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Use of Mining and Seismological Parameters as Premonitors of Rockbursts

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Comprising one of the deepest mines in the world, the gold mining region of the Kolar Gold Fields (KGF) in southern India is known to be confronted with the acute problem of rockbursts that pose a hazard to workmen and cause disruptions in the production schedule. In combination with mining parameters, seismological data of these rockbursts events systematically monitored over the years using a regional seismic network have been employed to examine and model premonitory characteristics of the events. Linear empirical relations are established relying on correlations seen between the seismic energy released due to a rockburst, total tonnage of ore mined out and total number of rockbursts, as well as seismic events in some shallow and deep workings currently active at KGF. The deterministic model, although not free from certain limitations at present, has been applied to predict rockburst activity with some success. © 1997 *Elsevier Science Ltd*

INTRODUCTION

Rockbursts inside any mining excavation are essentially rock failures due to alteration of the virgin state of stress by mining and creating an opening through the rock mass. As mining depth increases progressively, so do the ambient stresses, which proportionately increases the severity of mine seismicity. Commonly recognised as a seismic event, a rockburst usually results in damage to underground workings caused by the uncontrolled disruption of the rock equilibrium and is associated with violent release of strain energy stored in the rock body [1].

Rockbursts therefore constitute a subset of mining induced seismic events. Not all seismic events result in damage to underground excavations. Mining being a progressive activity, the excavations are modified in shape and made to grow with time. It is logical, therefore, to examine the strain energy changes resulting from specific changes in the mining geometry. It has been observed that noticeable seismic events produce elastic radiation equivalent to a body-wave magnitude up to 2 on the Richter scale, though bigger rockbursts are also known to occur at times. These seismic events cause considerable hardship to miners when causing damage to mine workings, often rendering the latter unproductive for some time. The rate of energy release is closely related to mine seismicity and physical damage within the mine [2].

Spatial, as well as temporal rate of strain energy released, closely allied to volumetric closure, are currently the most widely used parameters in designing mine layouts to reduce mine seismicity as, e.g. inside the deep mines in South Africa [3]. The deterministic dependence of seismic energy release on extracted volume has also been introduced [4]. A direct relation is known to exist between the spatial rate of energy released, and frequency of occurrence and magnitude of mining-induced seismic events [5]. This relation has been of central importance in developing strategies for mitigating rockburst hazards in a wide range of mining operations. It has been pointed out that the rate of release of seismic energy in proportion to mining rather than the total energy released in the excavated region needs to be considered in assessing the rockburst potential of that region [6].

Kolar Gold Fields (KGF) in southern India is one of the oldest gold mining areas in the world, where the mining activity has currently reached a depth of 3.3 km below the ground surface. The phenomenon of rockburst has commonly been observed here since the beginning of this century. In order to understand the dynamics of rockbursts and to premonitor their occurrence, several factors which influence rockbursts are to be correlated and evaluated. A regional seismic

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network was established at KGF in 1978 and it has been continuously operating since then for round-the-clock monitoring of rockbursts in the entire mine district that stretches approximately 8 km north–south and is *ca.* 3 km across. The instrumentation of and data generation by this network has been described by Subbaramu *et al.* [7]. Earlier, detailed seismic investigations of KGF rockbursts and the seismic velocity structure in the entire mine region traversed by the Schist belt has been carried out by Arora [8].

In the present study, the rockburst-prone region at deeper levels of the Champion Reef mine covering both the Northern Folds and Glen Ore Shoot areas (Fig. 1) has been chosen. Typical case studies correlating mined-out tonnage and rockbursts recorded from those areas are discussed. Since there is considerable geomechanical stress change due to a rockburst, it is reasonable to expect a predominant correlation between the seismic energy released and mined-out tonnage, which is related further to number of seismic events in a given period of time. Employing pertinent data for a period of six years from 1982 to 1987, we find that a linear relation best describes the connection among the three mining and seismological parameters mentioned above. We then use this algorithm to estimate the expected total number of seismic events and number of rockbursts among them in the years to follow, i.e. in the years 1988–1990. These numbers predicted by the model are compared with the actual data to establish the efficacy of the model. It is aimed at premonition of seismic events with a lead time of approximately 1 yr. Applicable also to shallow mine workings, this new approach has been tested with encouraging success.

