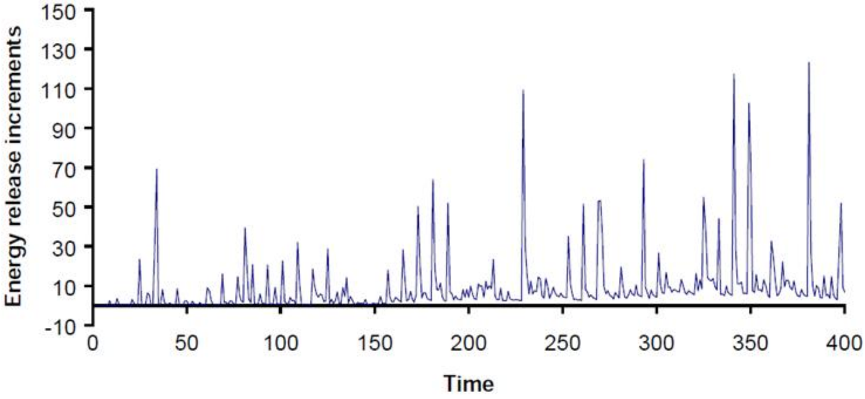
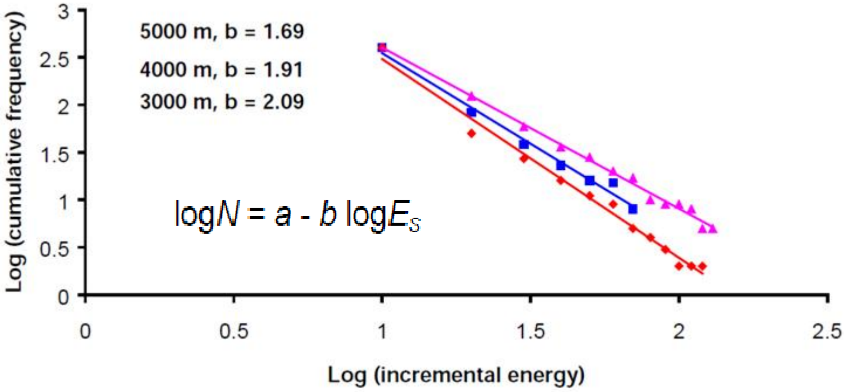
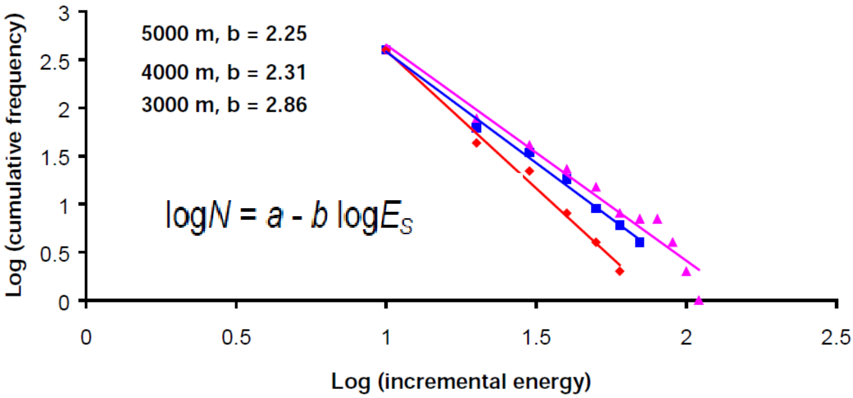


Fig. 2 Typical off-reef energy release increments observed in the simulation of mining a parallel-sided panel

(Fig.4) compares the cumulative mobilised fracture length for two simulation sequences with a coarse mesh and a fine mesh. It is apparent that the mobilised fracture length is proportional to the mesh grid density. In Figure 5, the off reef energy is plotted against the mobilised fracture length for a number of simulation runs, using both coarse and fine mesh tessellations. This plot indicates a rough proportionality between the cumulative energy release and the mobilized fracture length.



