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Real Time Microseismic Monitoring to Study Geomechanics of Underground Structures

C. Sivakumar, C. Srinivasan, Y. A. Willy
National Institute of Rock Mechanics, Champion Reefs, Kolar Gold Fields-563 117

Ch. S. N. Murthy
National Institute of Technology, Surathkal, Karnataka-575 025

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ABSTRACT: The study of Geomechanics of underground structures in real time requires capture of fracture information well in advance from structure failure to initiate remedial measures during development and after completion of structure. The advanced high dynamic range microseismic instrumentation with latest Computer methods/algorithms helped to investigate strata behaviour in real time. One such investigation was carried out at the Rajendra longwall underground coal mine, Madya Pradesh state India and addressed major concerns of the mines like roof falls, stability of workings, goaf caving process etc,. The results of this study demonstrated that microseismic monitoring is very useful in understanding the geomechanics of underground structures. Among the several seismic source parameters obtained, the reliable precursor found was the microseismic Event Release Rate (ERR) of micro fractures before failure, which is the most significant instability indicator of underground structure. Results from this work can be useful to other underground structures such as tunnels and LPG storage caverns.

1 Introduction

India is the world's third largest coal producing country in the world after China and USA. As the most abundant fossil fuel in India, it is heavily used in India's energy sector; approximately 55% of energy needs are catered by coal. Given the uncertainty over gas and oil sector in future, coal is expected to continue to dominate India's energy scene. The International Longwall census report says that early efforts at Longwall mining in India were poorly implemented but with experience, better equipment specification and improved infrastructure have increased the chances of success. Today in India, there are examples of moderately successful mechanized Longwall faces, which produce on an average 1500 Mt per day. Powered Support Longwall technology contributes nearly 50% of global production of coal from underground mines and is the most prevalent methodology in the leading coal producing countries. According to International longwall census done in 1997, on an average the production of coal from longwall mining continues to grow. (Meheta et. al, 2003)

Longwall technique introduced in India during 1960's and powered support longwall mining introduced in 1970's. In most of the longwall faces, the main problem was roof strata caving. It was mainly due to the presence of massive sandstone bed in which in general is difficult to cave and cave-in dynamically and violently. In order to understand the behaviour of strata the microseismic technique has been experimented in one of the longwall face at Rajendra underground coalmine of South Eastern Coal Fields (SECL) in Madhya Pradesh.

Today it is widely accepted that seismic data, in the form of event-triggered seismograms in real time yield much useful information about state of the rockmass (Mendecki,AJ et.al.,1999). If the seismic system dynamic ranges are good enough then the time, location, radiated energy and scalar seismic moment of a seismic event can be routinely estimated from several associated seismograms. Having recorded and processed a number of seismic events within a given volume of interest over time, one can then quantify the changes in the strain and stress regimes and in the rheological properties of the rock mass deformation associated with the seismic radiation. This in turn allows estimation of quantities like rock mass stability over space and time.

Every seismic network has a minimum magnitude below which events are not detected. For most modern geophone-based mine-wide seismic networks, the local magnitude above which all events may be consistently detected is about 0.0 to-0.5 (Lynch R.A. and Mendecki AJ. 2005). It is often argued that this sensitivity is good enough to obtain relevant information about the rockmass response to mining. A suitably designed microseismic sensors network can record the microseismic signal waveforms to obtain the source parameters information and enable to precisely, remotely and dynamically. The deformation data is available in real time, which pertains to whole region covered by sensor network in Australia (Heatherly et.al., 1995) and (Luo, et.al., 1998). NIRM has carried out one Science and Technology project on Prediction of roof falls in goaf area in Churcha West Coalmine SECL by using the microseismic monitoring method (Sivakumar, 1998) using PC based microseismic monitoring system. Based on this experience one more Science and Technology has been carried out in the Rajendra underground Coal mine.

In this paper the real time monitoring carried out, configuration of geophone network, installation of geophones in boreholes, acquisition of microseismic data, processing of microseismic data, report generation and usage of the results to assessing stability of structures including prediction of roof falls are discussed with case studies.