GENERAL SEISMICITY PATTERN OF MINES AT KGF

The rockbursts in and around the mine excavations have been continuously monitored since 1978 using the 14-channel cable telemetered seismic network at KGF. More than 10,000 seismic events have so far been recorded and hypocentres of a very large number of them determined with an accuracy of 50 m. They are found to occur throughout the mining region and are distributed nearly parallel to the main longitudinal axis (north–south) of the Kolar Schist belt [8–10]. However, the seismic activity is concentrated in the vicinity of current workings, i.e. the deep-level workings of the Champion Reef and Nundydroog mines (Fig. 1). The depthwise distribution of the rockburst events is found to be consistent with the profile of the underground workings. The region is crossed by a major geological fault striking NE–SW (Mysore North Fault or MNF) in whose vicinity many rockbursts tend to occur.

SEISMIC EVENTS AND ORE MINED OUT

The influence of mining activity on the occurrence of seismic events is revealed in Fig. 2, where we show the monthly status from January to December by summing in each of the months the tonnage and number of seismic events cumulatively over a period of seven years

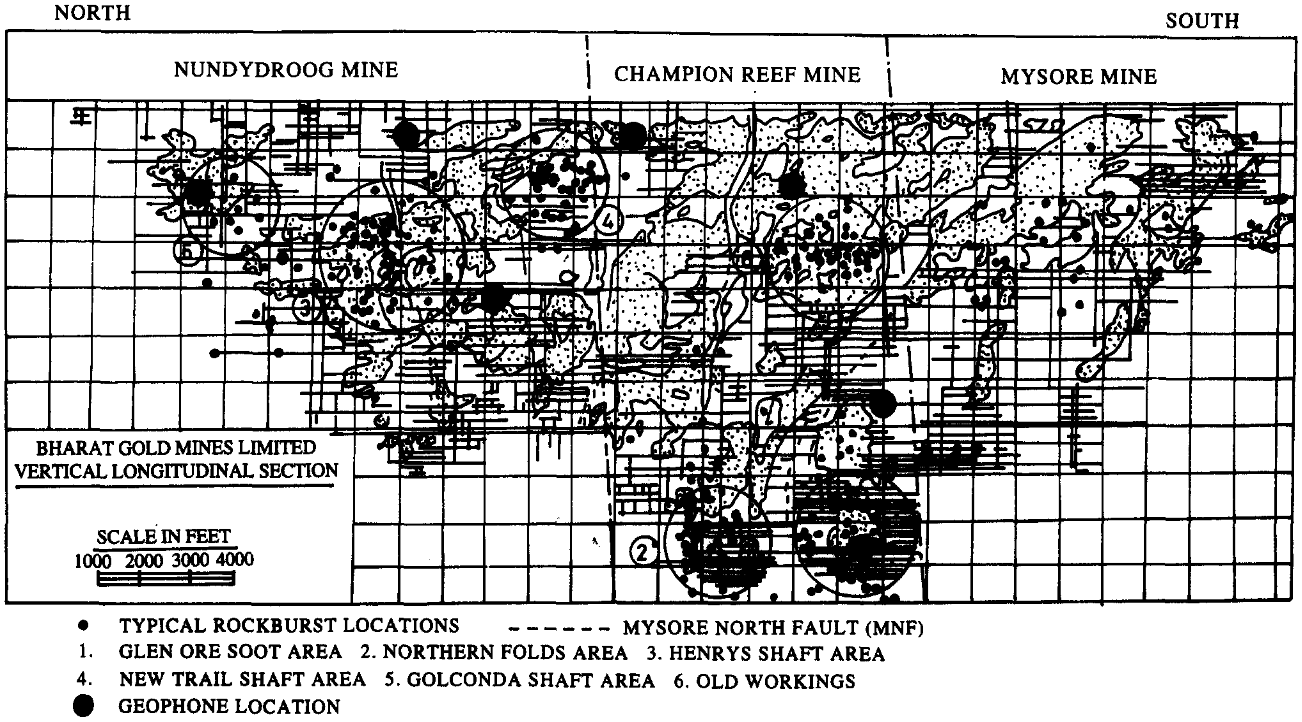

Fig. 1. Longitudinal (north–south) section through Kolar Gold Fields showing typical spatial distribution of rockbursts in one-year period (1987). Shaded areas—mined out portions; small dots—computed hypocentres of rockbursts; bigger dots—some of the geophone locations of the monitoring network; plain circles—areas enclosing bunches of rockbursts and broken line—strike of Mysore North Fault (MNF). (1) Glen Ore Shoot area, (2) Northern Folds area, (3) Henry's Shaft area, (4) New Trial Shaft area, (5) Golconda Shaft area and (6) Old workings.

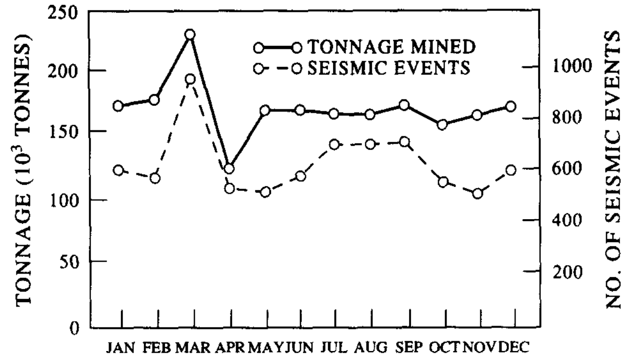

Fig. 2. Total monthly tonnage mined out (solid line) from January to December and total number of rockbursts (broken line) recorded during each month over the period 1981–1987.

(1981–1987). It is clearly seen that a reasonable correlation exists between the total tonnage of ore mined out each month and total number of seismic events detected in the same period. Every year, in the month of March, which marks the last month of the financial year, when the production level is high, a large number of seismic events is registered, compared to that normally registered during the other months. This accounts for the prominent peak in Fig. 2 contributed over the years by the total seismic count at *ca.* 1000 during March corresponding to the total tonnage peak in the same month. The sudden drop in the seismic count after March following a similar drop in the tonnage mined out is also clearly borne out.

