Stability analysis of a closed underground hard rock metal mine using Finite Element Method

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Abstract

Active deep hard rock metal mines with long mining history come with inherent problems of stability and mining induced issues. These hard rock mines once closed, still pose even greater environmental risks and stability concerns. The issues of post-mining impact on environment are usually undervalued and disregarded. It is very essential to give utmost importance to these mines by following standard mine closure methods and remediations using post-mining management plans for long-term monitoring and risk assessments associated with the mine for the safety of life and structures above.

The area identified for the study is Kolar Gold Fields mine located in Karnataka, India. The mine was completely closed in 2000. The underground mine has been posing post-mining induced seismicity even today. Due to the complexity of the underground mine and the inaccessibility to the mine post closure, the Finite Element Method of approach has been used. The approach is developed to simulate a model similar to actual field conditions, subjecting them to the seismic loads, varying the parameters which play a significant role, assessing the entire Kolar Gold Fields mines for vulnerable zones subjected to post-mining induced effects and finally making it possible to evaluate the stability conditions of the deep hard rock underground metal mine.

The simulations were carried out for the three cases with varying the peak ground acceleration (PGA) for a low PGA of 0.06g, for an intermediate PGA of 0.1g and high value of 0.2g. It can be inferred that as the acceleration is increased from 0.06g to 0.22g, there is a corresponding increase in ground acceleration observed at the ground surface for each case. The maximum acceleration for PGA of 0.06g is 0.071g, for PGA of 0.10g, it is 0.170g and for PGA of 0.22g it is 0.266g. The results were validated with the field observations (data of seismicity from installed seismic monitoring systems). The Finite Element Method of approach has aided in quick assessment of stability of the underground closed mine.

Keywords: Mine closure, post-mining, risk assessments, finite element method, seismic load, vulnerable zones.

Introduction

Several kinds of potential risks persist in the long term especially after a mine closure. The post mining induced effects presented by a closed mine seem to be quite similar from one country to another. They usually result in surface instabilities directly affecting loss of life and property. Sometimes closures can result in loss of jobs for the people of the locality and loss in economic development.

The progressive changes and developments have contributed to closure of old mining sites all over the world. Some countries have seen the complete disappearance of the mining industry also. In countries like Japan, there are around 6,000 inactive or closed mines (metallic and non-metallic mines). In Poland, about one-third of the collieries (zinc and lead) have been closed. There are around 1000 to 1500 post- mining sites in southern part of Poland. In Turkey some mercury mines were closed due to environmental issues. In Korea, a total of 1082 metallic mines were closed/abandoned[2]. In every country, the first objective should be to identify the suspected risks on a long-term basis in-order to prevent the local inhabitants using the areas affected by post-mining damages.

The area identified for the study is Kolar Gold Fields mine located in Karnataka, India. The mine has a history of being one of the deepest hard rocks underground metal mine with a mining depth of 3.2 km. Due to depletion of resources and availability of low grade of ore body, the mining in the deeper levels was discontinued in 1991. Mine was completely closed in 2000. The underground mine has been posing post-mining induced seismicity even today.

This study presents a finite element method (FEM) of analysis to investigate the influence of post mining-induced seismicity on the rockmass, the underground excavations and the tectonics of the mining area using implicit dynamic integration approach. The dynamic analysis approach is being used as it involves mining-induced seismic event to be applied equivalent to that of an earthquake (seismic) load but of a shorter duration and high frequency. In the analysis, the constitutive behaviour is taken as elastic and time-dependent.

Material and Methods

Study area: The area of study is part of the long linear kolar schist belt of the Archean greenstone belt of Karnataka. The Kolar Gold Fields (KGF) mines lie at southern end of the schist belt. The mining area mainly comprises of the most prominent hornblende schist and peninsular gneiss formations. The Kolar schist belt runs around 80 km along the North-South direction and about 4 km along the East-West direction. The general trend of the foliation is North-South to NNE-SSW with 30^0 at surface to 85^0 westerly dip in the deeper levels of the mine[6]. The Champion lode is a fissure filled ore body made up of several ore shoots of different dimensions. The Champion lode though dips towards the west, the dip varies at different depths. The host rock is hornblende schist with Champion gneiss for this gold bearing lodes.

