FE modelling of mining-induced energy release and storage rates

by H.S. Mitri*, B. Tang*, and R. Simon†

Synopsis

This paper describes a simple finite element (FE) modelling approach which leads to the computation of seismic energy release rate (ERR) and strain energy storage rate (ESR) which result from mining. The concept of critical strain energy is introduced as a means to help evaluate the strainburst potential in mine structures. A new, energy-based, burst potential index (BPI) is proposed. The use of ERR, ESR and BPI is demonstrated by a cut-and-fill stope case study. The merits of using such energy parameters in the interpretation and analysis of strainburst phenomena are discussed. While the study gives promising results, site-specific back analyses would be required to first calibrate the model and fit it with the local mine conditions, before it can be adopted as a routine design tool.

Introduction

Strainburst (strain-type rockburst) phenomena in deep underground hard rock mines are generally characterized by a sudden release of energy in a volume of highly stressed rock which, more often than not, caused local violent failure of the rock mass around the opening. Examples of such phenomena are crown pillar bursts in overhand cut-and-fill mining; face bursts at development headings at depth; and floor bursts commonly encountered with deep shaft sinking.

Since the sixties, several techniques and methods have been developed in an attempt to assess rockburst potential of underground mine structures. Several of these techniques are based on the energy balance around excavations. Among those is the Energy Release Rate (ERR) that was developed in South Africa (Cook *et al*., 1966). With the evolution of numerical modelling tools over the past two decades, this technique, along with similar concepts, have often been used in the assessment of rockburst potential (e.g., Cook, 1978; Boldstad, 1990; Minney and Naismith, 1993, Mitri *et al*., 1993).

This paper describes a simple, numerical modelling approach which leads to the calculation of the seismic energy release rate (ERR) and the strain energy storage rate (ESR) due to mining. The calculations take into consideration the geomechanical properties of rock mass, *in situ* stress conditions as well as the mine geometry. Such energy parameters can help identify areas of high-energy release and/or storage due to mining activity, and hence the location of potential strainburst.

Energy balance

To better understand the ERR and ESR concepts, one must consider the balance of stored energy in a rock mass and the energy that can be dissipated when a change (geometrical and/or in stress level) occurs in the rock mass. This balance can then be used to calculate the energy available for rockbursting. This energy balance was reviewed in detail by Salamon (1970, 1974, 1983, 1984), Walsh (1977), Budavari (1983), Brady and Brown (1985), McMahon (1988), and Hedley (1992).

Since 1960, many measurements of rock displacements have been performed and they suggest that the rock mass mechanical behaviour in rockburst situations is essentially of elastic nature (Ortlepp, 1983). Then, the energy balance is usually performed using elastic material laws. It could also be shown that using elastic laws to evaluate the energy available for rockbursting is a conservative approach since the energy dissipated by fracturing is neglected, hence, the stress concentration around opening is over-estimated.

* *Department of Mining and Metallurgical Engineering, McGill University, Montreal, Quebec, Canada.*

† *Department of Civil, Geological and Mineral Engineering, Ecole Polytechnique, Montreal, Quebec, Canada.*

Paper received Aug. 1998; revised paper received Jan. 1999.

When an opening is created or modified, the stored strain energy equilibrium is changed. Let stage I be the initial situation before the creation of the opening and the stage following the creation (or modification) of the opening be called stage II. The energy balance is concerned with the transition between stage I and stage II.

When an opening is created, energy becomes available and is provided from two sources. The first one is the work W (or the variation of potential energy in the system) done by the shifting of external and gravitational forces working on the convergence and deformation of the rock mass. The second source is the stored strain energy U_m in the mined rock. The sum of these two energies ($W + U_m$) is the total energy available when passing from stage I to stage II.

This energy can be dissipated in two ways. A portion of this energy will be dissipated with an increase in the strain energy U_c stored in the rock mass surrounding the excavation. It is also possible that the pressure on support elements surrounding the opening increases; this work W_s is the second way of energy dissipation.

If the rock mass is considered as an ideal elastic continuum, then no energy is dissipated through fracturing or inelastic deformation of the rock. With this simplification in mind, the sum ($U_c + W_s$) is the total energy dissipated during the mining of the opening.

It is obvious that the total energy dissipated cannot be larger than the energy available ($W + U_m$). Considering that the stored strain energy in stage I in the mined rock (U_m) is not available anymore and since $U_m > 0$, then

$$W + U_m > U_c + W_s. \quad [1]$$

This inequality implies the existence of an excess of energy that must be dissipated when passing from stage I to stage II. This energy is referred to as the released energy W_r. Then, one can write:

$$W_r = \left(W + U_m\right) - \left(U_c + W_s\right) > 0 \quad [2]$$

and

$$W_r \geq U_m > 0. \quad [3]$$

The amount of released energy W_r, when larger than the stored strain energy in the mined rock (U_m) in stage I, produces a wave (kinetic energy) that propagates from the new limits of the opening. The vibrations produced by the wave will be damped by minor flaws in the rock mass (the latter not being perfectly elastic). This kinetic energy, W_k, will be dissipated by the damping process.

