International Journal of Minerals, Metallurgy and Materials
Volume 16, Number 1, February 2009, Page 1

Minerals

Caving performance through the integration of microseismic activity and numerical modeling at DOZ-PT Freeport, Indonesia

Rubio Enrique[1)] *and Napitupulu Daulat*[2)]

1) Mining Engineering Department, Universidad de Chile, Santiago 8370451, Chile
2) Geotechnical Engineering Department, PT Freeport Indonesia, Tembagapura, Indonesia
(Received 2008-03-09)

Abstract: This article describes an undergoing research at PT Freeport, Indonesia, in which the main goal is to use the microseismic information recorded as a result of mining to analyze cave propagation and stress performance on the actual production and fixed infrastructure. At the moment, several numerical experiments have been conducted to correlate the mining activity with the microseismic events using the data collected during year 2005 and 2006. As a result of the preliminary analysis a micro- and a macrocracking envelop were proposed on the basis of computation of stress behavior at the location of the events. Stresses have been computed using standard elastic continuous boundary element models. The correlation between the average source radius and the stress performance has provided a method to propose a macrocracking criterion. Several techniques have been tested to nucleate the microseismic activity around different geological features. This last attempt was aimed to look at potential overstresses induced over the undercut and extraction level drifts. A method was devised to integrate the microseismicity into a 3-dimensional ride distribution model. This model has shown to be very effective to quantify the overstress induced as a result of computing volumetric microseismicity density. The volumetric microseismic model showed to induce overstress up to 10 MPa over a period of two months. The future work will concentrate on the calibration of the integrated model with actual damage observations made at the current mining infrastructure.

Key words: microseism; underground mining; block caving; stress distribution; microcrack criterion

1. Introduction

Cave mining induces microseismicity in the rock mass as a result of the fracturing process that takes place above and below the production and haulage level as reported by Glazer and Hepworth [1] and Dunlop and Gaete [2]. Microseismicity induced by mining at high stress in brittle rock masses has been investigated for years in order to find a pattern between microseismic activity and violent failure in a form of rock burst as shown by Simser and Falmagne [3], while Beck and Brady [4] have also proposed a parametric formulation to evaluate the controlling parameters for seismic events in hard rock mining.

In block and panel caving mining, there is always a need to better understand the caving propagation as a well as the stress distribution on the undercutting and production drifts to assess production performances and long term stability of the production facilities.

This article addresses the fact of whether the microseismic activity might be used to better understand the caving process. In particular, a relationship was sought to assess cave propagation. This was performed by combining the microseismic activity of the Deep Ore Zone mine (DOZ) of PT Freeport Indonesia and numerical modeling. The second question that the article intends to address is whether the microseismic activity is reporting some insights regarding rock mass behavior that are impossible to represent in a single elastic continuous model.

A fair amount of work has been conducted in the latest years on microseismicity induced by caving mining. The technique has been refined by adding different performances to the current practice of microseismic monitoring. Different performance indicators such as magnitude, energy index, stress drop, and others have been derived over time. Nevertheless very little mining interpretation has been given to these indicators. Even more, not a clear analogy between caving performance and seismic indicators has been established. The research presented in this article intends to overcome a few of these aspects by integrat-

Corresponding author: Rubio Enrique, **E-mail:** erubio@ing.uchile.cl

Also available online at www.sciencedirect.com

ing seismic activity into numerical modeling. This work aims to develop a methodology to use microseismic information to calibrate numerical models to be used in block cave mining.

2. Microseismicity at DOZ

DOZ is the underground mine of PT Freeport Indonesia located on the West Papua area. The mine currently produces about 50000 t/d. The mining method consists of panel caving with advanced and post undercutting. Since July 2004, the mine has been recording microseismic activity in order to better understand the cave propagation process as well as to find indicators that might guide the occurrence of large deformations on the mining infrastructure.

The microseismic network of DOZ is composed of 18 seismometers and 36 triaxial geophones (30, 14, and 4.5 Hz). The magnitude sensitivity of the DOZ microseismic network was set up at −3.0 and the location accuracy of the network is 10-20 m from elevation 3100 to 3800 m.

The range magnitude of seismic events recorded by the system was −3 to 3.3 during 2004-2007. The microseismic database used in the research was selected on the basis of the reliability of the network that was achieved by the end of 2004. Also the microseismic data was filtered to consider those events that are inside the network envelop to avoid the mixing of data with different location accuracies. Fig. 1 illustrates the filtering process.