The gold deposits occur in the Precambrian greenstones belt of Eastern Dharwar Craton. There are four major reefs mined for gold in the area which occur almost parallel to each other and trend in the North-South direction. The geotechnical setting of the underground mine comprises of prominent zones of faults, folds, shear zones, fractures, dykes and joints.

The identified Kolar Gold Fields mining area is bound by latitudes 12.92^0 N to 12.98^0 N and longitudes 78.24^0 E to 78.27^0 E at an altitude of 900 m above the mean sea level (MSL) (Fig. 1). The gold mines have three major mines in the mining region, the Nundydroog Mine in the north, Champion Reef Mine in central and Mysore Mine in the south. The three major geological fault systems identified in this mining region are, the prominent Mysore North Fault (MNF), striking NW-SE right through the centre of the region and the other two identified faults are minor faults running sub parallel to MNF, Tennant Fault and Gifford Fault[7,10].

Mining method: The gold reefs were accessed by three compartment shafts and developed up to levels at vertical interval of 30m. The drives were around 3 sqm and shafts were 7 sqm in area with rectangular/circular openings. The predominantly used method of mining in Kolar Gold Fields mines was the long hole open stopping method. With increasing depth, mechanized cut and fill method was implemented in all the production levels till the mines were completely closed. The stopes/ mine voids were significantly large occupying major part of the ore body/zones. The stopes are longitudinally laid and were filled by using sand/cement fills. The height of the stopes varies depending on the full length of ore body and on local conditions.

In the last stages, the pillars (made up of waste and low grade ore) were mined and backfilled with rock waste. The mining area includes huge mine dumps and mill tailings terraced upto a height of around 30 m. The support system comprised of swellex rock bolts used as regular support and grouted anchors in critical locations. For long term stability, extensive cable bolting was done. Mining activity was completely stopped by 2000[7].

Numerical Model: The entire stretch between Ribblesdales shaft and Haines shaft lying between 12.92^{0}N-12.98^{0}N and 78.24^{0}E - 78.27^{0}E with 70% stoped out workings (mine voids) is being considered for modelling. For analysis, the 3D Finite Element tool GTS NX is used. The generated 3D model of the entire mining area includes the geology, geotechnical details, faults (Mysore North Fault and Tennant's Fault), the mine voids and the hydrological details (Fig. 2). The dimension of the modelled area is 6.72 km x 3.36 km x 3.5 km. The geological details are from geological plan of Kolar Gold Fields from Survey Dept. 1956.

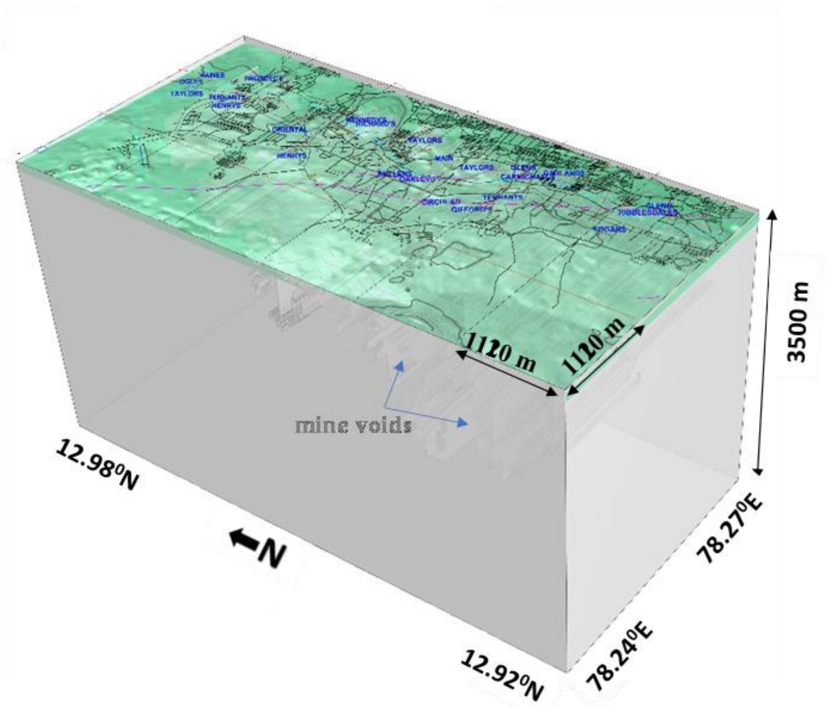


Fig. 1: 3D view of Kolar Gold Fields mining area[8]