Since there is no other way to dissipate the energy, then:

$$W_r = U_m + W_k \quad [4]$$

and

$$W_k = W - \left(U_c + W_s\right) \geq 0. \quad [5]$$

Energy release rate (ERR)—advantages and limitations

Based on the energy balance, an incremental approach can be used to follow the changes due to mining. The mining of an underground orebody usually implies the widening of excavations by increments. This leads to an energy release rate by unit surface (dW_r/dS), used when the opening geometry is regular, or a volumetric energy release rate (dW_r/dV), used for irregular geometry openings. Stacey and Page (1986) provided a way to evaluate, in a preliminary manner, this energy release rate (the symbol ERR is commonly used in the literature). Observations of the incidence of violent rock failures at two South African mines (5000' and 9000' deep) indicated that such failures increase with the spatial rate of energy release or ERR (Hodgson and Joughin, 1967). Salamon (1974) showed that for elastic conditions the relations among the energy components apply to any mining configuration. Also, when mining takes place in very small steps, the limiting conditions are:

$$\Delta W_t \cong \Delta U_c,\ \Delta W_r \cong \Delta U_m,\ and\ \Delta W_k \cong 0. \quad [6]$$

The above relations imply that when mining takes place in very small steps, no or little seismic energy, (ΔW_k), is released. Furthermore, Salamon (1983) demonstrated this point by considering a case of a circular opening subject to hydrostatic field stress; refer to Figure 1. As can be seen from the Figure, the kinetic energy released decreases as the number of mining steps increase.

As a result, ERR became one of the most used parameters for stope design in deep underground South African mines (Cook, 1978, Spottiswoode, 1990). Although the ERR has gained wide acceptance in South Africa, Salamon (1993) pointed out that it must be used with caution, and that it can be only of limited value in combating the rockburst hazard, because: (1) the magnitude of ERR only depends on the virgin field stress, the elastic properties of the rocks and the layout of the mining excavation, i.e. it is independent of the geological structure, the presence of flaws (discontinuities) in the rock mass and the potential instability of these flaws, (2) ERR alone is unable to recognize failure. The latter reason has been a motivating factor for the recent development of a new theory for the calculation of the so-called Burst Potential Index (BPI), based on energy considerations, which is described herein.

Present approach

The need to better understand rockburst phenomena, particularly pillar and strainbursts, has motivated the authors to

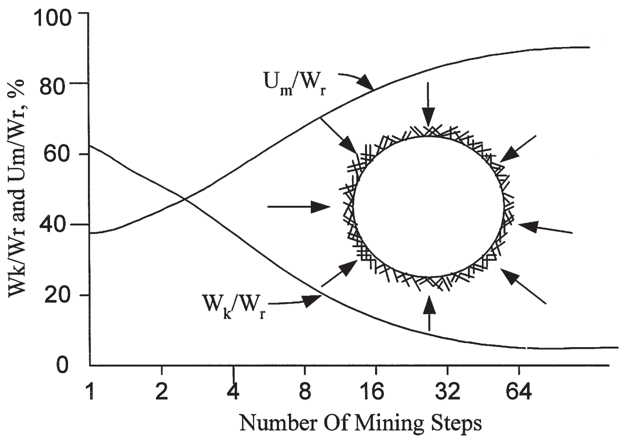


Figure 1—Variation of energy released with number of mining steps (after Salamon 1983)

expand on the concept of mining-induced strain energy density around mine cavities (Mitri *et al.*, 1993). Referring to Figure 2, the premining state of stress before any excavation is made σ_0. These stresses are in balance with the initial external loading P_0 representing the body forces in the rock mass, or simply its own weight in this case. The loading of the problem is initiated by the unbalance created by the removal of the rock mass inside the boundary. The initial stresses stored in the excavated volume disappear (due to mining) and as a result, an out-of-balance load, $\Delta P = P_1 - \int B^T \sigma_0 \, dV$, is induced. This induced load causes displacements u_1, strains ε_1, and stresses σ_1 around the excavation in order to reach state of equilibrium as per the following relation:

$$P_1 = K_1 u_1 + \int B^T \sigma_0 dV \qquad [7]$$

where, in finite element terms,

P_1 = external loading representing body forces in the rock mass

K_1 = stiffness matrix of elements in the surrounding rock mass

B = element strain-displacement matrix

σ_0 = initial (*in situ*) stresses.

When equilibrium is reached, the external load P_1 becomes in balance with the induced internal stresses $\sigma_{ind} = \sigma_1 - \sigma_0$, i.e.

$$P_1 = \int B^T (\sigma_1 - \sigma_0) dV + \int B^T \sigma_0 dV. \qquad [8]$$

Multiplying both sides of Equation [8] by the displacements u_1, one obtains the work done by induced load $u_1^T P_1$, or W in Equation [1]. Thus the work done by the external load is

$$W = \int \varepsilon_1^T (\sigma_1 - \sigma_0) dV + \int \varepsilon_1^T \sigma_0 dV. \qquad [9]$$

Part of the work is stored as strain energy due to induced stresses, e1 , in the surrounding rock mass. This can be easily shown to be given by:

$$e_1 = \frac{1}{2} \int \varepsilon_1^T \sigma_{ind} dV. \qquad [10]$$

As appears from Equation [9], the strain energy caused by *in situ* stresses σ_0 in the surrounding rock mass, e_2, can be expressed as

$$e_2 = \int \varepsilon_1^T \sigma_0 dV. \qquad [11]$$

The integration volume dV in Equations (7) to (11) represents $tdxdy$ or $t \mid J \mid d\xi d\eta$ in finite element notation, where t is the unit thickness of the rock material, and $\mid J \mid$ is the determinant of the Jacobian matrix.