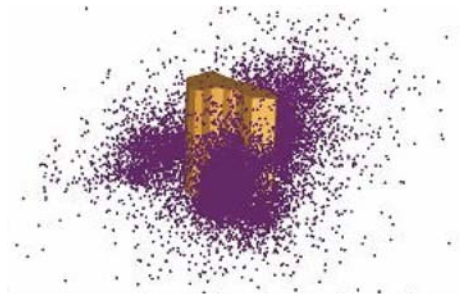

Fig. 1. Filtering seismic events using the three-dimensional representation of the seismic network.

The filtering process reduced from about 85.000 down to 45.000 events located from Jan 2005 to Mar 2006. The data that have been included in the study are from Jan 2005 until Mar 2007. The main seismological parameters are summarized in Table 1.

Table 1. Statistics of microseismic events source parameters

Time	Mean lg(*E*)	Mean lg(Mo)	Max. magnitude	Min. magnitude	Events
Jan-Mar, 2005	8.7	3.2	1.6	–2.5	6023
Apr, 2005	9.0	4.3	2.5	–2.2	4136
May-Jun, 2005	9.0	4.6	2.5	–2.4	4231
Jul-Aug, 2005	8.7	2.6	1.2	–2.8	6919
Sep-Oct, 2005	8.9	5.0	2.7	–2.3	9222
Nov-Dec, 2005	8.7	3.2	1.3	–2.1	5700
Jan-Feb, 2006	8.8	3.4	1.7	–2.2	4034
Mar-Apr, 2006	8.8	3.3	1.7	–2.2	4205

Note: Mean lg(*E*) is the average mean energy released in logarithmic scale; Mean lg(Mo) is the average seismic events moment in logarithmic scale; Max. magnitude and Min. magnitude are the maximum and minimum events magnitude in Richter scale; Events is the number of events recorded by the microseismic network, all these source parameters are reported to the referred time period.

3. Cave propagation through microseismicity

The main geotechnical parameters affecting the planning of the block cave were presented by Brown [5] as follows: cavability, cave initiation, cave propagation, fragmentation, and stress performance surrounding the cave boundary.

Cave propagation is a very important geotechnical assessment for block cave mining since it constraints draw rates and mining sequence. Cave propagation is called to the fracturing process that occurs at the cave back. Several attempts have been made to predict cave propagation. However, Szwedzicki *et al.* [6] reported an empirical chart to predict cavability as a result of studying time domain reflectometers (TDRs) breaking at DOZ. The approach taken in this research was to use the microseismic information to understand the stress behavior at event locations.

The first numerical experiment consisted of constructing a mine-wide boundary numerical model that could represent the mining geometry and the pre-mining stress state. The numerical model was constructed using the commercial package MAP3Di that uses boundary elements to resolve equilibrium. This software provides an efficient way to reproduce the complex caving mining geometry. The elements that were included in the model are listed in as follows:

- Previous mining represented by the intermediate ore zone (IOZ) cave;
- Actual mining represented by the DOZ cave back;
- Actual undercut and production level drifts;
- Undercut progression boundary, undercut level (UCL).

Fig. 2 shows the integration of the 3-dimensional components of the mine-wide numerical models listed above.

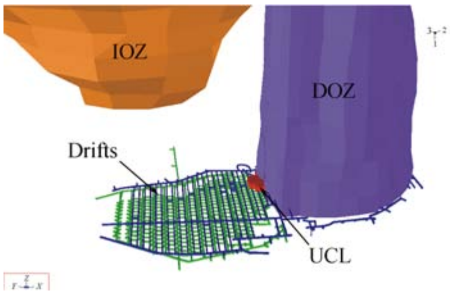

Fig. 2. Three-dimensional components of the numerical model.

The prominent rock mass that is present at the mine at the time of study is skarn that has the elastic parameters of a Young's modulus of 52 GPa and a Poisson's ratio of 0.28.

The premining stress state was estimated on the basis of available premining stress state derived from 10 stress field measurements that is represented by the stress tensor listed in Table 2.

Table 2. Premining stress tensor

Component	Magnitude/(MPa)	Trend/(°)	Plunge/(°)	Gradient
s_1	34.8	215	79	0.038
s_2	25.5	89	6	0.027
s_3	12.3	358	9	0.019

After constructing the numerical model the microseismic activity associated with the mining geometry was loaded in the model to compute the stress components at all the event locations. Fig. 3 shows the microseismic events recorded during Jan and Feb 2005 embedded into the numerical model.