ENERGY LIBERATED IN A SEISMIC EVENT

In the instrumentation deployed at sensor locations by us, seismograms of seismic events record the particle velocity of ground motion both at the surface and underground. Assuming a spherical wavefront at local distances and the particle motion to be simple harmonic over short intervals of time, an expression for the kinetic energy in a propagated phase may be derived as follows.

Consider a spherical shell in the medium of seismic wave propagation between radii r and $r + \mathrm{d}r$ from the source. If ρ is the density of the medium, we have

$$\text{volume of the shell } (V) = 4\pi r^2 \mathrm{d}r \qquad (1)$$

$$\text{mass of the shell } (M) = 4\pi \rho r^2 \mathrm{d}r. \qquad (2)$$

The kinetic energy associated with the shell due to the passage of the wavefront is given by [11]

$$E = \tfrac{1}{2}(4\pi\rho r^2 \mathrm{d}r) V_i^2 \mathrm{d}r \qquad (3)$$

where V_i is the particle velocity in the medium. But $\mathrm{d}r = V\mathrm{d}t$, where V is the velocity of wave propagation in the medium and $\mathrm{d}t$ represents the element of time for the passage of the wavefront through the shell.

Thus,

$$E = 2\pi\rho V r^2 V_i^2 \mathrm{d}t. \qquad (4)$$

Therefore, for the passage of the wave in a phase of duration τ, the total kinetic energy is given by

$$E_{\mathrm{T}} = 2\pi\rho V r^2 \int_0^{\tau} V_i^2 \mathrm{d}t. \qquad (5)$$

The wavefront at an observing station is assumed to be spherical in the far field (at a large distance from the source). However, if the source inside a large mining excavation resides in the near field (very close to the observing station), then the wavefront is considered to be hemispherical. Thus, the total kinetic energy is given by

$$E_{\mathrm{T}} = \pi\rho V r^2 \int_0^{\tau} V_i^2 \mathrm{d}t. \qquad (6)$$

Employing the above formulation, the seismic energy can be computed from the seismograms obtained from various observation points where three-component ground motion sensors are installed. In the existing seismic network at KGF, however, since all the geophones are uniaxial (vertical), the total seismic energy liberated is obtained by summing the energies represented in seismograms from geophones in different directions.

