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Preliminary assessment of seismic hazard in old mining area using surface mounted seismic sensors

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ABSTRACT
Seismic monitoring of the old mined-out areas of the Kolar Gold Fields is carried out for the assessment of probable seismic hazard due to the likely change of stress conditions in the underground rocks of the mine. The mining operations in these gold mines had stopped almost two decades ago. However, the occurrence of rockbursts due to failure of rockmass with increase in the depth and their stressed nature, is an inevitable consequence of the deep mining. This is apparently caused by the dynamic stress changes and these changes are always associated with generation of micro tremors, as the rocks under high stress slip, jerk or break suddenly. Monitoring the seismic signals, generated by micro tremors, gives a clue to the changing stress regime in the rock. The seismic monitoring system that is deployed for such monitoring is used to locate the source of seismic events and to demarcate potential zones of occurrence in the mining area and to further understand likely change in the stress regime of the abandoned mines. This paper focuses on preliminary assessment of the probable seismic hazard based on seismic events and their source parameters.

Key words: Seismic monitoring, Seismic events, Seismic hazard, Stress regime, Kolar gold fields.

INTRODUCTION

The well-known mines of Kolar Gold Fields (KGF) has mine workings extending as deep as 3200m. The KGF mines produced gold since 1880 till the operations stopped in the year 1995. As the mines got deeper, the energy state of the rocks changed, causing to build up of stress leading to sudden violent breaking in rockmass known as rockbursts. A series of efforts were put to establish seismic monitoring system to understand the occurrence of seismic events (Krishnamurthy et al., 1980; Arora et al., 1981). Accordingly, first seismic monitoring system for investigation was set up in 1978. As the time progressed, seismic events were recorded and used for assessing the stability of mine workings for over two decades. Later, with the decrease of mining activities, the mines remained abandoned for a significantly long time. It was observed previously that groundwater began swelling in the deeper mines with time and there have been some reported instances (Srinivasan et al., 2000) of effect of water on the state of stress due to combined influence of fluid in major joints, nearby contact at the Mysore North Fault, particularly during increasing and decreasing water level in the mines. However, the release of stress accumulated in the rocks due to gradual failure of supports, presence of water in the mines and lack of adequate mine reclamation measures continued to be factor for cause of regular seismic events witnessed in the area. Thus, in order to evaluate seismic hazard due to seismic events originating in the old underground mines, seismic monitoring of the gold field has been undertaken.

GEOLOGY OF THE KGF MINING AREA

The mining area of KGF is located at 12^0 57′N and $78^0$16′E lying at around 100 km east of Bangalore. It has an altitude of 900 m above mean sea level. The mining region lies in the Kolar Schist Belt of the Dharwar Craton of southern peninsular Indian shield. The Kolar Schist belt is about 8 km long and 4 km wide in the north-south and west-east direction respectively. Three mines, the Nundydroog Mine, Champion Reef Mine and Mysore Mine, are located on the Kolar schist belt, along a strike length of 8 km. The mining region also consists of three fault systems. The major one, the prominent Mysore North Fault (MNF), striking northwest-southeast while the other two, are minor ones (Tennant Fault and Gifford Fault), running sub parallel to MNF (Srinivasan et al., 2012). Figure 1 shows the geology and seismic monitoring stations in the mining area.

SEISMIC HAZARD DUE TO INDUCED SEISMICITY IN MINES

Stress related rock deformations and associated problems do occur in mines all around the world (Krishnamurthy and Nagarajan 1981; Kijko and Funk, 1994; Srinivasan et al., 2009). This is apparently due to the change in the state of equilibrium setting in a rockmass, termed as perturbation, caused by excavation. The extent of perturbation alone is sometimes enough to generate the significant change in the stress condition of rockmass and the energy accumulated in the rocks get released suddenly in the form of micro of tremors in the surrounding.