The same numerical experiments have been reported by Beck [7] and Martin [8], wherein both authors reproduced the mining excavation geometry and computed the stresses at each event location. Beck at Brunswick mine, after removing those events that were associated with the existing geological structure, found that these stresses could be fit by a linear regression given by $\sigma_1-\sigma_3\approx30$ MPa. At AECL's underground research laboratory, it was found that these stresses could be fit by a line given by $\sigma_1-\sigma_3\approx60$ MPa. Thus, both authors have found a linear relationship between the compressive and the confinement component of the stress behavior at the source. The results of performing the same experiment at DOZ using the Jan-Feb 2005 microseismic activity are shown in Fig. 4. The regression of the stress state at the microseismic events is $\sigma_1-\sigma_3\approx20$ MPa.

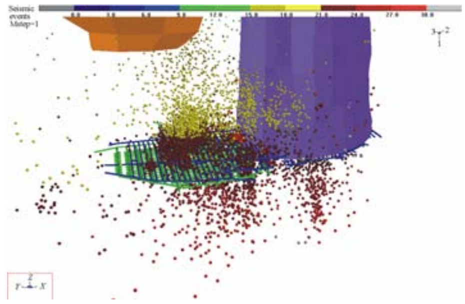

Fig. 3. DOZ mine geometry and associated microseismic activity for Jan 2005.

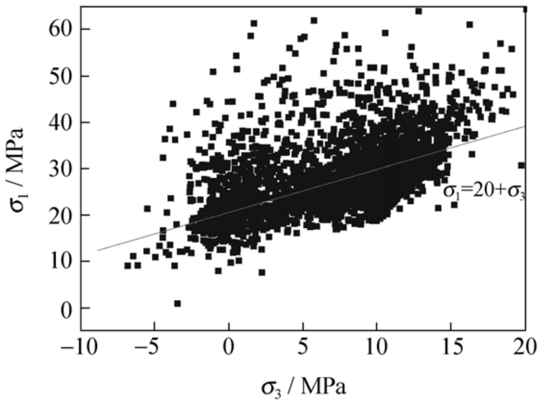

Fig. 4. Seismic envelop for period May-Jun 2005.

After computing the seismic envelop for every event, the difference between the computed stress state (s_1) and the regressed stress was computed. Then, this difference was displayed in the numerical model to identify the locations of larger deviations with respect to the regressed stress state.

Fig. 5 shows that the most deviated values are associated with two geological faults and the stress concentration at the cave boundary, which is not reflecting the caving propagation process. By filtering these two events the standard deviation of the regression shown above could improve from 14% to 3%.

The above numerical experience was repeated every two months and the results are shown to be consistent in presenting similar regression. Table 3 shows the parameters of 8 different periods, in which the microseismic envelop has been computed, where slope and intercept are referred to the best fit linear regression parameters, r_2 represents the regression coefficient of the fitted linear regression, SD represents the standard deviation of seismic points to the linear fitted regression, and b is the slope of the Gutenberg-Richter model fitted to the seismic events collected in the time period.

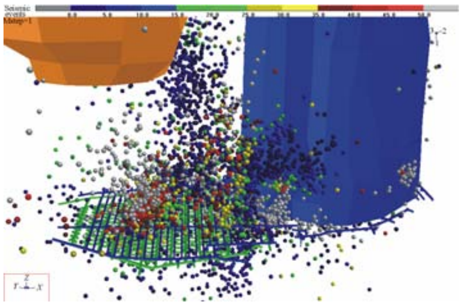

Fig. 5. Square difference of the stress state between the model and regression.

Martin [8] defined three strength parameters determined from laboratory triaxial compression tests: crack initiation (σ_{ci}), crack damage (σ_{cd}), and peak strength (σ_f), in which the following relationships were proposed:

$$2.5\sigma_{ci} = \sigma_f,$$
$$2.5\sigma_{cd} = \sigma_f.$$

The seismic envelop $\sigma_1-\sigma_3$=20 represents the stress state for the crack initiation process (σ_{ci}). This parameter can be used to assess cave initiation. Nevertheless, it is necessary to identify the crack damage (σ_{cd}) strength to better assess the cave propagation. In order to compute this point it was decided to study the microseismic source parameters further, in particular, the seismic radius and source displacement. McGarr [9] proposed a formula to compute these two parameters at the source. The seismic average displacement at the source is defined by $u = M/G\pi r^2$, where M is the seismic moment (N·m), G the rigidity modulus (Pa), and r the microseismic radius (m). The seismic radius at the source is defined by $r = (4M/3\Delta\sigma)^{1/3}$, where M is the seismic moment (N·m) and $\Delta\sigma$ the stress drop at the source (Pa). These relationships were applied to all the events recorded in the period of study. For a given numerical model representing the mining geometry at the time (Sep 2005) the events recorded in that period and the subsequent month were imported into the model. Then, the seismic events were clustered in a regular grid conformed out of cubes of regular sizes, in this case 20-m wide, 20-m high, and 20-m long. Every cube will be called a voxel and the overall 3-dimensional array of voxels will be called a voxel model. The clustering facilitates the estimation of a continuous 2-dimensional view of the source radius by applying simple interpolation between voxels. Fig. 6 shows the vertical section voxel model to interpret the average source radius.

Table 3. Slope and intercept of the best fit linear regression for different microseismic envelops

Time	Slope	Intercept	r_2	SD / MPa	b
Jan, 2005	0.91	19.30	0.21	6.30	0.63
Apr, 2005	0.77	21.40	0.13	7.10	0.66
May, 2005	1.06	19.20	0.25	7.50	0.66
Jul, 2005	0.89	20.70	0.22	6.50	0.75
Sep, 2005	1.07	17.50	0.40	5.40	0.76
Nov, 2005	0.95	19.40	0.40	6.40	0.69
Jan, 2006	0.65	22.90	0.13	7.30	0.72
Mar, 2006	0.64	23.20	0.15	6.70	0.85

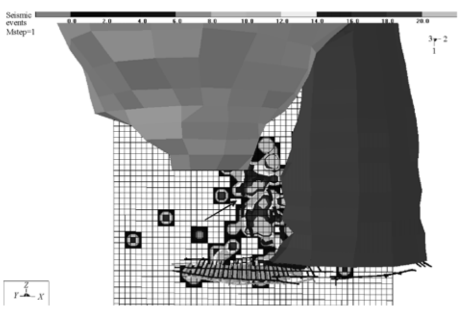

Fig. 6. Average source radius in a 20 m×20 m×20 m voxel for Sep 2005.

On the basis of Fig. 6, a macrocrack envelop can be defined if the average source radius in the voxel is greater than the voxel size. On the basis of this criterion, the area of potential macrocracking is outlined and the stress performance is computed within this area. Fig. 7 shows the ratio between stress and rock mass strength using the microcrack criterion ($\sigma_1/(\sigma_3+20)$).

Fig. 7 shows the overstress with respect to the seismic envelop or the microcracking criterion. It is found that at an outline of 1.2 there is macrocracking formation. On the basis of this result it is possible to propose the following macrocracking damage criterion:

$$\sigma_{cd} = 1.2\sigma_3 + 24.$$

On the basis of the crack damage criterion a cave propagation factor can be proposed by computing the overstress over the regression as follows:

$$\mathrm{CPF} = \frac{\sigma_1}{1.2\sigma_3 + 24}\ .$$

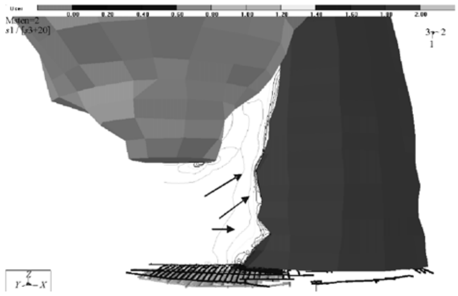

Fig. 7. Cave propagation factor using the seismic envelop $\sigma_1+\sigma_3$=20.

If $\mathrm{CPF} \geq 1$ there is caving, otherwise the rock might be cracking and it is not caving trough the surface. This criterion was used to predict the cave propagation in Jun 2006 as shown in Fig. 8. This estimated cave propagation has been compared against caving observed at preexisting tunnels in order to confirm the estimate.

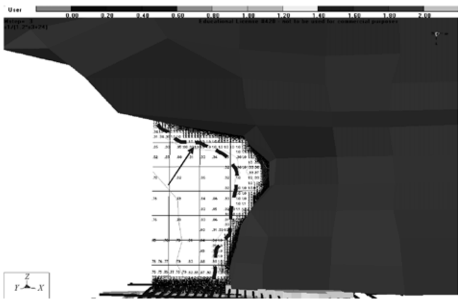

Fig. 8. *CPF* used at DOZ to predict Jun 2006 cave back location.