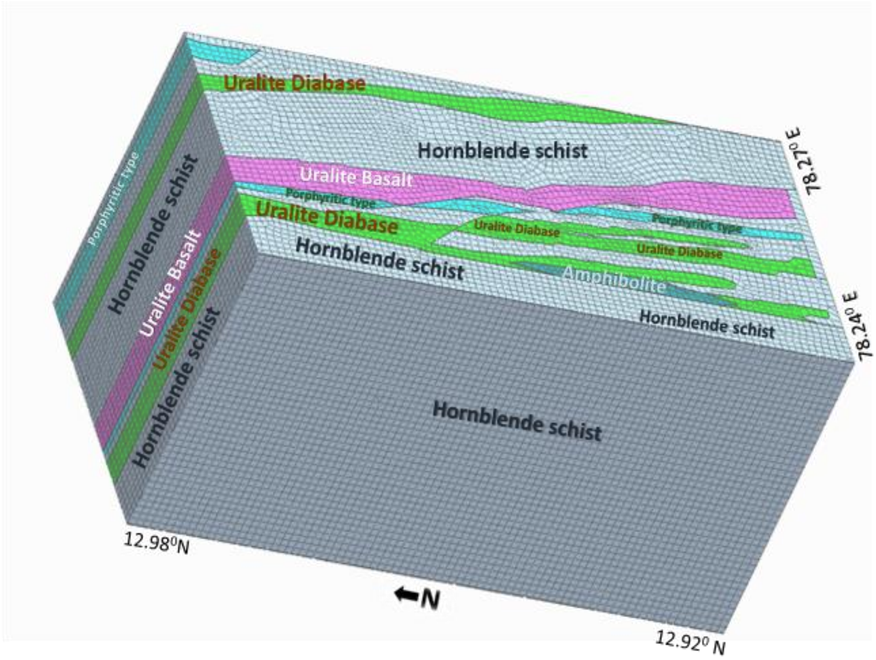


Fig. 2: 3D model of entire mining area showing geology

Table 1
Material properties defined in the model

Material properties	Elastic Modulus x 10^7 (kN/m^2)	Unit Weight (kN/m^3)	GSI	Intact Rock Parameter	mb	s	a	Uniaxial Comp. Strength (kN/m^2)
Uralite Diabase	8.54	28.63	40	7	0.1968	0.00011	0.5114	87377
Porphyritic type	6.82	26.68	45	30	1.1359	0.00024	0.5081	166713
Uralite Basalt	9.36	29.61	40	17	0.4780	0.00011	0.5114	294200
Hornblende Schist	8.26	29.62	30	4	0.0620	0.00002	0.5223	152199
Amphibolite	8.40	29.40	40	25	0.7028	0.00011	0.5113	196133

The Generalized Hoek Brown constitutive continuum behaviour is used to study the stability of the modelled area subjected to different seismic loads. This stress decrease phenomenon is considered as per jointed rock mass. The input data for rock masses is required for the analyses of underground excavations in hard rock; the non-linear Generalized Hoek-Brown criterion is used. The criterion defines material strength, other constants and parameters like m_b, s and a related to the geological strength index (GSI) and the disturbance factor(D).

The physico-mechanical material properties used as inputs are uniaxial compressive strength, elastic modulus, triaxial properties, unit weight etc. The properties are laboratory tested values of Kolar Gold Fields mine location (study area) from Geological Survey of India (GSI) report [6]. Based on laboratory test results, the intact rock and GSI parameters were decided using the Hoek and Brown[3]. Table 1 shows the non-linear and elastic properties used in the model.