SEISMIC ENERGY AND ORE MINED OUT

The plot in Fig. 3 illustrates a striking similarity between seismic energy released and tonnage mined out annually from all the KGF mines during the years 1981–1987. It is noticed that the energy profile, that follows reasonably well the amount of rock extracted each year, has an abnormally large value during the year 1985. It is because, in this particular year, there were exceptionally large sequences of moderate seismic events induced and triggered by chemical explosives fired to displace rock to facilitate intense mining activity, as compared to other years.

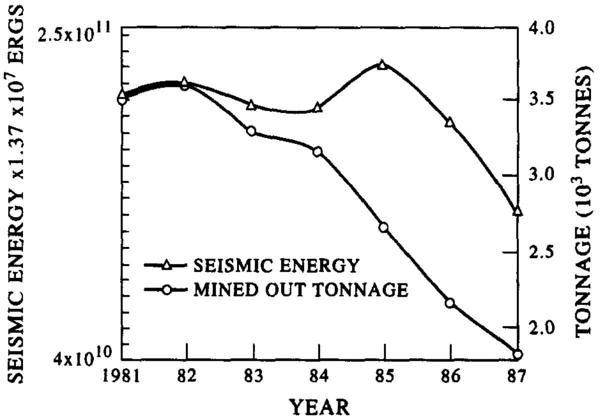

Fig. 3. Seismic energy released in rockbursts yearly as a function of tonnage mined out during the years from 1981 to 1987.

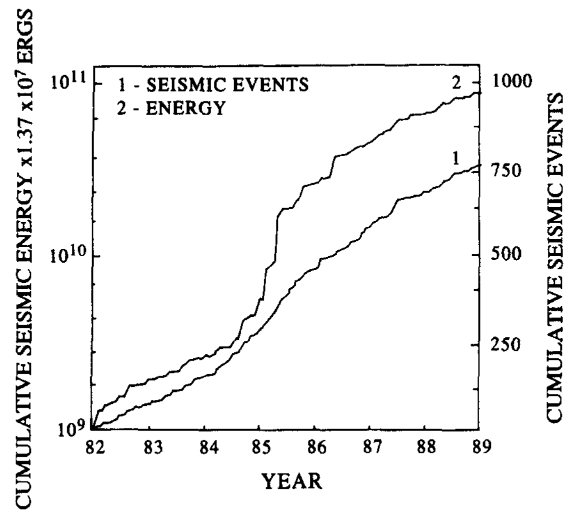

Fig. 4. Plot of (1) cumulative rockburst count and (2) cumulative seismic energy release over the period 1982–1989.

SEISMIC ENERGY IN RELATION TO NUMBER OF SEISMIC EVENTS

A typical plot of the cumulative number of seismic events and the associated seismic energy for the 8-yr period from 1982 to 1989 is shown in Fig. 4. Similarly, a correlation is generally seen between the two parameters plotted. However, identical to the feature noticed in Fig. 3, the curve in respect of the event count shows a steady rise, whereas the corresponding energy shows a steep increase in the year 1985 indicating anomalously higher energy release in that year. This is ascribed to a few major seismic events with higher energy content recorded during the period indicated. From the seismic database, it is also confirmed that the number of seismic events recorded during 1985 exceeds those in other years. The gentle gradient before the steep rise of energy (Fig. 4) represents an extended phase of stress accumulation or build-up while the steep gradient indicates stress redistribution owing to a sudden release of seismic energy. The rate of stress accumulation is, in fact, a function of many other parameters, which include the method of mining, the rate of advance of mining, etc.

CASE STUDIES

On the basis of similarity between the pairs of parameters discussed above and supported by the illustrations in Figs 2–4, we attempted to establish linear empirical relations between them and found the relations to be linear. We describe here case studies in which seismic data obtained from the deeper level workings in the two areas of the Champion Reef mine, viz. Glen Ore Shoot and Northern Folds, are selected for further processing. In particular, we intend to establish empirical relations interconnecting three important parametric pairs operating on their cumulative values over an extended period of time. The time frame of the input data in the present case is 6 yr (1982–1987) and the parametric pairs are as follows:

A—Mined-out tonnage and seismic energy released.
B—Seismic energy released and number of rockbursts.
C—Number of rockbursts and number of all seismic events.