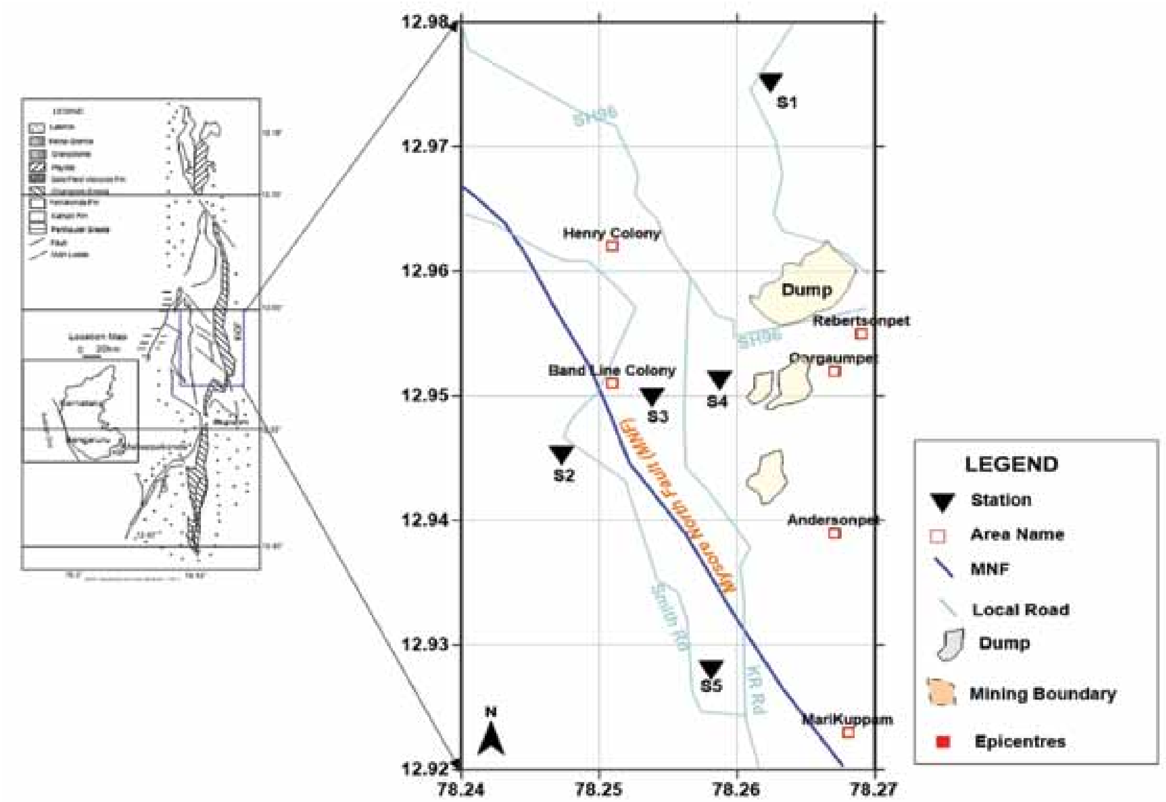

Figure 1. Plan map of geology of Kolar Gold Fields mining area (inset, left) (Srinivasan et al. 2012) and schematic layout of seismic sensors in the mining area (right).

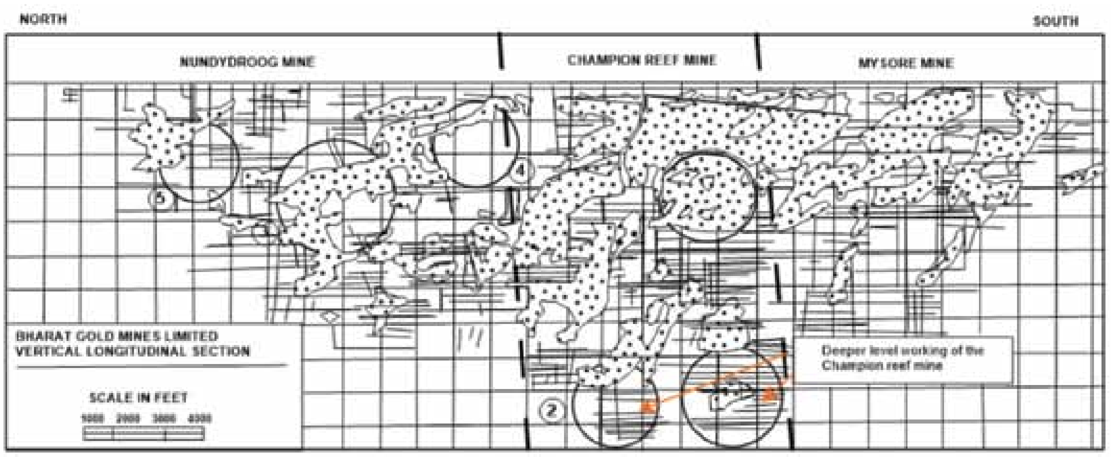

Figure 2. Longitudinal section of KGF mines with three mining zones. The numbers indicated therein are mine markers.

Although, tectonic condition in the subcontinent is relatively stable, there might be some effects of stress changes in the mines due to tectonic forces, probably over much longer period on the regional level, however, they may not have significant impact on the state of stress as observed over a finite time window during which the seismic hazard is assessed. Therefore, in this paper the effect of stress changes and subsequent seismic events in the local mining area alone is considered. The events were relatively large in number more than a decade ago and in the recent times, there has been few rockbursts. However, in view occurrence of micro seismic events causing safety concerns in and around the mining area, and stray incidences of subsidence or caving of earth, the seismic monitoring has become important. Figure 2 depicts the seismic section in the north to south direction, consisting of three major mining zones of the Kolar Gold Field mines. The deepest among the three mining zones is in the central part namely Champion Reefs mine.