Hence the total energy stored in the surrounding rock mass, U_c [Equation 1], due to mining, is $e_1 + e_2$ and the storage rate, *ESR*, is

$$ESR = \frac{d}{dV}(e_1 + e_2). \qquad [12]$$

Since body forces existed before any excavation took place, the kinetic energy released, W_k, in this process must cause a seismic effect, and thus be referred to as 'seismic energy release'. This can be formed by applying Equation [5],

$$e_r = W - (e_1 + e_2) \qquad [13]$$

which or after substitution gives

$$e_r = \frac{1}{2} \int \varepsilon_1^T (\sigma_1 - \sigma_0) dV. \qquad [14]$$

Thus the seismic energy release rate, *ERR*, can be obtained from

$$ERR = \frac{d}{dV}(e_r). \qquad [15]$$

To summarize, the total strain energy stored in the surrounding rock mass due to a mining step, U_c, is equal to

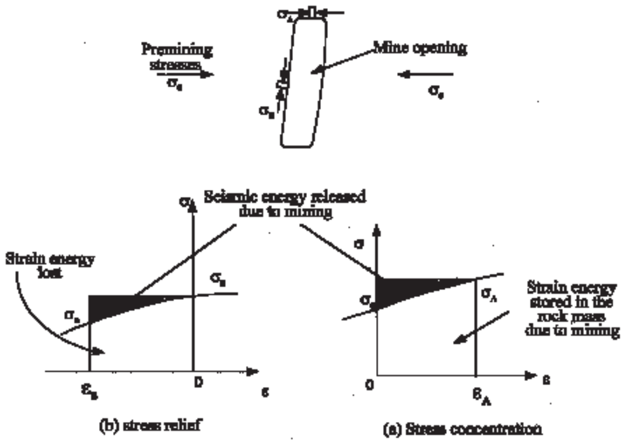


Figure 2—Definition of mining-induced energy components

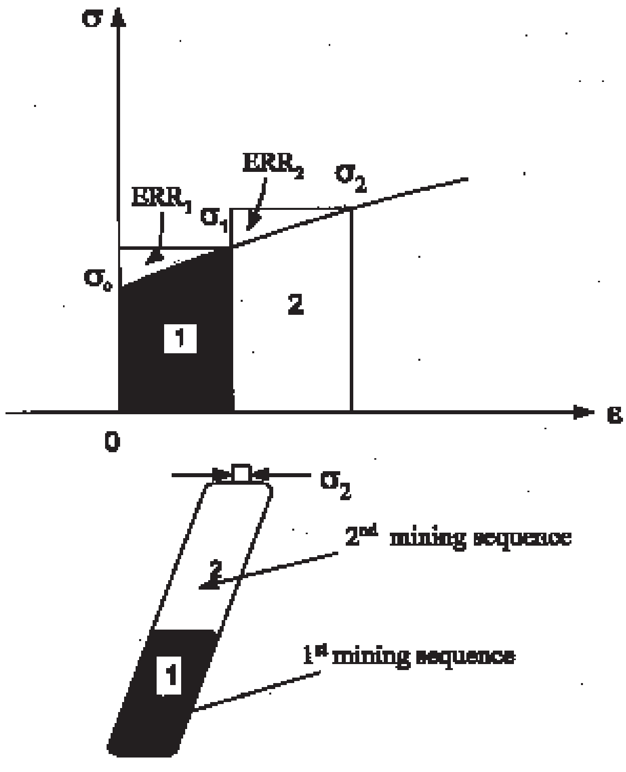


Figure 3—Energy components when mining in sequences

$e_1 + e_2$, while the seismic energy released, e_r, is given by Equation [13]. The summation of all energy components is then $e_1 + e_2 + e_r$ as illustrated in Figure 2. This can be shown to be equal to the work done by the body forces or the own weight+ of the surrounding rock mass, W, which is calculated from:

$$W = \int u_1^T \gamma \, dV \qquad [16]$$

where γ is the body force per unit volume.

Effect of mining sequences

Let us now suppose that the excavation of Figure 2 is to be created in two steps, as illustrated in Figure 3. Since the behaviour of the rock mass is linear elastic, the state of stress and strain at the end of the two mining steps must be the same as when mining in one step. Moreover, the total strain energy stored in the rock mass should be the same. However, the amount of seismic energy released is significantly smaller when mining in two steps. From Equation [14], it can be seen that the seismic energy released in the first mining step is:

$$e_r^1 = \int \frac{1}{2}(\sigma_1 - \sigma_0)\varepsilon_1 dV \qquad [17]$$

whereas mining in the second step results in the release of:

$$e_r^2 = \int \frac{1}{2}(\sigma_2 - \sigma_1)\varepsilon_2 dV. \qquad [18]$$

Adding the above two quantities, it can be seen that there is significantly less seismic energy released when mining in two steps than in one step. It can be shown that the reduction in seismic energy release when mining in two steps, instead of one, is given by $\int \varepsilon_1(\sigma_2 - \sigma_1)dV$.