2 Microseismic investigation at the Rajendra colliery

A Science and Technology project entitled Monitoring of Strata behaviour during longwall coal mining using Microseismic monitoring technique and estimation of caving height was undertaken jointly by SECL and NIRM at Rajendra Colliery as mentioned (Sivakumar et.al, 2004). The introduction of modern digital seismic systems to the mines and progress in the theory and methods of quantitative seismology enabled the implementations of real time monitoring to quantify rock mass response to mining in a better manner as reported by (Mendecki et.al 2001). During the period of microseismic monitoring, several thousands of microseismic events and roof fall events were recorded. Induced blasting was carried out on the surface of working panel through drilled boreholes to release the buildup stresses and avoid overload on the powered support (Srinivasan et.al, 2004).

3 Instrumentation and monitoring systems

At Rajendra Colliery P-2 longwall face the microseismic monitoring system, namely Integrated Seismic System (ISS) manufactured by ISSI, South Africa was installed. The ISS system had sophisticated Hardware and powerful software features in data acquisition and data analysis. The system was developed around network technology and built on the distributed Data Acquisition Units (DAS) with Central access to online data processing system. Figure 1. Illustrates the block diagram of ISS system used at Rajendra underground mine. The geophones were installed from surface through Boreholes, Ahead of the face, behind the face and both at Main gate and Tailgate. Total 8 geophones at a time covering an area of 200m length, 150m width and 75m depth were connected to the ISS system

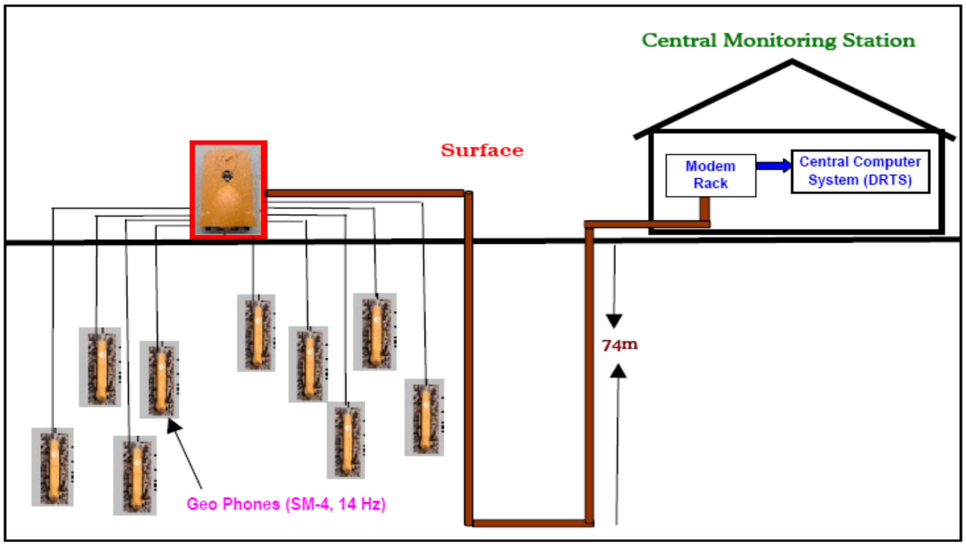


Figure 1. Microseismic monitoring system block Diagram installed at Rajendra underground coal Mines

The ISS system consisted of 18 uni-axial geophones, deployed in Boreholes drilled from surface. These sensors installed at the selected heights and boundaries of roof strata at a different depths varying from 36m to 67m and covering about 200m in length and 150m in width (face of the panel) on surface. The cables from all geophones brought to the Junction box situated in the middle of the panel on surface and connected to a MS-9 data acquisition unit, housed in the moveable metal box to protect from environment conditions. From the field the cable connected to the modem back and to HP Kayak Xu 800 workstation, through RS232 port. This Central Computer was capable of setting and changing the data acquisition parameters of MS-9 unit and received the collected data on demand once the event was detected by satisfying the prerequisite conditions like trigger levels at number of channels. The real time Microseismic monitoring system instrumentation layout installed at Rajendra mine is shown in Figure 2. The typical roof fall signal recorded by ISS unit is shown in figure.3.