Effect of groundwater or inundation of mines in mines around the world have also been reported in various works (Board et al., 1992; Wetmiller et al., 1993). In Falconbridge Mine, Canada, once the mine operations ceased, seismic events with magnitude greater than 3 were recorded. Board (1992) and McGarr (2002) also carried out a real time simulation by injecting water along a fault surface in deep level mines, where increase in pore pressure and small-scale (magnitude) seismicity has further been recorded. As cited before, one of the possible factors that could have lead to occurrence of seismic events are discontinuation of dewatering that lead to increase in mine water level, regular seepage, collection and gradual spreading of water through spaces or weak zones (Srinivasan et al., 2000). The seismic events in the KGF mines are also suspected to have been triggered by fluid-induced effects like percolation into pre-existing joint spaces, faults and zones of structural weakness, thereby increasing the pore pressure (McGarr et al., 2002). Such a possibility synchronised with increase in the number of seismic events observed during a time window, as supported by the hypocentres of the seismic events were found to be occurring around the water-level in the mines. Seismic sources were found to be clustering around the Mysore North fault (MNF) (Srinivasan et al., 2013; Jennifer et al., 2016) and the scale of seismic events recorded with local magnitudes in the range of -1.6 to 3.1 The seismic events of the mines are so low, that they are akin to treating them as micro-earthquakes and such seismicity refers to discrete rock-deformation events, analogous to tiny earthquakes, which are generally of moment magnitude <0 (M. Hudyma et al., 2004). These events are linked to small seismic events (microseismic) at low end to micro-earthquakes at high end. In the following section, monitoring of seismic events in the old mining area carried out using an array of seismic sensors is described.

DATA ACQUISITION

The surface seismic sensors used in this seismic network are portable triaxial geophone (GeoSIG make) with short period and wide frequency range. The sensor has housing and is mounted on a base plate. Once the base plate is levelled as per specification, the instrument can be replaced on the base plate without need for further levelling. The sensor housing has provision for GPS, ethernet and power from mains and in-built battery. The location of sensors was so chosen as to monitor the old mining area covering underground excavation limits, availability of power and safety of instruments. The signal-to-noise ratio (SNR) has been observed to generally good (10dB) for shallow events with relatively higher magnitude >0. For smaller events noise could be seen above 25Hz signal. In general, moderate SNR has been observed due to greater depth of the mine workings and hence there was a possibility surface noises tending to dominate weaker seismic events signals. Frequency filtering considerably improved the SNR.

A set of five triaxial geophones are installed as part of the seismic network. The sensors used in this work are three component velocity geophones, installed with a portable power source and a GPS receiver. The triaxial geophones network system was put in continuous operation, covering the mining area, for round the clock monitoring of seismic events in the old mining area stretching about 6km long (N-S) and 2km wide (E-W). The instruments are setup and the seismic events are monitored continuously to enumerate, classify and analyse the seismic signals based on their pattern, strength and frequency. The layout of seismic network installed for the monitoring is as shown in Figure 1 (right). The details of the triaxial sensors are as given below.

Frequency Band	: 4.5 – 315 Hz
Geophone type	: Triaxial (N, E and Z)
Sensivitiy	: 27.3 Vs/m
Dynamic range	: > 96dB
Seismic Data	: Continuous and Triggered
Data Storage	: Memory card
Communication	: GSM network based
Format	: miniSEED
Processing Software	: SEISAN and GeoDAS

Data processing

The raw micro seismic data were checked for processing. For the consistency of picking of P and S-wave arrivals, its amplitudes, wave form duration and event location detection were done over number of seismic stations. Only those signals that were detected by at least three seismic stations were basically considered for processing. Data processing and analysis of the acquired signal was carried out using SEISAN (Figure 3). During processing noise components were filtered using bandpass filtering. The frequency band applied for filtering are in the range of 4-20Hz. Majority of the signals were found to have predominant frequencies in the low frequency range of 5-15Hz. The representative dominant frequency spectrum of the signals is given in Figure 4. The signals consist of many frequencies riding on the actual desired signal in the form of noise.

Noisy signals were thoroughly studied, and the noises were filtered out. P and S time arrivals were picked up (Figure 3) from the signals. In a few cases, only P- wave arrivals could be seen while the S-wave was masked by the noise. All the picking and computation were done using SEISAN software. The objective of the study is to find out source of shallow level events instead of the conventional practice of homogeneous velocity model (5500m/s). In addition, a comparative analysis was also done with an assumed increasing velocity model (apriori) from surface to