Supposing that the occurrence of strainburst depends, at least partly, on the amount of seismic energy released due to mining, it may be concluded, in the light of the above, that the potential for strainburst hazard is reduced when mining in small steps. The hatched rectangular area shown in Figure 4 represents this reduction in 'seismic energy'. Furthermore, the maximum reduction of seismic energy (maximum area of the hatched rectangle) can be achieved by making two mining steps leading to equal stress increments, i.e. the optimum mining sequence would be the one which satisfies the condition (refer to Figure 4):

$$\sigma_2 - \sigma_1 = \sigma_1 - \sigma_0. \qquad [19]$$

Since mining is a continuous process, it is possible to

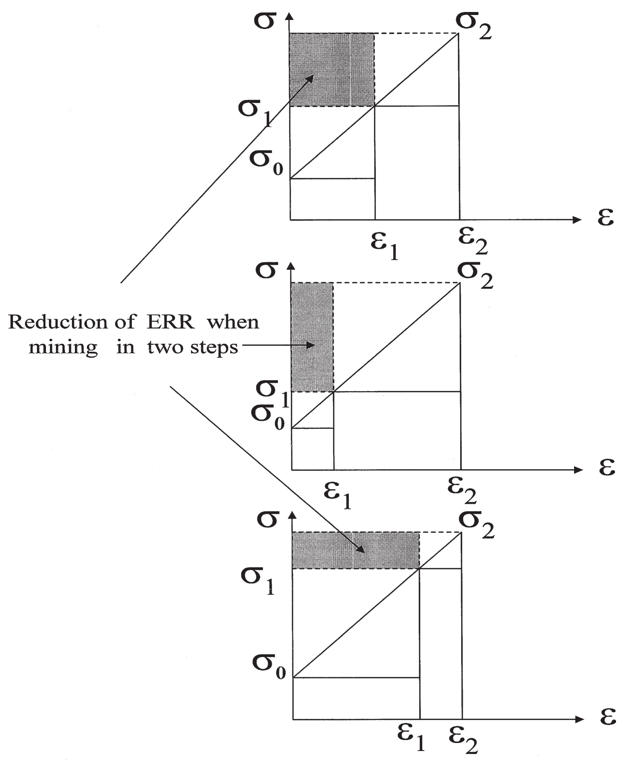


Figure 4—Reduction of energy released when mining in steps

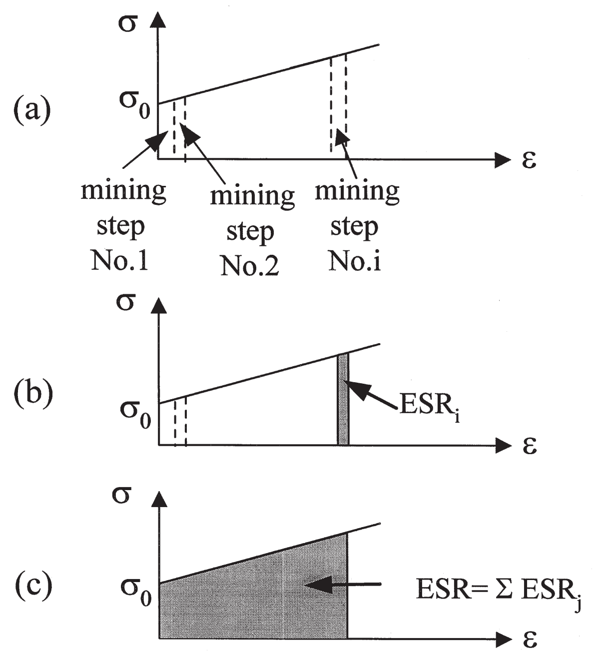


Figure 5—Energy components for mining step No.i

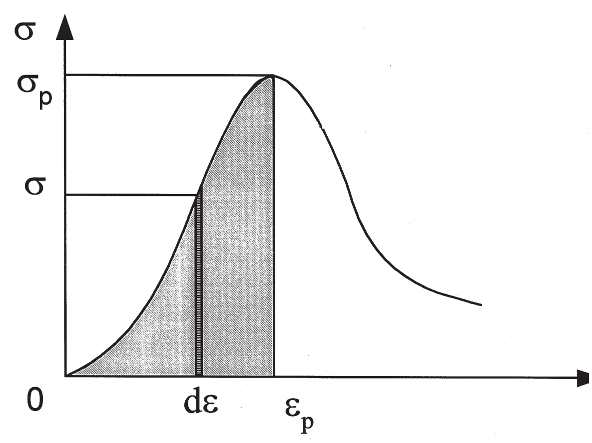


Figure 6—Definition of critical strain energy stored in uniaxial test

design the mining sequences to satisfy the above condition. It should be noted that mining in equal size lifts does not necessarily result in equal stress (and energy) increments. In general, when mining in sequences, two strain energy components can be calculated after each mining step. These are illustrated in Figure 5 for i^{th} mining step of a given mining sequence.

ESR_i = mining-induced strain energy in the rock mass after a given mining step, = $\frac{d}{dV}(e_1 + e_2)$

ESR = total mining-induced strain energy stored in the rock mass from the beginning of the mining process.