An artificial earthquake generation approach[4] is used to generate the seismic load. The power spectral density of design spectrum is used as expected maximum response. The parameter of Peak Ground Acceleration (PGA) of the highest magnitude seismic event experienced in the mining area is being used to simulate a real earthquake with parameters equal to that of the seismic event. An Eigen value iterative process is run to match the target spectrum. The design spectrum of the Kolar Gold Fields area is considered according to IS 1893 (2002).

The response spectrum is converted to acceleration time history. The maximum, intermediate and minimum accelerations of 0.22g, 0.10g and 0.06g are being considered based on the previous ground motion studies related to Kolar Gold Fields mining area[9] (Fig. 3).

On application of seismic load, both surface and body waves travel over an infinite medium. The infinite medium is simulated by assigning viscous boundaries. The viscous boundary also helps in eliminating the reflected waves. The stiffness of the viscous springs and damping constants are calculated as per Lysmer and Kuhlmeyer[5] and modulus of subgrade reaction approaches respectively.

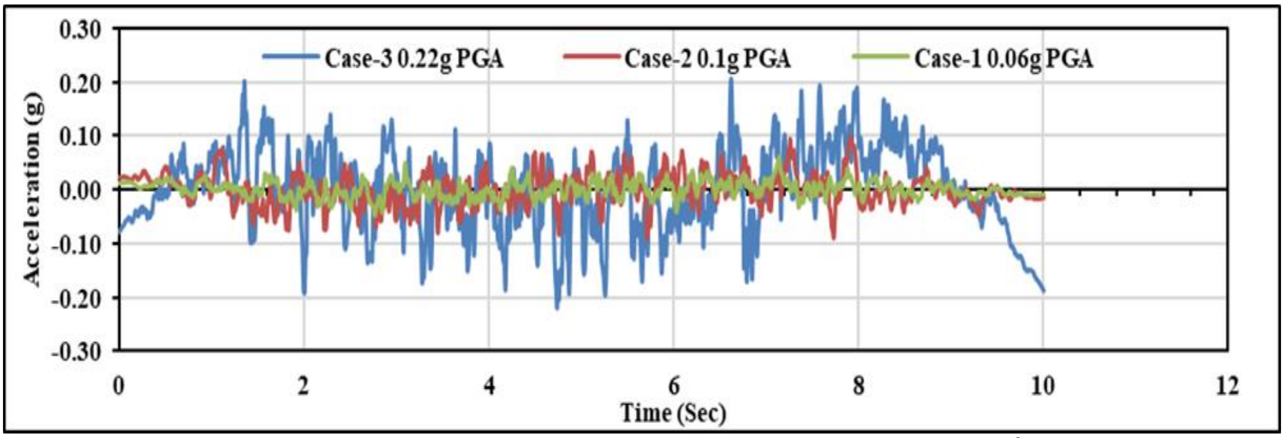


Fig. 3: Acceleration time history plot of PGA for all three cases[8]

The stopes are assumed to be filled with water from the deepest level of 3200m up to a level of 500 m from the surface. Water is being modelled as a continuum linear material with Poisson's ratio of 0.49 to study the hydrodynamic fluid-rock interaction. Two major faults are traversing across the modelled area. To simulate fault behaviour, interfaces are assigned at the fault locations. Viscous boundary is assigned at the boundaries of the model to absorb all the waves generated by the seismic load.

Results and Discussion

The Rayleigh damping approach is applied in this model. Eigen value analysis needs to be run before the nonlinear time history analysis can be run for the model. The mass participation was found to be 46% of the mass and the two frequencies (f1 and f2) of the model. It is observed that the first two frequencies of the model were 0.869 and 0.8634 cycles/sec respectively. The Rayleigh damping coefficients alpha (mass proportional coefficient) and beta (stiffness proportional coefficient) were calculated for the seismic analysis. Damping plays a very important role in the dissipation of energy when applying earthquake as loads.

A parametric seismic – nonlinear time history analyses was carried out for Peak Ground Accelerations of 0.06g (Case 1), 0.10g (Case 2) and 0.22g (Case 3) respectively. The ground acceleration was applied at the bottom of the model at distance of 3.5 km from the ground surface. The initial stress in rock is computed using K0 condition.