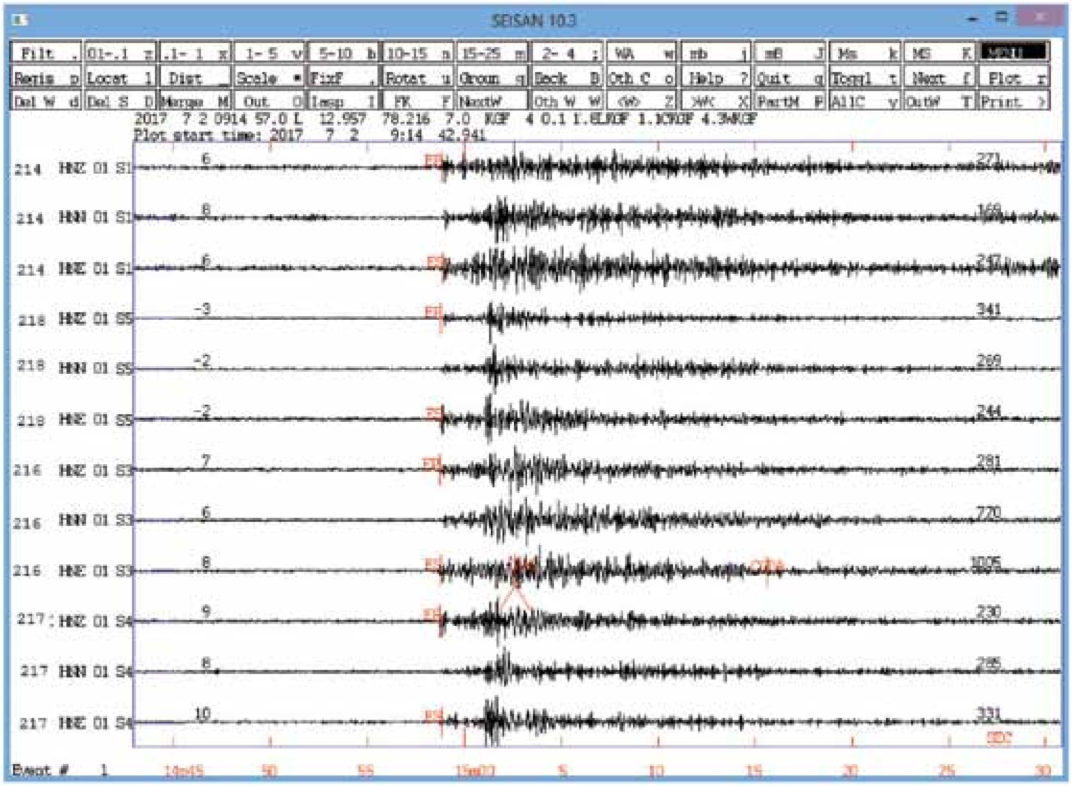

Figure 3. Data processing screenshot showing P and S pick at seismic stations.

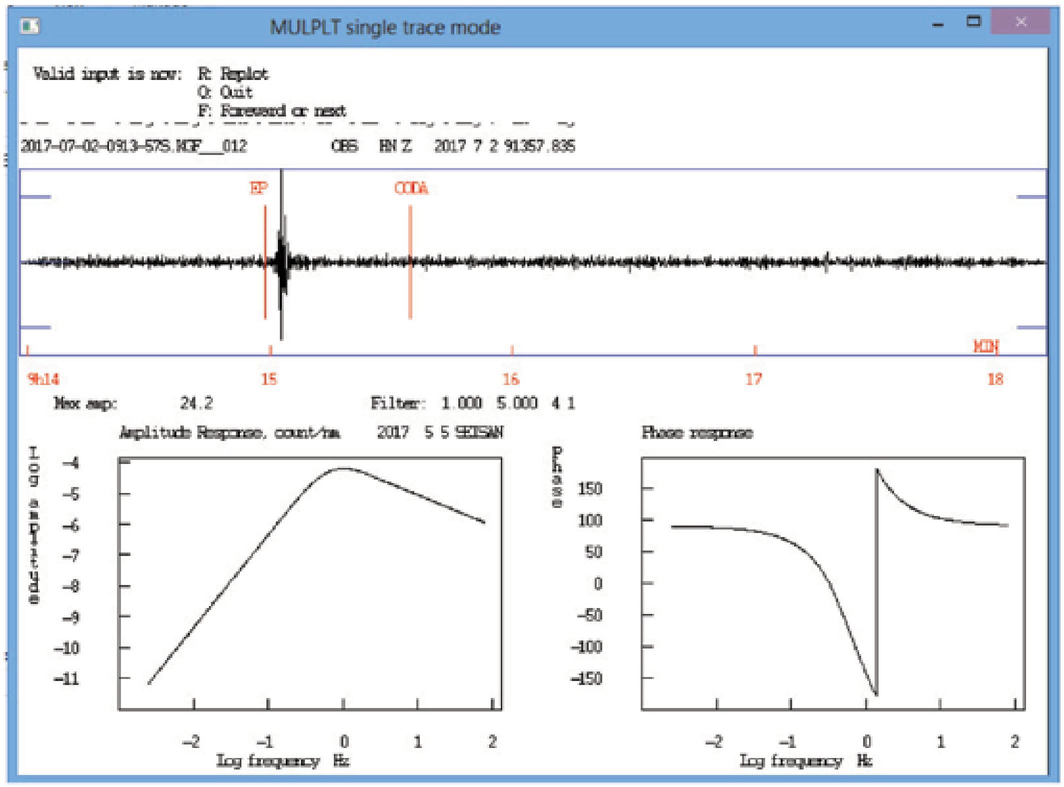

Figure 4. Frequency spectrum of the seismic event at S3.