An energy-based burst potential index (BPI)

The present approach permits the calculation of mining-induced energy stored in the rock mass. Following the line of thought that rockburst is due to sudden release of energy from a volume of highly stressed rock, it can be supposed that violent failure will take place when the energy stored in the rock mass exceeds a critical value, thus rendering the rock material to its post-peak (unstable) range. In a simple uniaxial test, the critical energy density value, e_c, can be defined as the area under the stress-strain curve up to the point of peak stress, as shown in Figure 6. Thus:

$$e_c = \int_0^{\varepsilon_p} \sigma \, d\varepsilon \qquad [20]$$

where ε_p, is the uniaxial peak strain. A burst potential index (BPI), can then be defined as,

$$BPI = \frac{ESR}{e_c} \text{ x } 100\% \qquad [21]$$

It may be argued that the above burst potential index calculation is limited in its application to the uniaxial loading condition, which is not the case inside the rock mass surrounding the mine stopes. While this is theoretically true, strainburst problems in reality are often associated with failure which takes place at the pillar skin, or at least is triggered at the skin, where stress concentration, as well as energy stored are the highest. In such cases, the state of stress at the skin is uniaxial (since the stresses normal to the boundary must be zero). Also, it is to be noted that equations [20] and [21] consider not only the strength of the rock (σ_p), but also its ability to deform (E); and hence its 'strain energy storage capacity'. This aspect is thought to be important in the assessment of rockburst potential and, in effect, more representative than conventional rock failure criteria, which consider only the rock strength parameters.

All the equations deduced in the model are based on linear elastic rock behaviour. Actually, around mine openings, there exist naturally fractured zones as shown in Figure 7. Part of the ESR in Figure 4 will be released through fracturing the surrounding rock, which actually is a time-dependent phenomenon (COMRO,1988). The fracturing leads to the increase of energy released, but the seismic released energy has not been changed. That means the formation of the fractured zone in computing the ERR can be neglected. The computed ESR value in this model is higher than the value in reality. So does the BPI.

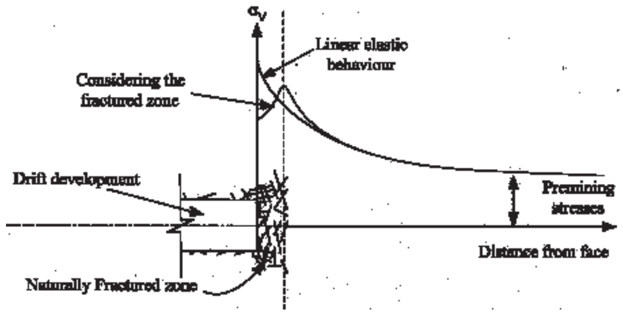


Figure 7—Vertical stress distributions ahead of a development face with and without consideration of natural face fracturing

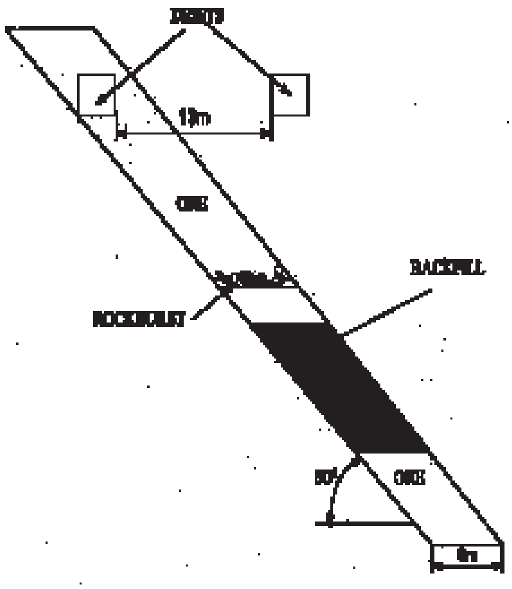


Figure 8—Cross-section of a cut-and-fill stope

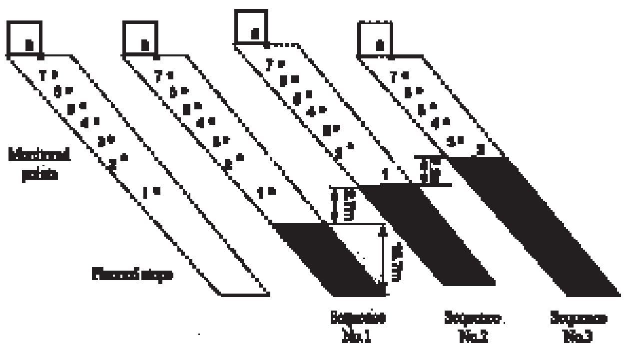


Figure 9—Excavation sequence and monitored points

Table I

Geomechanical properties

Properties	Orebody	Hanging/footwall
Density	0.027 MN/m^3	0.027 MN/m^3
Poisson's ratio	0.28	0.30
Elastic modulus	50 GPa	70 GPa
Uniaxial strength	135 MPa	175 MPa

Case study

Figure 8 shows a cross-sectional view of a cut-and-fill stope of a Canadian underground mine where a rockburst occurred in the crown pillar. Figure 9 shows the simulation of the mining sequence. Numerical modelling was carried out by simulating five modelling steps as follows:

- Step 1: Static analysis of the model with no excavation. There should be no displacements at the nodes.
- Step 2: The overcut and the hangingwall drift.
- Step 3: First stope mining sequence simulated.
- Step 4: Second stope mining sequence simulated.
- Step 5: Third stope mining sequence simulated. This is the stage at which rockburst occurred.

The relevant steps in the simulation are the third, fourth and fifth steps corresponding respectively to the first, second and third mining sequences. At each step of the analysis, stresses, displacements and energy rates ERR and ESR are computed. The third sequence (fifth modelling step) is the critical stage after which the mine experienced dramatic changes that led to a rockburst. While a gradual increase in the strain energy rates around the excavations is expected between modelling step 1 and step 4, the change in energy densities ESR and ERR between step 4 and step 5 is expected to be significantly greater, thus indicating a greater potential for rock mass instability in the area.