Eventually, the sequence of relations (A–C) can be used to obtain projections of future seismicity by linear extrapolation justifiably in the neighbourhood of the data segment.

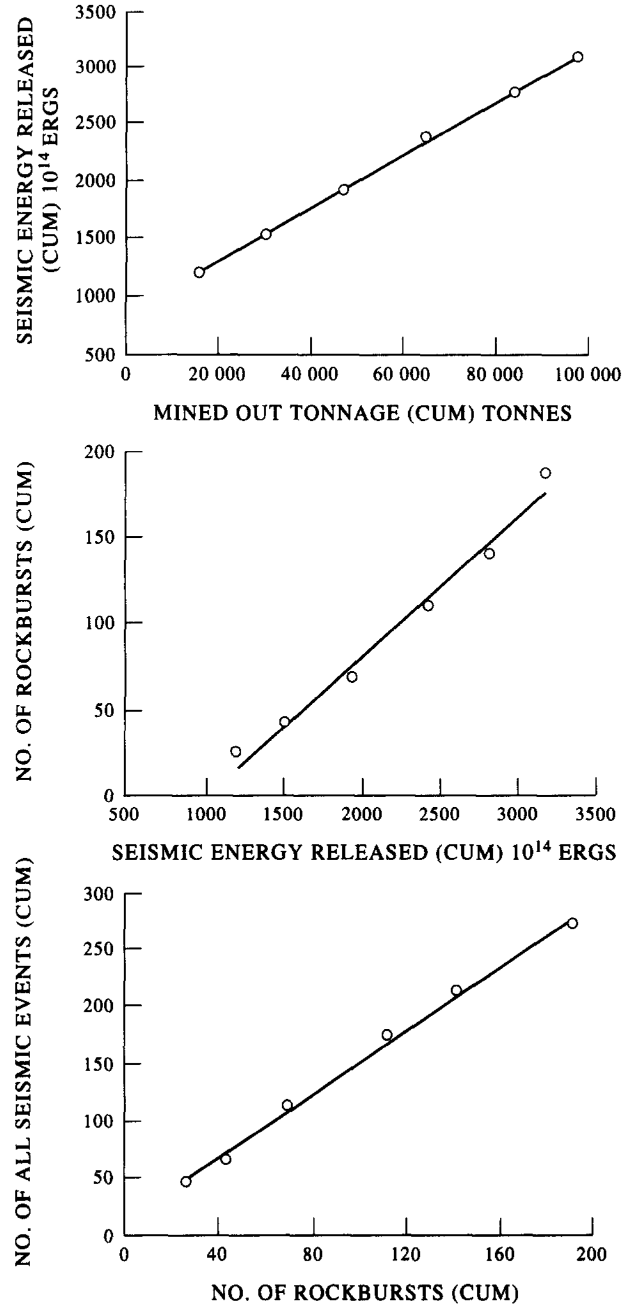

Fig. 5. Illustrations of typical linear relations between different parametric pairs and best-line fit through the corresponding data points (cumulative values) for Glen Ore Shoot area and Champion Reef mine: (a) mined out tonnage and seismic energy released; (b) seismic energy released and number of rockbursts and (c) number of rockbursts and number of seismic events.

Table 1. Linear regression analysis applicable to Glen Ore Shoot area

Parametric pair	x(cumulative)	y(cumulative)	Best-fit line
A	Mined-out tonnage (tonnes)	Seismic energy released (ergs)	$y = 0.0333084x + 1098.64$
B	Seismic energy released (ergs)	Number of rockbursts	$y = 0.0610498x - 103.886$
C	Number of rockbursts	Number of all seismic events	$y = 1.42592x + 10.7316$

Glen Ore Shoot area

For the Glen Ore Shoot area, pertinent data corresponding to the parameters listed in A–C are plotted in Fig. 5. A trend line obtained by least-squares fitting is also drawn in each of those figures. The results of regression analysis are summarised in Table 1. The regression coefficients in each of the best-fit lines listed in Table 1 are valid when quantities are measured in units shown therein.