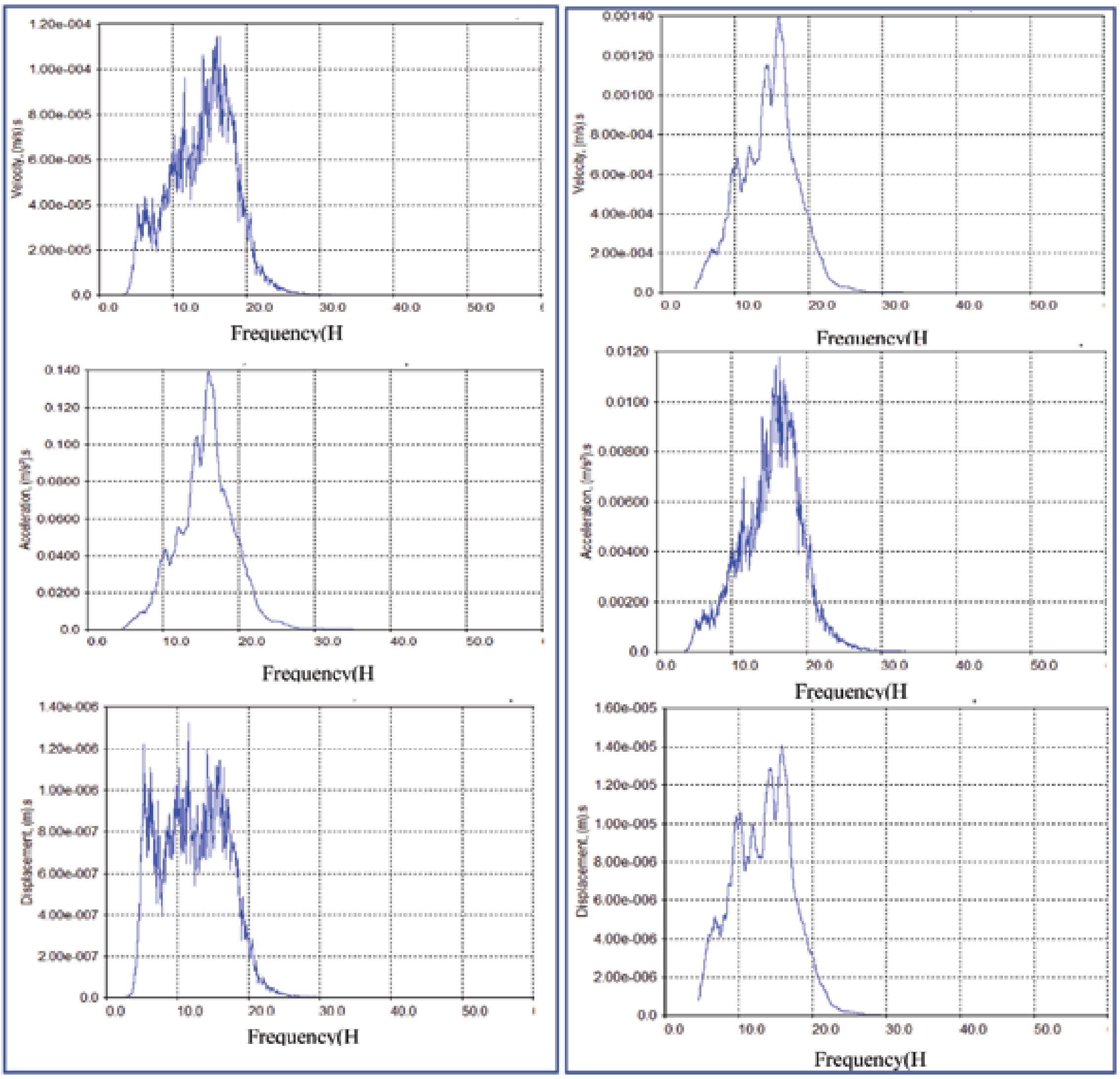

Figure 5. Frequency and FFT domains of different magnitudes (Mc) of rockburst event at KGF.

depth of the mines were considered in the processing. Thus, the initial average velocity was pegged at 4800 increasing to 5500 m/s (Srinivasan et al, 1995, NIRM Report).

All the picked-up signals were given as input into the magnitude computation routine of the computation software along with the response file specific to the triaxial sensors. Magnitudes are calculated using maximum amplitude of the vertical component. The coda length was also computed using the waveform window. The local magnitude and coda are directly influenced by the amplitude of the seismic wave and the proper choice of the time window covering the waveform representing the event.

Spectral amplitudes of seismic data (Figure 5) from mine induced seismic event (rockburst) seismograms are used to compare the site response. Spectral ratios are from horizontal to vertical component (H/V) following Nakamura's technique (Nakamura, 1989). The response at the sites was examined using the ratio technique. H/V ratios would not be effective in estimating the ground shaking hazard over a region of widely varying geology. But in this case, the spectral ratios are obtained over underground mines characterised predominantly with gneissic rocks. Thus, the frequencies of the H/V ratios agreed with the local geology.