Geomechanical properties

The relevant geomechanical properties of the rock masses used in this analysis are shown in Table I.

The natural stress tensor in the vicinity of the mine stope is:

$\sigma_V = 40\text{MPa}$

$\sigma_{h1} = 70\text{MPa}$ (in the plane of the section)

$\sigma_{h2} = 50\text{MPa}$ (out of plane of the section).

All rock masses modelled were considered homogeneous, isotropic and linear-elastic. The influence of mine backfill was assumed to be negligible.

Detailed final analysis and discussion of result

For the crown pillar, strain energy components at 8 monitoring points p_1 to p_8 along its cross-section were monitored as shown in Figure 9. Point p_2 is the centre of the skin element at the bottom of the crown pillar, point p_5 is the centre of the crown pillar while point p_8 is the centre of the skin element at the top of the crown pillar. The intermediate points, p_3, p_4, p_6, and p_7 are symmetrically situated above and below the central point, p_5. Point p_1 is located at the limit of mining sequence No.2 (and disappears in sequence No.3) for comparison purpose with point p_2.

The values of strain energy are the averages surrounding elements at these points and are shown in Table II and graphically in Figure 10. The variation of strain energy at monitoring point p_2 (skin element at lower end of final crown pillar) is of particular interest because this is the area most likely to be affected by a rockburst occurring in the pillar. It can be seen from Table II that the values at the monitored points rise gradually as mining progresses toward the final crown pillar (mining sequence No.1 and No.2), and then substantially at sequence No.3. Changes in strain energies at points remote from this zone (monitoring points 5 to 8) are gradual throughout the excavation sequencing. The substantial increase in the ERR and ESR values at monitoring points close to the lower end of the crown pillar is noteworthy. With reference to the ERR, it can be seen that it has relatively very small value at monitoring points 4, 5, 6, 7, 8. At monitoring point 2, between sequences No.2 and No.3, there is nearly a 10-fold increase in the ERR value and a 4-fold increase in the ESR value.

Monitoring Point 1 in Table II is the mid-skin element of the 2nd mining sequence. Note that at sequence No.3, this point disappears (is mined out) so that it could only be monitored for sequence No.1 and No.2. During sequence No.2, this point is comparable to point 2 at sequence No.3. By comparing the respective values for these two points in Table II, it can clearly be deduced that as mining progresses upwards, thus reducing the size of the crown pillar, the magnitudes of the monitored parameters increase.

Finally, Equation [21] is used to estimate the burst potential index (BPI) at the monitored points. In the absence of detailed stress-strain data of the rock material, the critical strain energy has been approximated by the quantity $\frac{\sigma^2_p}{2E}$,

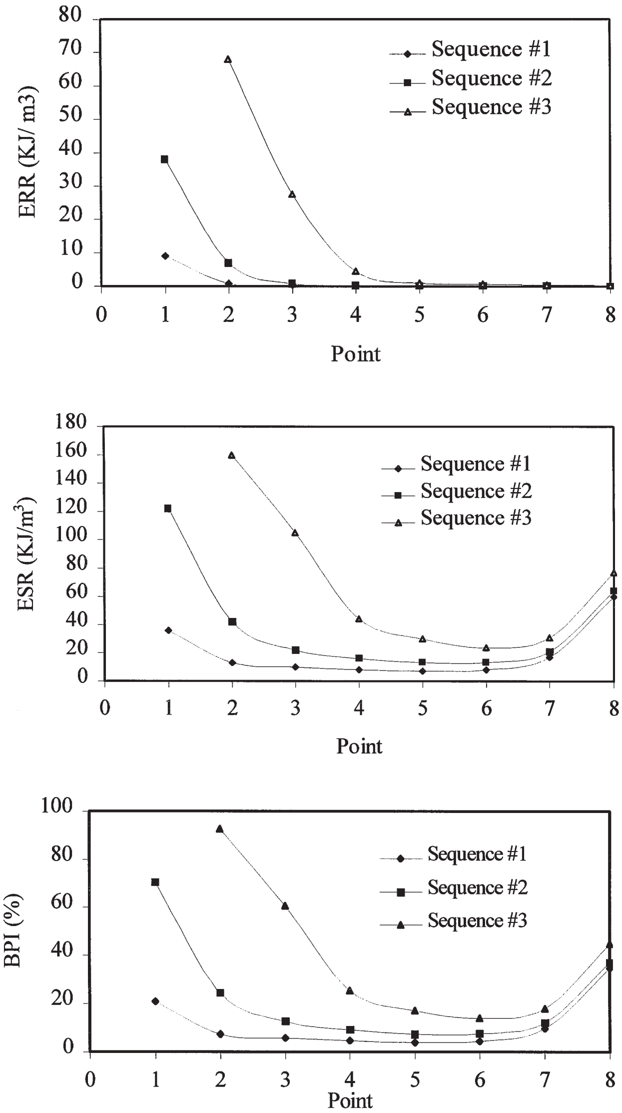


Figure 10—Variations of energy parameters and BPI at monitored points

Table II

Computed energy and BPI results at monitored points p_1 to p_8.