Northern Folds area

Pertinent data for this area with regard to parametric combinations A–C are plotted in Fig. 6. Least-squares lines through each set of the data points are also drawn to deduce the trend. Regression analysis performed on the data has been summarised in Table 2.

Projected seismicity of the Champion Reef mine

The formulations established from the past data, summarised in Tables 1 and 2, have been applied to estimate the number and size of expected rockbursts in the Champion Reef mine in the subsequent years, 1988–1990. As a test case, these have been compared with the actual data obtained during the period 1988–1990. For these three years, Table 3 lists the number of actually recorded rockbursts from the Glen Ore Shoot and Northern Folds areas, and those predicted by the model.

It is seen from Table 3 that the total number of seismic events predicted for the Champion Reef mine is generally more than those actually observed. This is due to the fact that relatively small seismic events detected by the monitoring network are not routinely retrieved from the tape records, hitherto due to their insignificance to the mining engineers at the Gold Mining Establishment. However, on scanning and scrutinising the helicorder (paper chart) records, one finds that if detections of those small events are also taken into account, the differences between the two sets of data narrow down considerably. Motivated by this result, it is now planned to augment the seismic database to make it more comprehensive than it has so far been. It would also probably improve prediction with regard to major rockbursts since the parameters in the configurations A–C are interconnected. This will be demonstrated in a reassessment of the present model when the seismic database at KGF is fully upgraded.

Seismicity of the Nundydroog mine

We now extend the present approach to another large mine of the KGF, i.e. the Nundydroog mine. The major current workings in this mine are the New Trial Shaft, Henry's Shaft and Golconda Shaft areas. The workings of the New Trial Shaft area extend up to a depth of 600 m from the surface (shallow workings). In the case of Henry's Shaft, the workings range from shallow to deeper levels up to 1500 m, while the Golconda workings go down 1000 m from the surface. Occurrences of

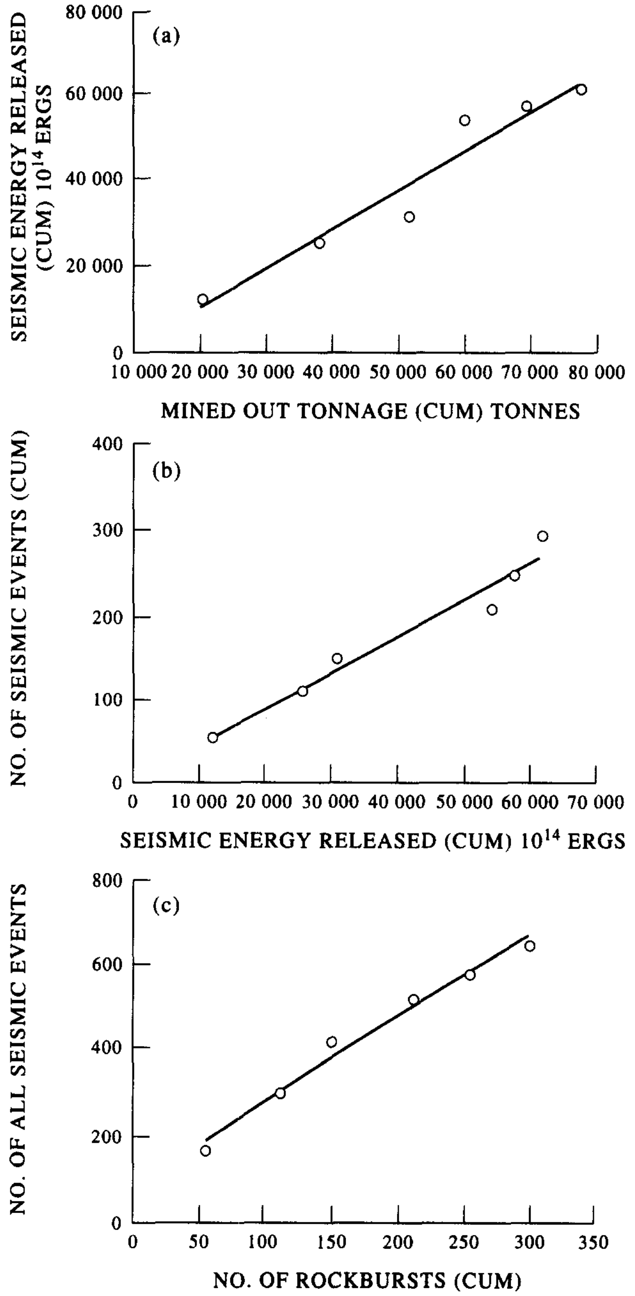

Fig. 6. As in Fig. 5 but applicable to the North Folds area of the Champion Reef mine.