Table 1 gives an example of two noticeable rockburst that occurred on 19.11.2017 at 07:09:26.2 hrs of KGF 1.9km EW and 14.12.2017 at 18:11:28.5 hrs in the old abandoned mines of KGF 1km NE quadrant from the observatory (S3) station. H/V spectral ratios were considered only on above parameters, like predominant frequencies, amplifications and velocity, and accelerations due to small ground motions.

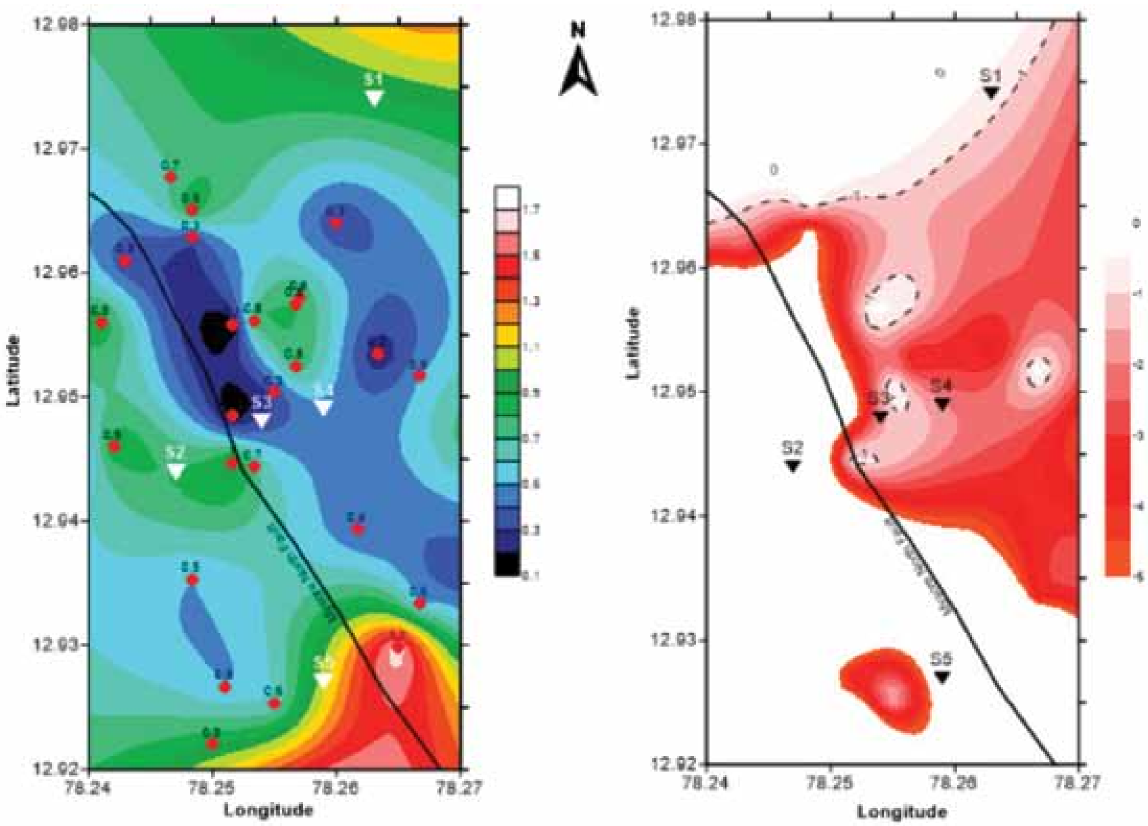

Figure 6. Spatial distribution of magnitude in the proximity of seismic stations (left) and hypo-central distribution of the events in the mining area. There shallow zones earmarked with dotted lines in the central part of the mining area can be seen (right).

Table 1. Example of two events spectral parameters

Event parameters	19.11.2017	14.12.2017
Magnitude (Mc)	-0.3	0.5
Maximum Velocity(ms^{-1})	0.00140	1.15e-004
Maximum Acceleration(ms^{-2})	0.139	0.0118
Maximum Displacement(m)	1.4e-005	1.33e-006
Predominant Frequency (Hz)	15.8	16.5
Peak Amplitude(ms^{-1})	0.1445	0.1075

PRELIMINARY RESULTS

During the period from July 2017 to December 2017, seismic events totalling 44 were recorded by the seismic network. Comparing and analysing them for their seismic signature, P-wave and S-wave arrival times, presence of noisy components, time of arrival at all the stations, as many as 14 events were discarded as they were not related to mine induced seismic events orginating form the old mines' rock movements or stress changes in the underground mining regime. The remaining 30 events were taken up for phase picking and source parameter computation. Distinct and umambigous P-wave arrivals and S-wave arrivals were used for computing local magnitude.

The local magnitude of some of the events were found to vary quite widely and hence not considered in this work for further analysis and interpretation. Thus, during analysis another 8 more events were filtered out, rendering the number of events as 22 only. In view of the wide variation, only the waveform magnitude (CODA) were considered that ranged from 0.1–1.8. The events were located between surface and upto a depth of 2km. These events found to concentrate around the central and eastern portion of the monitoring zone.