4. Future work

The micro- and macrocracking envelops are to be validated using the damage observations on the mined out levels that are located at higher elevations than the DOZ production level at IOZ. At the moment several observations related to cave propagation and damage are taken at the mine site in order to provide enough data to validate the cave propagation factor proposed in this article.

The seismic envelop has to be divided into the shear fractures and microcracks in order to better assess the regression of macrocrack formation. Definitely, the seismic source mechanism should be included in the analysis. It has been shown that the shear mechanism is associated more with the fault slip mechanism, which should be separated from the stress mechanism that is related to cave propagation.

Further investigation should be performed to integrate the seismic activity of a given period as part of the 3-dimensional numerical model. This could provide different insights regarding stress distribution. There is evidence in deep and selective mining methods, in which the integration of seismicity associated to mining has produced strong correlation between stress performance and observed damage. The induced stress resulting from integrating the deformations reported by the seismic density model should guide caving and also the damage observed on the production and haulage levels of panel cave mines. One of the main challenges on integrating the cave induced seismicity in mine-wide numerical models has to do with developing a 3-dimensional ride distribution model that can facilitate the inference of displacements between seismic observed clusters.

5. Conclusions

(1) Cave propagation can be estimated on the basis of macrocracking criteria that have been devised integrating elastic linear models with the recorded historical microseismic activity. Crack initiation also can be estimated with the direct correlation of compressive and confinement stress estimated at the source using numerical models.

(2) At DOZ, at the moment, there is still uncertainty regarding how to use the microseismic information to assess potential production and fixed infrastructure damage. It is difficult to observe direct correlations between source parameters such as moment, energy, energy index, or magnitude and damage. The integration of microseismic information into numerical modeling provides a way in which field observations can be correlated with stress performance, in particular, using simple relationships such as overstress for rock mass and excess shear stress for faults.

(3) It has been proposed that microcrack should be identified when observing overstress on $\sigma_1-\sigma_3$=20. Also macrocrack damage should start when observing overstress over $\sigma_{\mathrm{cd}} = 1.2\sigma_3 + 24$. These two simple relationships should assist mining engineers to compute cave back location and provide sound information to cave management regarding the maximum rates of draw and development performance.

(4) The work presented in this article is subjected to the conditions presented at DOZ. Therefore, the criteria proposed should be carefully assessed in order to use at different sites. Nevertheless, the methodology is still valid and meaningful as an exercise to learn about cave propagation.

Acknowledgements

Authors would like to acknowledge Universidad de Chile for providing the academic support to conduct the research presented in this article and also PT Freeport Indonesia for supporting this project and facilitating the edition of this article.

References

[1] S. Glazer and N. Hepworth, Seismic monitoring of block cave crown Pillar-Palabora Mining Company, RSA, [in] A. Karzulovic and M. Alfaro, eds. *MassMin 2004 Proceedings*, Santiago, p.565.

[2] R. Dunlop and S. Gaete, Seismicity at El Teniente mine: a mining process approach, [in] *4th International Symposium on Mine Planning and Equipment Selection*, Calgary, 1995, p.210.

[3] B. Simser and V. Falmagne, Seismic source parameters used to monitor rockmass response at Brunswick mine, *CIM Bull.*, 97(2004), p.1080.

[4] D.A. Beck and B.H.G. Brady, Evaluation and application of controlling parameters for seismic events in hard-rock mines, *Int. J. Rock Mech. Min. Sci.*, 39(2002), p.633.

[5] E.T. Brown, *Block Caving Geomechanics*, Brisbane: Julius Kruttschnitt Mineral Research Center, University of Queensland, 2003, p.515.

[6] T. Szwedzicki, E. Widijanto, and F. Sinaga, Propagation of a caving zone, A case study from PT Freeport, Indonesia, [in] A. Karzulovic and M. Alfaro, eds., *MassMin 2004 Proceedings*, Santiago, p.508.

[7] D.A. Beck, B.H. Brady, and D.R. Grant, Induced stress and seismicity in the 3000 Orebody, Mount Isa., *Geotech. Geol. Eng*., 15(1997), p.222.

[8] Martin, The progressive fracture of Lac DuBonnet Granite, *Int. J. Rock Mech. Min. Sci*., 31(1994), p.643.

[9] A. McGarr, Some applications of seismic source mechanism studies to assessing underground hazard, [in] *Proceedings of the 1st International Symposium on Rockbursts and Seismicity in Mines*, Johannesburg, 1984, p.199.