(a)



(b)

Fig. 3 Plots of cumulative frequency against energy release increment size in mining a parallel-sided panel at different depths. (a) Stope width = 1.0m. (b) Stope width =0.5m

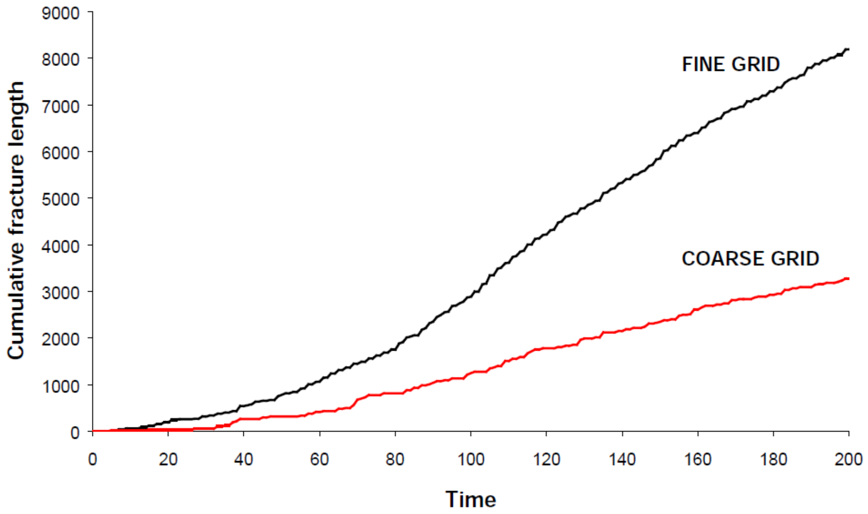


Fig. 4 Comparison of cumulative fracture length, as a function of time and excavation span, for two different tessellation densities

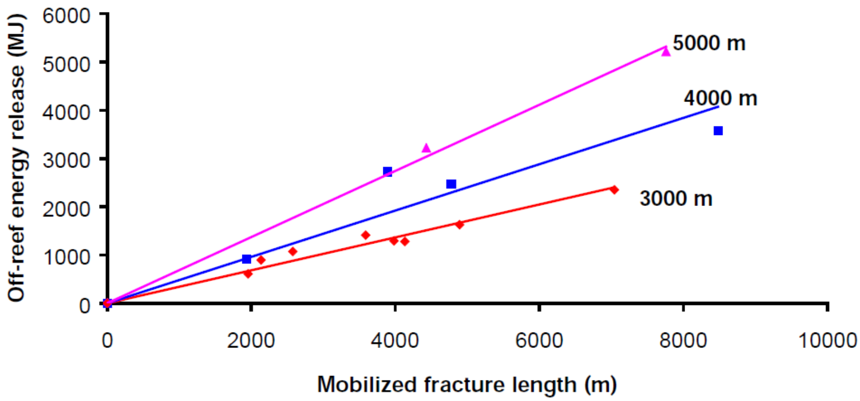


Fig. 5 Cumulative off-reef energy release plotted against cumulative fracture length for different mining depths and mesh grid densities

4 Conclusions

The major conclusions from the work undertaken are:

The modern seismic monitoring systems are capable of providing high quality data about the local seismicity in mines. The seismological analysis of the records about a particular seismic event could, in principle, reconstruct the seismic source mechanism and produce the values of the relevant source parameters. The statistical processing of long local seismicity records can throw light on the correlations between the character of the mining activity, the existing geological structures and could even highlight some general trends in the seismic activity. However, neither of these approaches would lead to a statement about how a certain sequence of real seismic events would affect the stability of a particular volume of rock, in a particular interval of time and under specified production conditions in the mine. It is precisely the answers to this type of question that is vital for planning and organising the mining process for maximum safety and efficiency.

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