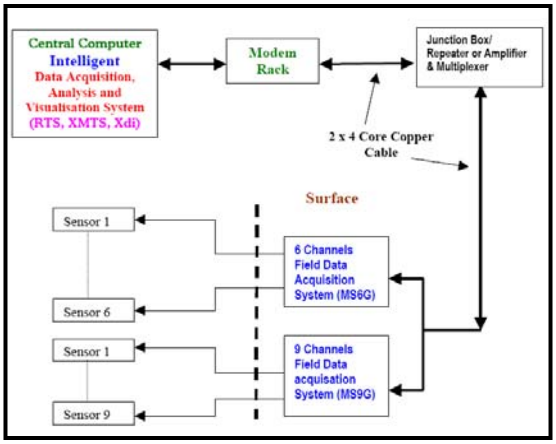


Figure 2. Real time microseismic monitoring System instrumentation layout

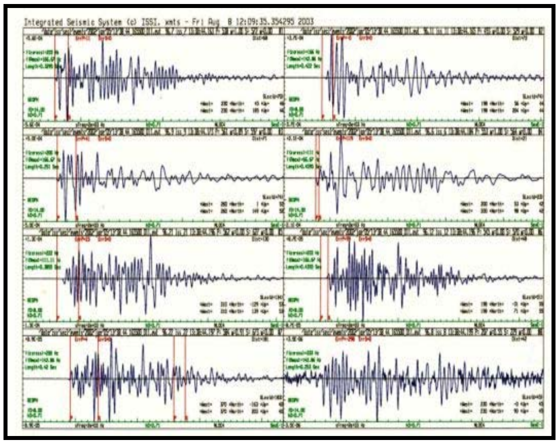


Figure 3. Typical Roof fall signal recorded by ISS unit at Rajendra Longwall mine

The Microseismic monitoring system is capable of acquiring and processing a large amount of microseismic data in real time and provid seismic source parameters which include event location, energy index, seismic moment, apparent stress, event magnitude, apparent volume and spectral parameters of waveform. The microseismic data stored in the database is easy to access for generating reports by simple quarrying and for the data presentation in 3D visualization mode. The contours of various source parameters for selected times along with results of statistically analysed data provided information to understand the strata behaviour from time to time in real time.

4 Data generated

Microseismic data recorded were during 750 m longwall face advance. Continuous real time data were recorded upto 500m round the clock with minimal interruptions for six days during the interfacing of new geophone network microseismic monitoring system. The system recorded thousands of microseismic events and out of them; the events with large source location errors rejected. The raw data so generated were saved in database which are available for offline processing, checking onsets and for further data analysis.

5 Data analysis

The microseismic events, roof falls associated with Longwall mining and induced blasts were recorded at the Rajendra mine. These events were picked up by minimum five geophones in the network and their locations are available. The events were located with an accuracy of less than 5m. The LTA and STA criteria were used to record the events in real time. Following are the signal characteristics shown in Table-1. These parameters are site specific depends on the strength of rockmass and stress profile at the time of recording.

From the microseismic data obtained in real time, analysis were carried out and extracted the source location of each event. Many events accepted after subjected to source location by auto processing in online and rest of the events, were manually processed. From the waveforms of microseismic events, roof falls and blasts source parameters extracted. The source parameters of microseismic events, Roof falls and Blasts recorded by ISS system in Rajendra mine is mentioned below.

Table 1. Details of Source parameters computed from Rajendra mine

Sl. No	Source Parameters	Microseismic events	Roof Falls	Blasts
1	Amplitude in m/sec	10^{-06} -- 10^{-05}	10^{-06} -- 10^{-04}	10^{-04} -- 10^{-02}
2	Magnitude	-4.0 -- 3.0	-1.0 -- 0.0	-0.8 -- 1.8
3	Seismic Moment Nm	8.9x10^{07} --7.3$10^{08}$	1x10^{07} –4x10^{08}	7.1x10^{07} --8.5x10^{08}
4	Seismic Energy Joule	1.9x10^{02} --1.6x10^{04}	1x10-^{03} ---1x10^{05}	5.4x10^{02} --9.2x10^{07}
5	Predominant Frequency	37 -- 500	10 -- 330	21 -- 250
6	Source radius in m	3.66 --6.25	3.0 --16.5	2.0 -- 34
7	Static stress drop in Bars	2.16 --10.58	0.0 --40	3.0 -- 556

The time history plot of microseismic events rate and cumulative apparent volume of events used to extract the instability indicator and prepare daily report for forewarning the occurrence of roof falls. The apparent stress of microseismic events used to obtain contours for obtaining stress zones. The definitions of terms used are mentioned below.