Table 2. Linear regression analysis applicable to Northern Folds area

Parametric pair	x(cumulative)	y(cumulative)	Best-fit line
A	Mined-out tonnage (tonnes)	Seismic energy released (ergs)	$y = 1.26132x - 11{,}498$
B	Seismic energy released (ergs)	Number of rockbursts	$y = 0.0032456x + 0.403551$
C	Number of rockbursts	Number of all seismic events	$y = 1.99269x + 79.32$

rockbursts are also common and frequent in these mining sections.

In accordance with the method discussed above and applied to Champion Reef mine, the seismic and mining data obtained from the current workings of the Nundydroog mine over a period of 6 yr (1982–1987) have been processed. The results of regression analysis seeking to establish linear relations among the three sets of standardised pairs of parameters, i.e. A–C as before (Tables 1 and 2), are presented in Table 4.

Applying the formulations compiled in Table 4, the total number of rockbursts and seismic events in the mostly shallow workings of the Nundydroog mine are estimated for 4 yr from 1988 to 1991. The predicted seismicity is presented in Table 5 along with the real data of rockbursts from the Nundydroog mine for comparison.

It is noticed from Table 5 that, as in the case of the Champion Reef mine, rockbursts predicted by our model generally outnumber those actually recorded. The agreement between the two data sets improves considerably, however, when relatively small detections not included in the present database are also taken into account. If this condition is fulfilled, then interactively the number of major rockbursts predicted by the model would also match the real data more closely.

In the case of the Henry's Shaft (HS) area, intense mining operations have continued from past till present. The mining area is intersected with many faults which is geologically a weak plane prone to rockbursts. The triggering of seismic events due to blasting is quite prominent here. The mining operation in the New Trial Shaft (NTS) area is much less compared to the other mines discussed in this paper. The area of the NTS mine is covered with old workings in both the north and south side of the mine which has many pillars. The Golconda Shaft (GS) area is in between the shallow NTS area and moderately deep HS area. A large number of working points are being mined simultaneously and the GS area is intersected with many faults. This mine is a mechanised mine where deep hole operations are carried out to increase the production in the mine.

IMPORTANCE AND LIMITATIONS OF THE MODEL

The model approach that establishes regionwise relations between mining and seismological parameters in order to estimate mine seismicity, with regard to the temporal pattern of occurrence of seismic events, has been considered by the mine planners as one of vital importance. Systematically evolved and tested with moderate success in the case of some current underground workings at KGF, this effort, although still underway to render the model more comprehensive and useful, has thus far helped in evaluating seismic effects of the ongoing mining activity. Besides, since it uses essentially the data of only the tonnage mined out which the mine management readily provides, the algorithm is straightforward and simple to use.

There are, however, certain limitations of the approach at present, chief among which are stated below. Efforts are being taken to overcome these limitations as best possible.

(i) In the premonitory estimation of rockburst pattern with a lead time of 1 yr, the model presupposes that the cumulative tonnage mined in the past years has nearly the same gradient of rise in the year that follows, there being no sharp changes in the rate of rock removal. However, any significant departures in the mining schedule, which may not be uncommon, are likely to lead to disproportionately large errors in the prediction of mine seismicity. This gives rise to an uncertainty as to whether linear extrapolation in time to determine future

Table 3. Number of events in the deep-level workings of the Champion Reef mine actually recorded in comparison with those predicted over the period 1988–1990

Year	Predicted number of events		Actually recorded number of events		Success rate (%)	
	Rockbursts	Seismic events	Rockbursts	Seismic events	RB	SE
			Glen Ore Shoot area			
1988	24	40	28	37	85	92
1989	46	66	30	54	65	81
1990	26	36	17	43	65	83
			Northern Folds area			
1988	15	53	26	39	57	73
1989	34	67	25	48	73	71
1990	29	58	22	28	75	48

with the aim of refining the present model of premonitoring rockbursts and to establish its efficacy.