On the overall mining map, these event fall under the central part of the mining area. This area has several old structures most of which are being used as dwellings now, railway lines and old mining dumps. The distribution of

Table 2. Monthly summary of the seismic events identified and their location.

Month	Events	Depth Range(km)	Distance(km)	Magnitude (CODA)
Jul-17	6	0.10 to 0.90	1.30 to 2.98	0.10 to 1.70
Aug-17	2	Up to 01	1.20 to 2.60	0.10 to 0.60
Sep-17	3	0.10 to 1.90	0.90 to 2.10	0.10 to 0.80
Oct-17	6	0.10 to 0.40	0.25 to 2.30	0.10 to 1.00
Nov-17	2	0.30 to 1.60	0.22 to 1.61	0.30 to 2.20
Dec-17	3	0.10 to 1.80	1.75 to 2.41	0.10 to 1.40

Table 3. Example of some events source parameters from the spectral analysis of the displacement seismographs in the area.

S. No	Date	Latitude (Deg)	Longitude (Deg)	Time (IST)	Stress Drop (Bars)	Moment Magnitude (MW)	Corner Frequency (Hz)
1	05-07-17	12.958	78.257	1130 42.55	332.8	3.269	8.860
2	30-07-17	12.961	78.243	1921 25.73	130.1	3.301	6.238
3	03-08-17	12.939	78.262	1848 18.81	157.8	3.302	7.459
4	01-10-17	12.970	78.245	1838 15.10	393.9	3.814	8.084
5	16-10-17	12.952	78.267	0808 42.19	878.3	4.223	6.592
6	19-11-17	12.950	78.255	0709 26.22	91.10	3.370	8.266
7	25-11-17	12.939	78.267	18 16 16.40	551.7	3.451	8.450
8	09-12-17	12.963	78.248	18 14 40.92	752.3	3.518	9.748
9	14-12-17	12.939	78.269	18 11 28.00	865.7	3.562	8.690
10	30-12-17	12.942	78.268	18 10 29.50	818.4	3.507	9.094

events are identified on the ground and most of them lying on the eastern side of the MNF have been found to coincide with older workings. There have been very less number of events on the western side of the MNF, apparently this area does not have very deep seated mine workings. The preliminary analysis has brought out the size of the seismic events and the approximate hyprocentral location. The seismic data is being subjected to further deep analysis in order to ascertain the source parameters.

The Table 2 gives a representative summary of the seismic events, that occurred over a period of six months of seismic monitoring, with their distances and depths along with their direction with respect to the central point at KGF observatory. Based on the period of study taken up for analysis of the seismic events, the total no of recorded seismic events during this period sums up to 30 events were finalized from 44 nos.

Going by their location most of the events appear to fall well within the mining zone. However, as per the initial seismic event parameters obtained in this preliminary analysis, their depth(>500) and the magnitude of most these events gives an indication of no significant and immediate hazard due to shallower events. This observation also agrees with fact that there has been absence of any major seismic event felt at surface during the period of analysis.

The micro seismic data have been used to compute the source parameters of mine induced rockbursts. Analysis of these events (Table 3) revealed that the stress drop varied between 91.10 and 878.3 bars, seismic moment between 3.269 and 4.223 and average corner frequency between 6.238 and 9.748 Hz. The results of the source parameters of the old mining induced rockbursts completely agree with corresponding results for natural earthquakes. Thus, the KGF rockbursts are generated by a similar mechanism to the Konya dam earthquakes. Both may be of triggered nature due to pore-pressure diffusion (Srinivasan et al., 2009).

DISCUSSION

Based on the above results, the number of seismic events or the rate of seismic events, serve as an indicator for potential hazard to the structures closer to the event locations. In addition, the initial seismic hazard scenario has been arrived at based on their magnitude and depth of occurrence (Srinivasan et al., 2010). As number and magnitude alone do not help effectively to quantify seismic hazard (Kijko and Funk, 1994), further analysis is being carried out to derive more source parameters and unambiguously quantify the seismic hazard. In this paper, the scope of results is limited to assessment based on magnitude and location of events.