5.1 Apparent volume

The cumulative apparent volume, which provides a measure of the total volume of rock deforming during a fracture event.

Apparent stress: Apparent stress is recognized as a model independent measure of the stress change at the seismic source.

The microseismic events versus apparent volume, time plot of roof falls occurred on 30.11.2001 is shown in Figure 4. These roof falls were recorded in the Rajendra colliery of South Eastern Coal Fields. As can be seen from the Figure 4, that the microseismic event rate gradually increased and attained a peak value. After three hours of this peak, roof fall occurred followed by two more roof falls. The apparent volume also showed a peak value indicating increase in fracture volume before the roof falls. Thus, the increase in microseismic event rate and apparent volume were an indication of the roof fall. Based on this criteria advance information was provided to the mine authority in many instances of roof falls.

The distribution of microseismic events recorded during the month of March, 2002 is shown in Figure 5.

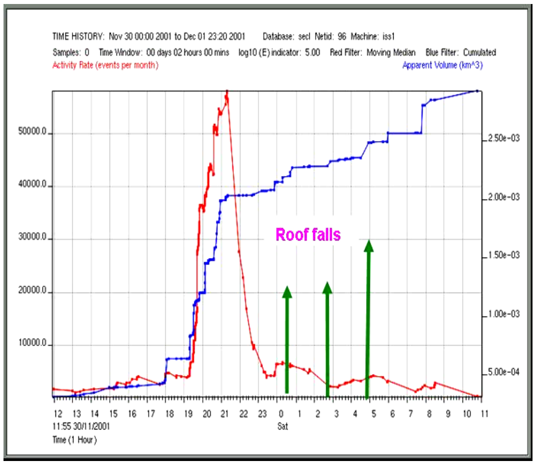


Figure 4. A Time history plot of Microseismic events rate and Cumulative apparent volume for events recorded on 30.11.2001

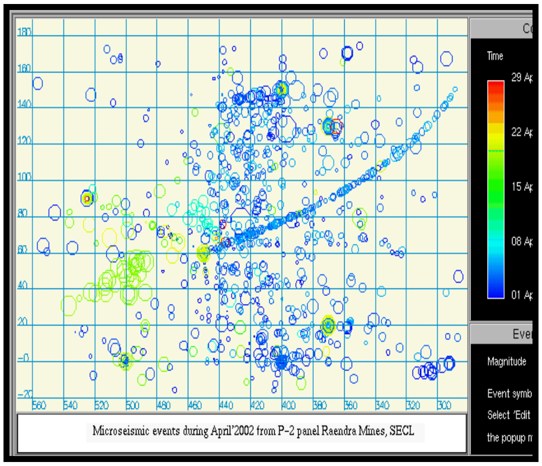


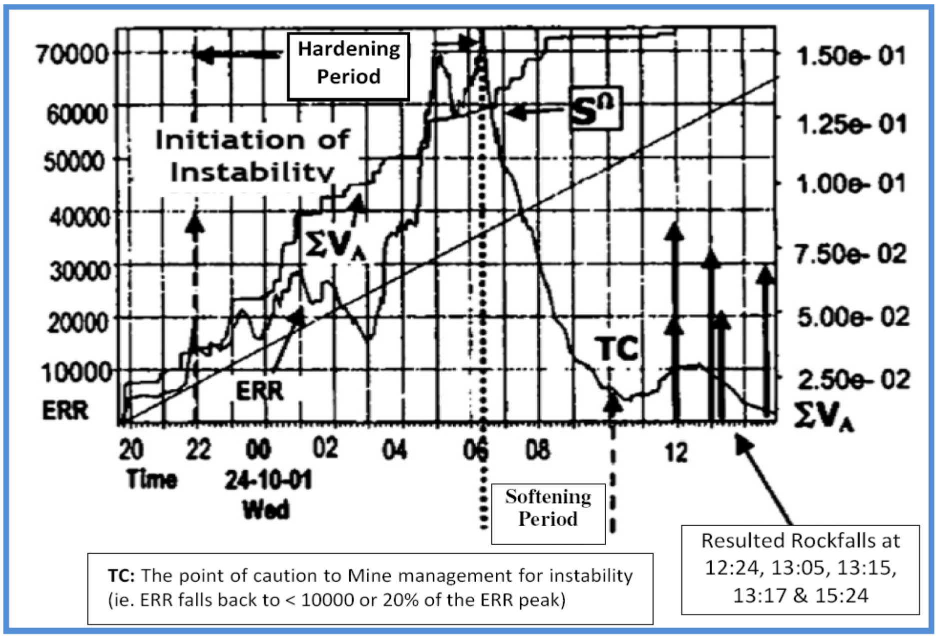
Figure 5. Plot showing the distribution of microseismic events during the month March,2002. on the plan of the Rajendra mine (length and width of the panel)