The peak ground acceleration values were taken from the recent history of events experienced in the deep hard rock mines post-mining. The continuously changing stress regime is responsible for the events of such magnitudes to take place especially post-mining. The results of the model analysis show areas that are highly vulnerable, vulnerable and safe zones (Fig. 4) for all the three cases of seismic loading.

For case (1), PGA=0.06g shows the highly vulnerable zones to be concentrated along the interface of voids with that of the rockmass from the surface till a depth of 1200 m from the ground surface and some very small pockets at the lower levels. The ground surface is not much affected due to this seismic load. For case (2), PGA=0.10g shows the highly vulnerable zones to be concentrated along the interface of voids with that of the rockmass from the surface till a depth of 1500 m from the ground surface and some sections at the deepest levels. The ground surface is slightly impacted due to this seismic load. For case (3), PGA=0.22g shows the highly vulnerable zones to be concentrated along the interface of voids with that of the rock mass from very close to the surface till deeper levels. The ground surface is affected due to this seismic load.

It is observed that the vulnerable zones are zones of high shear stress and at these zones especially the zones are in transition in their state from elastic to nearing plastic state (Fig. 5). The plastic state is an indication of yielding of rockmass taking place at those zones. The ground motion spatial distribution helps to understand the type of failure and zones of failure.

All three cases are being presented to show the actual phenomenon of yielding taking place. The transition is well depicted in the all the stages starting from case (1) of lower PGA value of 0.06g wherein the transitions zones are found mostly at the interface zones near the boundaries of voids and the rock mass. From case (2) of intermediate PGA value of 0.10g, the transition zones have increased and at some zones, the tensile failure of rock mass is observed. For case (3) of higher PGA value of 0.22g, the plastic zones are formed at the interface zones between the voids and the rock mass. Tensile failure zones have increased indicating that the zones have completely failed. The plastic failure zones are found on the ground surface, giving an indication of vulnerable zones of instability. These zones can be taken as weak zones where visible subsidence, sinkhole formations and settlement in foundation may be observed. There is physical visible evidence of surface events at these locations.

The three case conditions of varying the input parameter of peak ground acceleration from a minimum PGA value of 0.06g to a maximum PGA value of 0.22g have helped in the mapping of vulnerable zones and the effect of such magnitude event on the surface. The plastic failure zones are the vulnerable zones and the tensile zones are failed zones.