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Table 4. Linear regression analysis of the seismic and mining data obtained from the three currently main workings of the Nundydroog mine during the period 1982–1987

Parametric pair	Best-fit line		
	Henry's Shaft area	New Trial Shaft area	Golconda Shaft area
A	$y = 0.0415415x - 1121.11$	$y = 0.382622x - 10751.3$	$y = 0.0147731x - 744.888$
B	$y = 0.0118628x - 14.2748$	$y = 0.000163515x - 0.618487$	$y = 0.000673312x - 0.636028$
C	$y = 15.0584x + 335.948$	$y = 37.1932x + 112.216$	$y = 8.44477x + 29.7108$

For descriptions of the variables x and y in the linear equations governing the parametric pairs A–C, see case studies of this paper, and also Tables 1 and 2.

seismicity is correct. A two-way (forward and backward) modelling to examine any non-linear effects would probably better constrain the model.

(ii) The model is insensitive to the presence of vulnerable geological structures such as a fault, dyke, intrusion, shear zone, etc. all of which are known to influence seismicity, especially in deep-level workings where the excavations progress through highly stressed ore bodies. It calls for more careful spatio-temporal considerations, particularly while modelling rockburst associated seismic events.

(iii) A major limitation of the present method is its inability to decipher the exact location of an impending seismic event. Presently, seismic events are presumed to occur anywhere in the mine area modelled (*ca.* 500 by 500 m). It is desirable, therefore, that the areas of various mine workings are divided into smaller grids, and all mining and seismological data gathered from those small space grids so as to reduce the areal extent of premonitored rockbursts.

CONCLUSIONS

A large amount of seismological data for rockbursts that occurred in and around the mining excavations at the Kolar Gold Fields over a number of years, and the corresponding mining related data have been processed to examine a useful connection between them. This has led to the deduction of linear empirical relations between the seismic energy released due to seismic events, total tonnage of ore mined out and rockbursts, as well as the total number of seismic events applicable to some of the current deep-level and relatively shallow workings of the Champion Reef and Nundydroog mines at KGF. It is clearly seen that the induced seismic events systematically follow the profile of progress in mining activity.

The correlation found to exist between different pairs of seismic and mining parameters could be modelled into sets of regionwise relations that help to predict mine seismicity by linear extrapolation over future intervals of time. Several test cases are demonstrated in which predicted rockbursts and total number of seismic events in a year are compared with the observed rockbursts and seismic events. The agreement between the two is considered to be reasonably good, especially when small seismic detections by the regional monitoring network are duly taken into account. The algorithm is indeed found to be useful in mine planning and ground control.

Nevertheless, the present model of seismic event premonitory characteristics is not free from certain limitations. These relate mainly to frequent temporal variations in the removal of rock mass owing to some necessary alterations in the mining schedule, which tend to produce non-linear effects in the spatio-temporal pattern of strain energy release. The model is also not able to sense exact sites of rockbursts, but that was not intended to be an element of the present study.

Efforts are underway to make the seismological database at KGF more comprehensive. It is in keeping

Table 5. Number of events actually recorded from three different workings of the Nundydroog mine and those predicted over the period 1988–1991

Year	Predicted number of events		Actually recorded number of events		Success rate (%)	
	Rockbursts	Seismic events	Rockbursts	Seismic events	RB	SE
			Henry's Shaft area			
1988	87	1654	101	1611	86	97
1989	98	1822	109	1679	90	92
1990	103	1897	119	1709	86	90
1991	106	1939	122	1714	87	88
			New Trial Shaft area			
1988	7	372	6	310	85	83
1989	9	446	11	327	81	73
1990	10	483	12	333	83	88
1991	11	521	13	338	84	64
			Golconda Shaft area			
1988	3	57	2	51	66	89
1989	3	57	2	54	66	94
1990	3	57	2	54	66	94
1991	4	63	2	54	50	85