The microseismic events of different magnitude occurred from the beginning of the month to end of month is shown in blue color to red color. The initiation of fracturing process, till it resulted in roof fall has been mapped. This process helps to understand the strata behaviour below the surface during mining operation. The Figure-5 is plotted on the plan (XY) of the mine and the locations of the fractures can be seen in section (XZ). The fracturing taking place at different layers of the mine below the surface can be observed for assessing the stability of mine working.

6 Instability indicator (S^{Ω})

During the microseismic monitoring at Rajendra mines ERR scaled to number of events per month and Apparent Volume ($\sum$VA) plots (time series) of the processed microseismic data was used to derive the Empirical Potential Instability Indicator (S^{Ω}) to give seismic warning to the mine authority through daily reports indicating the estimated time of impending rockfalls and high stress zones. Among the several parameters of source parameters examined to find out stability indicator, only the ERR was found to be the most prominent parameter for short range prediction of rockmass instability. S^{Ω} was used to provide the daily roof strata condition and prior information of impending falls to the mine authority. Figure 6 shows the method of obtaining the instability indicator (S^{Ω}), with example of successful seismic event prediction time, (cautioning time-TC) and actually occurred rockfalls.

The instability indicator can be defined conventionally, as seen in the time series plot of ERR versus $\sum$V**A** for a selected time block as shown in Figure 8. A point where $\sum V_A$ intersects the ERR in a course of time before attaining peak value ($\sum V_A$). The stability indicator can be explained as a point at which the seismic hardening process of local rockmass ends and the rapid softening process begins which is an indication for instability in deforming rockmass. For practical purpose the point TC (at which ERR sharp fall touches 20% of the ERR peak or $\sum V_A$ attains maximum and become almost constant) found to be more accurate with 4-6 hours real time warning period for rooffalls. The characteristic changes in other source parameters before the occurrence of instability need to be analysed to improve the precision of $\mathbf{S^{\Omega}}$. It was found that $\mathbf{S^{\Omega}}$ is the most suitable point for issuing seismic warning. The microseismic data pertaining to rockfalls during September 2001 were analysed to obtain the threshold level of ERR for the initiation of instability process, which was found to be 10,000 events/month (scaled). This threshold level can be obtained easily during the initial stages of monitoring, which was just above the mine's background microseismic noise level.



TC: The point of caution to Mine management for instability (ie. ERR falls back to < 10000 or 20% of the ERR peak)

Resulted Rockfalls at
12:24, 13:05, 13:15,
13:17 & 15:24

Figure 6. Microseismic event release rate (scaled to events per month) and cumulative apparent volume Vs time plot showing instability indicator **(S^{Ω})** warning time point **(TC)** and rooffalls

Figure 7 show the plot of ERR Vs time for the period of 9th to 19th September 2001. It can be observed from the plot that the rockfalls (shown as arrows) were taken place after the raise and sharp fall of ERR in majority of cases. The ERR peak value, hardening and softening period vary depending on rockfall size. The ERR threshold value which is the microseismic background noise of Rajendra mine was found to be 10000 events/month.