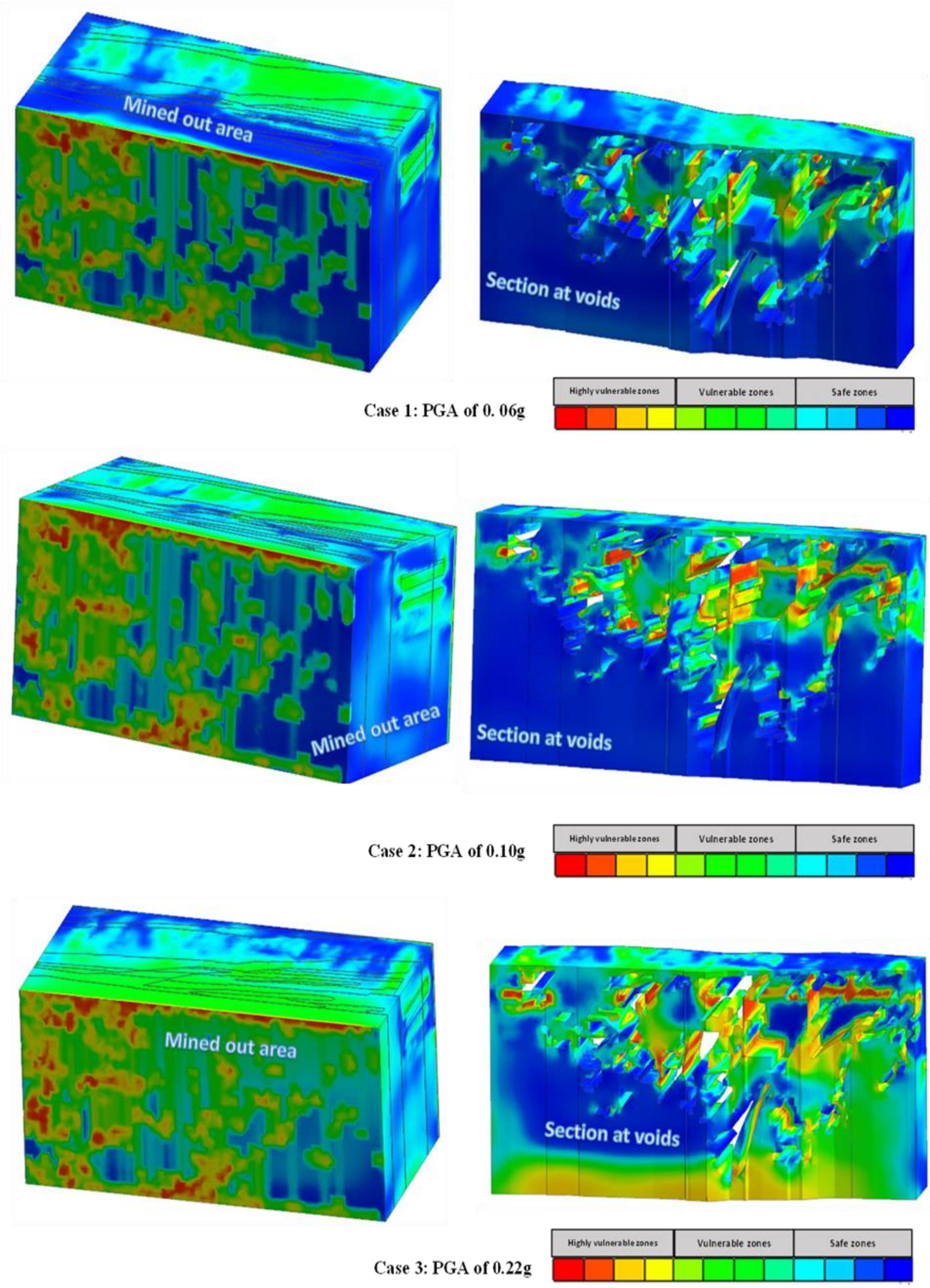
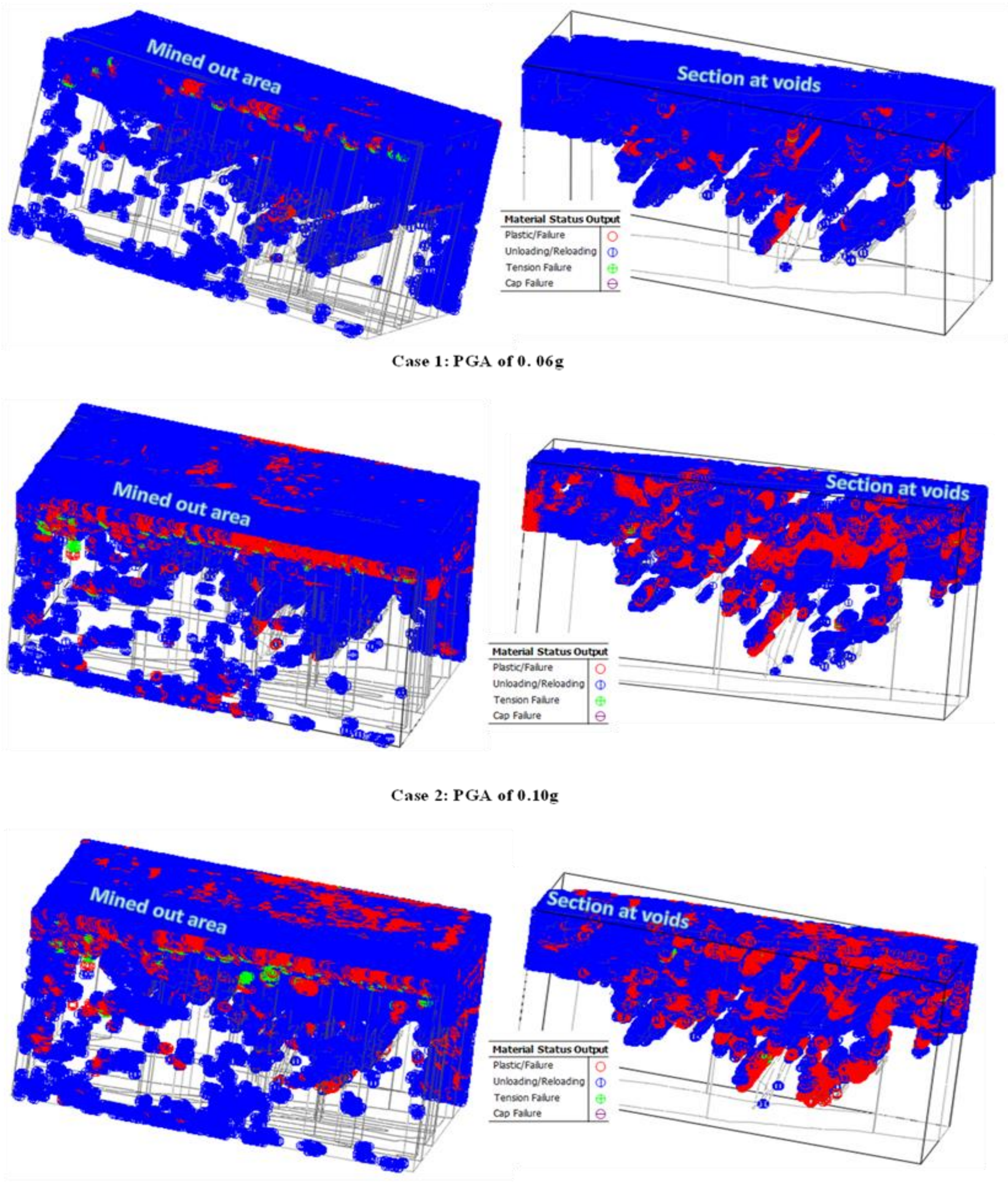