Point	Mining sequence	ERR (kJ/m³)	ESR (kJ/m³)	BPI (%)
1	1	9.0	36.0	20.8
	2	38.0	122	70.4
2 (lower skin element)	1	.86	13.0	7.5
	2	7.00	42.0	24.3
	3	68.0	160	92.6
3	1	.42	10.0	5.8
	2	.83	22.0	12.7
	3	27.5	105	60.6
4	1	.23	8.10	4.7
	2	.31	16.1	9.3
	3	4.5	44.2	25.5
5 (pillar centre)	1	.15	7.05	4.0
	2	.17	13.3	7.5
	3	1.0	30.0	17.3
6	1	.11	8.00	4.6
	2	.11	13.2	7.6
	3	.68	24.0	13.9
7	1	.09	17.0	9.8
	2	.07	21.0	12.1
	3	.36	31.0	17.9
8 (upper skin element)	1	.09	60.1	34.7
	2	.06	64.2	37.0
	3	.27	77.2	44.6

where σ_p is the average uniaxial peak strength, E is the average elastic modulus. The critical strain energy is calculated using the data in Table I. As can be seen from Table II, the highest BPI value after the first mining sequence is only 34.7% at point 8, suggesting little potential for burst. After the second mining sequence, the highest BPI is shifted to point 1 to a moderate value of 70.4%. However, after the third mining sequence, the highest BPI value is 92.6% and is located at the lower skin of the crown pillar where rockburst actually occurred.

From the results obtained, it can be seen that both energy parameters are increasing at the back of the stope as the pillar is mined. Comparing energy densities at the back of the stope after mining sequence No.2 and after sequence No.3, it appears that the ERR value rises from 38 to 68 kJ/m³ and the ESR value rises from 122 to 160 kJ/m³. Also, the burst potential index (BPI) given by Equation [22] increases from 70.4% to 92.6% which is theoretically close to instability.

If the seismic ERR values obtained in this back analysis are compared with the South African experience, it can be noted that the values in this case are much lower than those leading to rockburst problems in South African mines. This shows that the experience drawn from South African mines can not be directly transposed to the particular situation of Canadian mines. It also demonstrates the importance of fitting the model with the local mine conditions before rationalizing its use as a design tool.

Conclusion

A number of concluding remarks can be drawn from the work reported in this paper. These are:

- ➤ Two energy parameters, namely the energy release rate, ERR, and the energy storage rate, ESR, are defined to help estimate strainburst potential due to mining
- ➤ The present modelling technique uses the finite element method. Nonetheless, other numerical methods like boundary elements can equally be used
- ➤ According to the present approach, mining in smaller steps will result in significant reduction of the kinetic (seismic) energy released, this should help reduce the potential of strainburst. The ideal situation is one which will permit equal stress increments in high stress zones (refer to equation [19]). Consideration of the naturally fractured zone will not affect the calculation of seismic released energy, although the total released strain energy will increase
- ➤ A burst-potential index, BPI, is introduced as a new index to estimate in percentage the potential for strainburst. Thorough, yet simple, laboratory uniaxial tests will be required to estimate the critical strain energy of the rock. The advantage of the BPI calculation over the well-known safety level calculation using traditional rock failure criteria, such as Mohr-Coulomb or Hoek-Brown, is that the BPI accounts for both the rock strength and stiffness characteristics, whilst traditional rock failure criteria are based solely on strength parameters
- ➤ The present energy-based approach has the advantage over the traditional stress approach in that it accounts for both mining-induced stresses and deformations (rock stiffness)
- ➤ Even though the results obtained from this back analysis appear very interesting, many more site-specific analyses work needs to be carried out to better establish the ERR and ESR levels that can be considered crucial for strainburst occurrence
- ➤ We must notice that the current model employs linear elastic rock behaviour, which makes the calculated value of the energy parameters ERR and ESR, and the newly introduced BPI higher than the practical value. That means this is a conservative model.

Acknowledgement

This work has been financially supported by a research grant from l'Institute de recheche en santé et en sécurité du travail du Québec (IRSST). The authors are grateful for their support.

References

Bolstad, D.D. 'Rockburst control research by the US Bureau of Mines', *Rockbursts and Seismicity in Mines*, Fairhurst (ed.), *Balkema,* 1990. pp. 371–375.

Brady, B.H.G. and Brown, E.T., Rock Mechanics for Underground Mining, 1985. *George Allen & Unwin.*

Budavari, S. 'Response of the rock mass to excavations underground', Rock Mech. in Mining Practice, *S. Afr. Inst. Min. Metall.*, Monograph Series, vol. 5, 1983. pp. 55–76.

Chamber of Mines of Research Organization of South Africa, 1988, An Industry Guide to Methods of Ameliorating the Hazards of Rockfall and Rockbursts.

Cook, N.G.W., An Industry Guide to the Amelioration of Hazards of Rockbursts and Rockfalls, *Chamber of Mines of South Africa*. 1978.

Cook, N.G.W., Hoek, E., Pretorius, J.P.G., Ortlepp, W.D., and Salamon, M.D.G. 'Rock mechanics applied to the study of rockbursts', *J. S. Afr. Inst. of Min. and Metall.*, 1966. vol. 66. pp. 435–528.

HEDLEY, D.G.F., 'Rockburst Handbook for Ontario Hardrock Mines', CANMET *Special Report* SP92-1E. 1992.

HODGSON, K. and JOUGHIN, N.C. The relationship between energy release rate, damage and seismicity in deep mines. *Proc. 8th Symp. on Rock Mech., University of Minnesota*, In *Failure and Breakage of Rock*, C. Fairhurst (ed.), 1967. pp. 194–203.

MCMAHON, T., 'Rock burst research and the Coeur d'Alene District', *Bureau of Mines Information Circular*, (IC 9186). 1988.