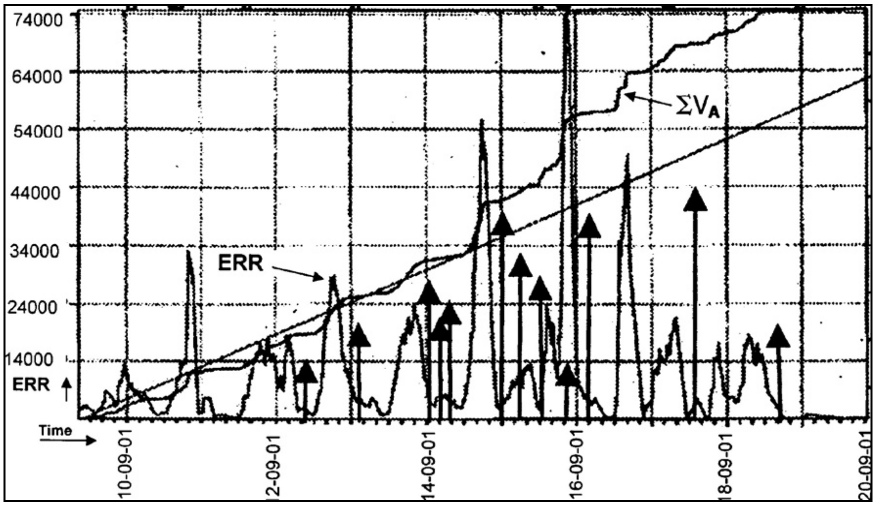


Figure 7. Time series plot of ERR & $\sum V_{\mathbf{A}}$ during 09-19 of September 2001

7 Case studies

The rooffalls taking place in the Rajendra coal mine has been classified and explained in case studies as follows. Rooffalls were devided into two catagerioes, case study one is for local rooffall events and other is for large rooffall events. Large rooffalls generelly take place inside to deep inside of the goaf in coal mine, which involves huge volome of rock and extends deep in to the roof. Whereas in case of local falls take place from immediate roof and generally takes place close to working face or in the gate roads which involves less volume volume of rock as explained in case study two. The same can be explained using ERR as follows. For a large rooffall ERR peak will be 6 to 12 times greater than the selected threshold value. In the case of local falls ERR peak will be 3 to 5 times greater than threshold value. The Hardning period was greater (6 to 10 Hours) for large rooffall than for local falls which is (3-5 Hrs).

7.1 Case study-1 (Local rooffall)

The figure 8 shows the ERR Versus time for the period of 9 November 2001,12:00 Hrs to 10 November 2001 23:59 Hrs. Many rooffalls were taken place during the period of 8th to 12th November 2001 and it resulted as Goaf pack on12th November,2001. In the figure the rooffalls shown are local rooffalls taken place before large rooffalls in the goaf. The ERR Peaks P_1, P_2 and P_3 were resulted as rooffalls RF_1, RF_2, RF_{3-4} and, RF_5 respectively. These local rooffalls took place at different locations and these locations can be obtained before the falls with the help of stress contours.

It can be observed from the figure 8 that the peaks are of 2 to 4 times of ERR threshold (10000 events per month (scaled)) and raise and fall times are very short but a lead time of 2 to 4 hours is possible for warning the instability in real time.