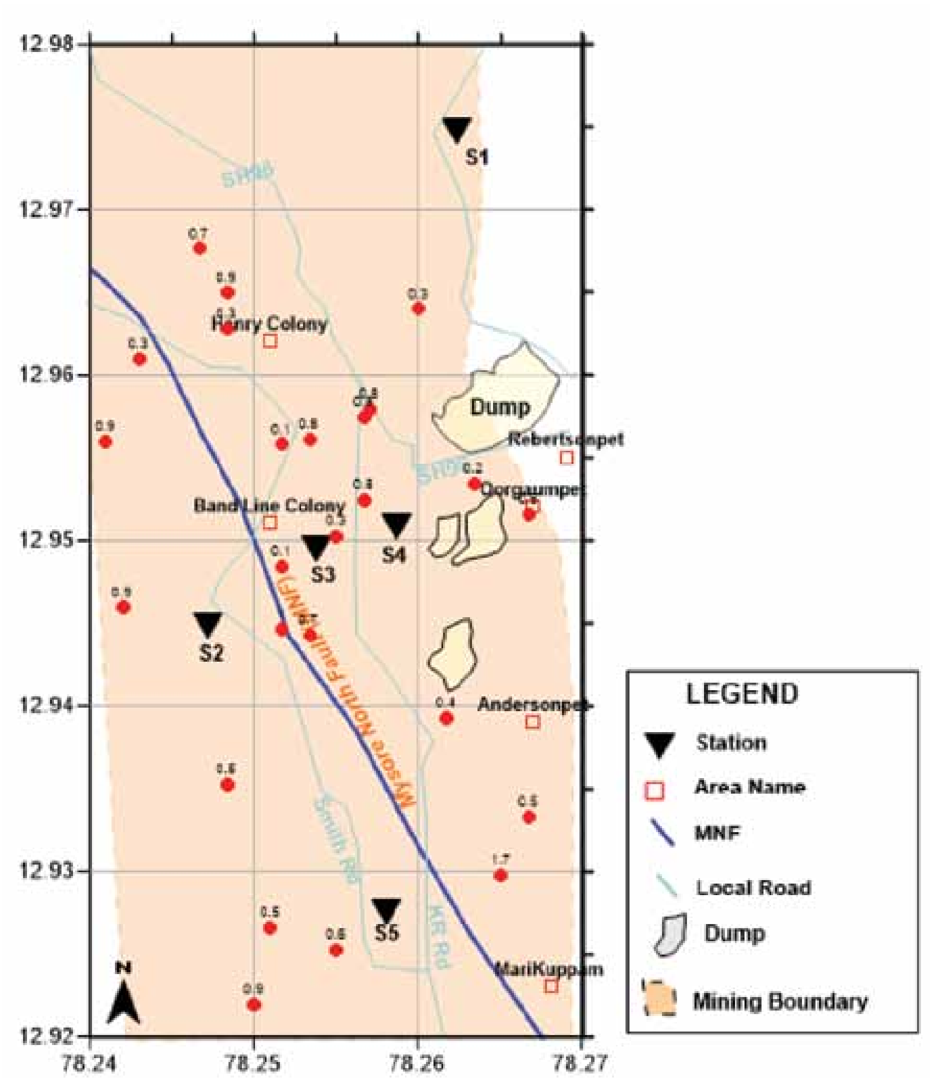

Figure 7. Spatial distribution of the seismic events in the mining area in the backdrop of the seismic network and the MNF.

The seismic observations indicate that seismic events have been more on the eastern side of the MNF than on its western side. The identified events are rather scattered over the mining area and like previous cases there is also no clear indication of these events clustering close to the fault line. They are plotted in the backdrop of the mining area plan (Figure 7) with major features indicated therein. H/V Spectral ratio estimation shows predominant frequency varying from 15.8 to 16.5 Hz with amplitudes are 0.1445 to 0.1075 ms^{-1} respectively.

From the past literature (NIRM seismic records and technical reports, 1991 to 2013), seismic events with magnitude as high as 4 and as low as 0.5 have been noticed in the radial distance range of 1-4 km from the recording station at seismic observatory (S3) and more number of events were reported within the epicentral radius of 1 km with respect to the observatory (S3). At farther distances, the events have been either sparse or scattered. On the overall, the events have be found to have reduced in number (Jennifer et al., 2016) and there has been no significantly high magnitude event in the recent past.

From the analysis the recently recorded events, the seismic events have been found to fall in the 0-2km depth range. The epicentral locations of these events have been found to lie within 0.2 to 3km from the seismic observatory at S3. The magnitude of these events is in the range of 0.1-2.2.

The shallower and low magnitude events have been found to be in the top 1km range. Higher magnitude events are relatively deep seated. Still, further analysis of the data is in progress to identify source parameters of shallower events (~500m) that could pose some threat to safety and stability to structures at surface in efforts quantify the actual potential hazard due to these old mines.

CONCLUSION

Based on the analysis of the seismic data acquired, there are indications of events occurring in the top 1km of mining regime. There are very few events recorded deeper than this depth. Epicentral location of most of the events are found be lying in the old mining area or within the mine lease boundary. The locations in the first analysis are quite encouraging as they fall with in the mining area. However, further deeper analysis with phase rotation, amplitude and frequency window might bring better accuracy of the event locations. Once this is done further parameters like energy released, stress drop, peak ground velocity at source etc can be computed for understanding actual scenario of stress concentration in the abandoned mines and the related seismic hazard. The predominant frequency of majority of events is 20Hz which is due to the site effect where seismograph installed. The micro seismic data has been adequate to estimate the H/V spectral ratios and can be utilized for hazard zonation studies. This qualitative preliminary analysis is based on number of events over a period, their magnitude above certain threshold value, depth and their concentration or distribution, is an indicator of probable potential hazard due to the seismic events. The other source parameters like energy released and frequency of vibration at surface, peak ground velocity would further help quantify the seismic hazard.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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