MINNEY, D.S., and NAISMITH, W.A. 'Quantitative analysis of seismic activity associated with the extraction of a remnant pillar in a moderately deep level gold mine', *Rockbursts and Seismicity in Mines,* Young (ed.), *Balkema*, 1993. pp. 95–100.

MITRI, H.S., HASSANI, F.P., and KEBBE, R. 'A strain energy approach for the prediction of rockburst potential in underground hard rock mines', *Proc. First Can. Symp. on Numerical Modelling Applications in Mining and Geomech.*, McGill University, 1993. pp. 228–239.

ORTLEPP, W.D. 'The mechanics and control of rockbursts', Rock Mechanics in Mining Practice, Budavari (ed.), *S. Afr. Inst. Min. Metall.*, 1983. pp. 257–282.

SALAMON, M.D.G. 'Pillar stability/instability and design of pillar workings', *Int. J. Rock Mech. Min. Sci.,* 1970. vol. 7. pp. 613–631.

SALAMON, M.D.G. 'Rock mechanics of underground excavations', Advances in Rock Mechanics, *Proc. 3rd Cong. Int. Soc. Rock. Mech.,* vol. 1-B, 1974. pp. 951–1099.

SALAMON, M.D.G. 'Rockburst hazard and the fight for its alleviation in South African gold mines', *Proc. Rockbursts Prediction and Control, IMM,* London, 1983. pp. 11–36.

SALAMON, M.D.G. 'Energy considerations in rock mechanics: fundamental results,' *J. S. Afr. Inst. Min. and Metall.*, 1984. vol. 84. pp. 233–246.

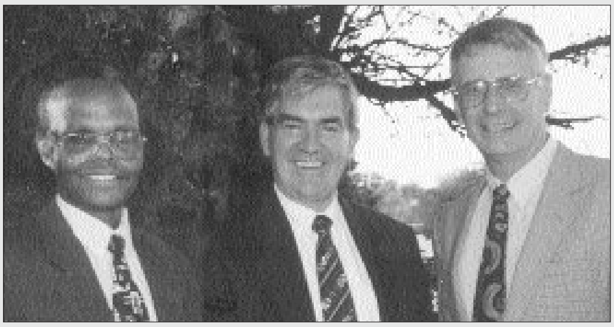
SALAMON, M.D.G. 'Some applications of geomechanical modelling in rockburst and related research' *Rockbursts and Seismicity in Mines*, Young (ed.), *Balkema*, 1993. pp. 297–309.

SPOTTISWOODE, S.M. 'Volume excess shear stress and cumulative seismic moments' *Rockbursts and Seismicity in Mines,* Fairhurst (ed.), *Balkema,* 1990, pp. 39–43.

STACEY, T.R., and PAGE, C.H., 'Practical Handbook for Underground Rock Mechanics', *Trans-Tech Publ.* 1986.

WALSH, J.B., 'Energy changes due to mining. '*Int. J. Rock Mech. Min. Sci.*, 1977. vol. 14, pp. 25–33. ◆

Foundation programme gives Wits engineering students a better chance*



Launching the new Foundation Cirriculum for 1999 in the Engineering Faculty at Wits University were (from left): Prof. Winston Onsongo, Director of Undergraduate Engineering Education, Prof. Colin Bundy, Vice Chancellor of the University, and Prof. Jan Reynders, Dean of the Engineering Faculty

The Engineering Faculty at the University of the Witwatersrand has officially launched a new foundation programme aimed at increasing the number of engineers graduating from the university.

The new programme will be introduced next year in response to increasing numbers of under-prepared students from all educational backgrounds entering the faculty, the low numbers of students who actually graduate (about 55%), and under-developed abilities of many students.

The restructured degree includes a new foundation year in which students will be taught mathematics, mechanics, physics, chemistry and communications skills. Students will not be automatically enrolled in the foundation curriculum. They will enrol in the first year of the normal four-year degree course, but may revert to the foundation curriculum based on the results of their first quarter or mid-year exams.

This should not be seen as a backward step as 50% of the foundation programme syllabus will allow students to obtain credits towards their degrees. A student can obtain first year maths and mechanics credits at foundation level, and will also receive valuable grounding in physics, chemistry, English language, drawing and computer skills within the engineering environment. In an address to business and industry to launch the new initiative, Prof. Winston Onsongo, Director of Undergraduate Engineering Education at Wits, explained that the foundation curriculum was designed to prepare students fully for the challenges of the normal four-year degree.

Prof. Onsongo said, 'It will assist students in areas like communication which commonly cause problems throughout the degree period and, by allowing the student to obtain some first year credits, alleviate some of the pressure commonly experienced in the first two years of the traditional engineering degree'.

The approach in the foundation curriculum will centre around small-group tutorials, teamwork, oral and written reports, the development of basic engineering skills and effective study skills. The workload will be similar to that in the mainstream degree. Students successfully completing the foundation curriculum continue with the mainstream engineering programme; those who fail will not be re-admitted to the Faculty, but will be assisted in seeking alternative avenues of study.

In a further effort to improve pass rates, the Faculty of Engineering plans to introduce a summer term for concentrated study for those students who marginally fail one course in the year-end exams. If the student passes the supplementary exam it will save him or her one year of registration. The summer term is to be run during the December/January vacation, commencing in the 1999/2000 vacation. ◆

** Issued by: Lynne Hancock Communications, P.O. Box 180, Witkoppen 2068*