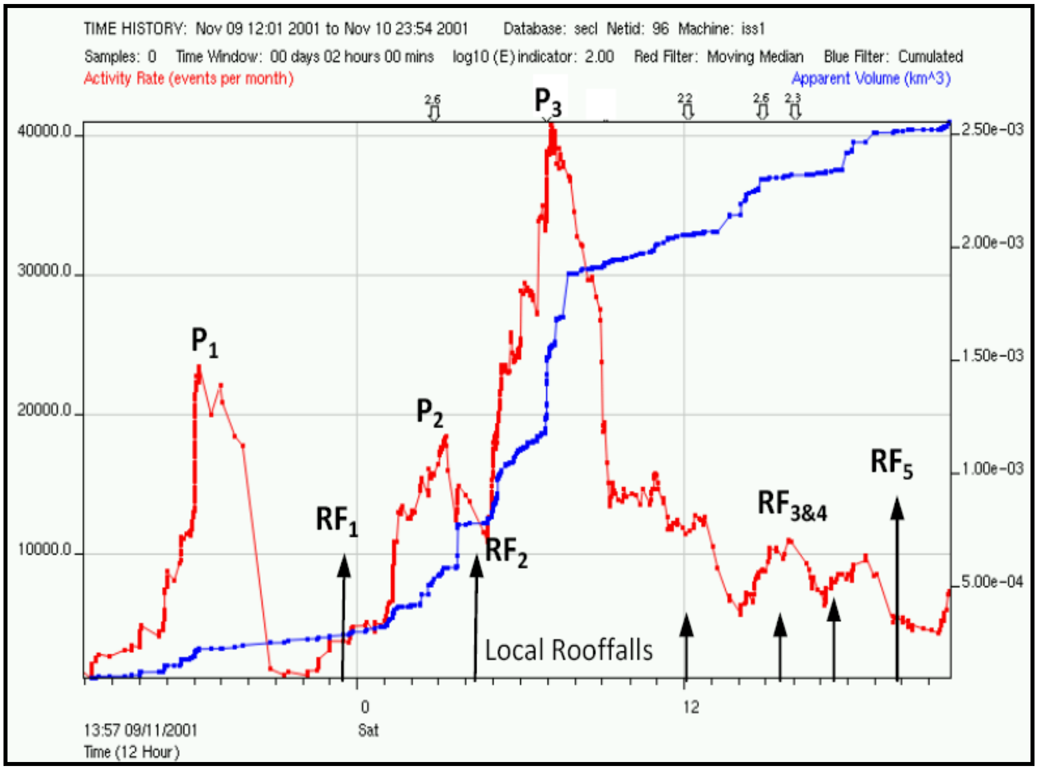


Figure 8. Time series plot of ERR & ∑V**A** during 09-10 of November 2001, showing the short range ERR peaks and resultant local falls

7.2 Case Study-2 (Large Rooffalls)

From the figure 9 shows the ERR Versus time on 23 March 2002. There are large rooffalls on 23 and 24 March 2002 . From the ERR plot it can be observed that the ERR peak attained in 10 hours (00:30 Hrs to 10:30 Hrs) and sharp fall within 1hour 30 minutes (10:00Hrs to 11:30Hrs). The sharp fall was 20% of ERR Peak value. The time of warning information point (TC) from real time was possible at 14:00 Hrs. The large rooffalls resulted between 17:00 Hrs and 18:00 hrs.

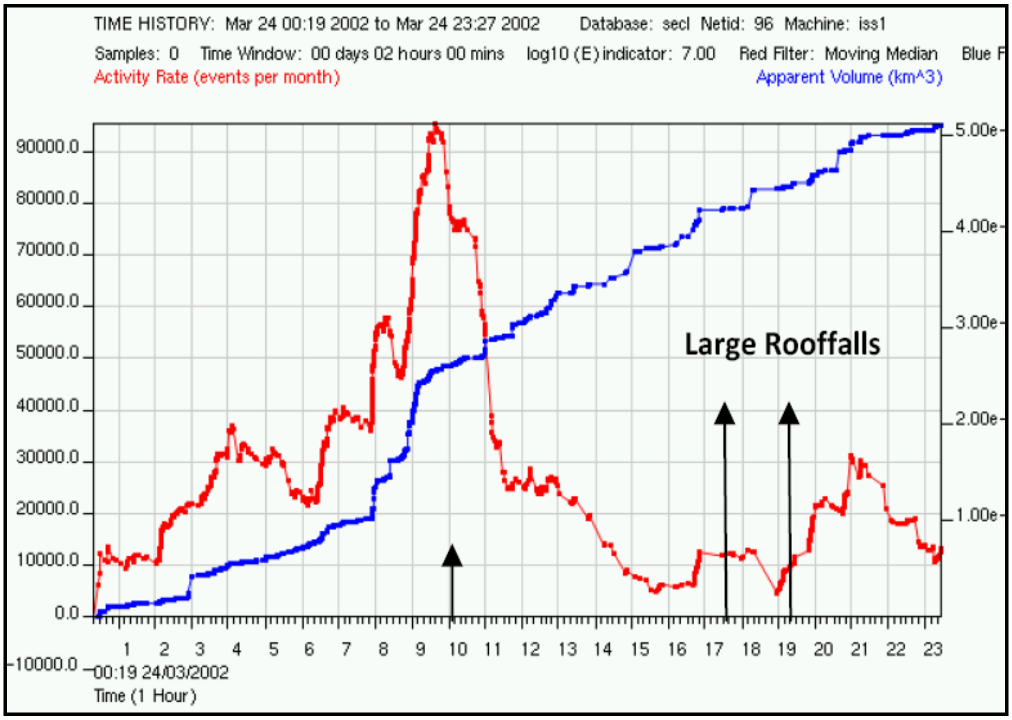


Figure 9. Time series plot of ERR & ∑V**A** during 24 March 2002, showing the long range ERR peaks and resultant large rooffalls

The figure 10 shows the ERR Vs time plot for the period of March 2002, The small peaks before 23 March resulted as the local falls (gradual rise in size of local falls) prior to the large rooffalls (major Instability) during 23 to 24 March 2002.

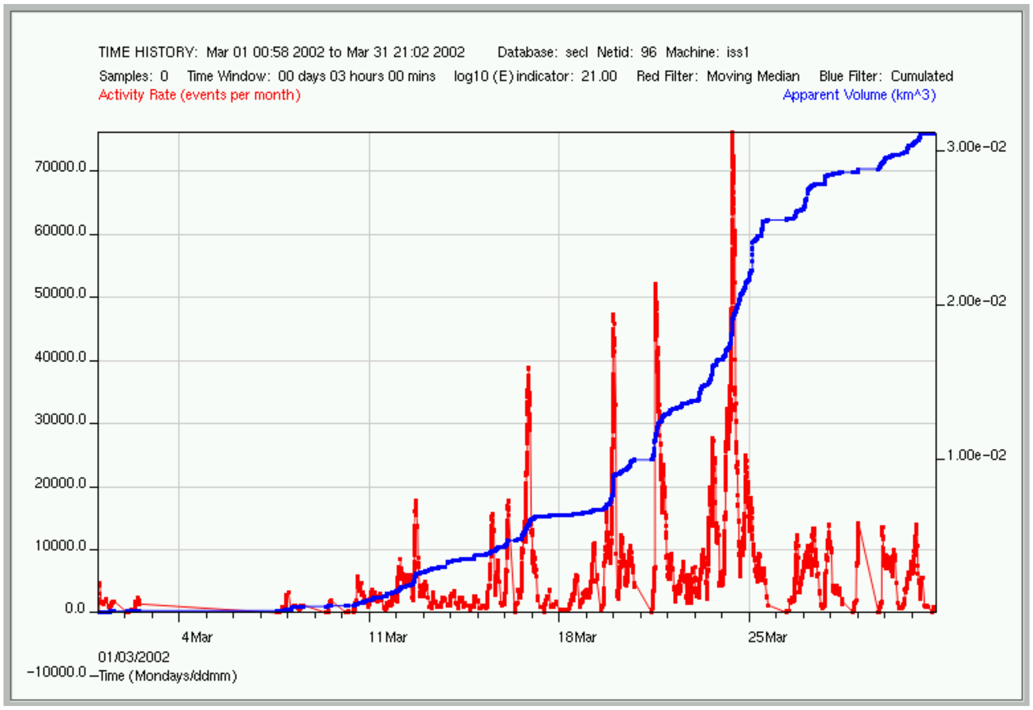


Figure 10. Plot of Microseismic event rate, ERR day wise for the month of March 2002

8 Conclusions

The microseismic investigation carried out at Rajendra underground coal mine has enabled to acquire large amount of microseismic data in real time during mining operation. The accurate source locations of microseismic events helped to identify high stress zone and in turn to carry out induced blast for distressing the high stress zone. From the waveform of microseismic events, it was possible to compute the source parameters of microseismic events, rooffalls and induced blasts. The Event Release rate and the instability factor were used to prepare daily report on day to day basis for the mine authority for assessing the stability of mine workings including forewarning the occurrence of rooffalls. Thus the real time monitoring has been successfully applied to monitor stability on mine workings and understand the geomechanics of underground mine which can be extended to other underground structures such as tunnels and LPG storage caverns.

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