Fig. 4: Spatial distribution of shear stress for all three cases

It can be further observed that as the input acceleration at the bottom is increased, the acceleration at the vulnerable zones has also increased indicating zones of high stresses (failure zones). The acceleration in these models at the indicated zones respectively has triggered rock burst at different time periods in all the three cases. The acceleration time history plots aids in better visualising the effect of acceleration with time (Fig. 6).



Case 1: PGA of 0. 06g

Case 2: PGA of 0.10g

(c.) Case 3: PGA of 0.22g

Fig. 5: Plastic and Tensile failure zones for all three cases of PGA

The mechanism of application of seismic load of different peak ground acceleration similar to that of an actual event of such magnitude has taken place over the mining area and the changes in acceleration profiles through the area are shown in the acceleration time history plots for all three cases.

The amplification of waves moves towards rock burst zone (Fig. 6). The accelerations observed at the rock burst zones are much higher, as they get amplified when passing through different medium of rock layers and lots of factors play a very important role that affect the amplification process like the shape and size of the voids, the presence of fluid in the void spaces, the geology and time taken for travel. It is observed that as the input acceleration is increased from 0.06g to 0.22g, there is a corresponding increase in ground acceleration observed at the rock burst zones ranging from 0.053 g to 0.185 g.

Finite element numerical solution only allows for continuum modelling and zones of rock bursts (failed zones) may result in the divergence in the solution. Hence the analysis clearly indicates failed rock masses at the highly vulnerable zones. The seismic load at these vulnerable zones at their corresponding depths of occurrence in turn affects the structures.

The accelerations was finally observed at the ground surface (Fig. 7). It can be inferred that as the acceleration is increased from 0.06g to 0.22g, there is a corresponding increase in ground acceleration observed at the surface for each case. The maximum acceleration for PGA of 0.06g is 0.071g, for PGA of 0.10g, it is 0.170g and for PGA of 0.22g, it is 0.266g (Fig. 8).

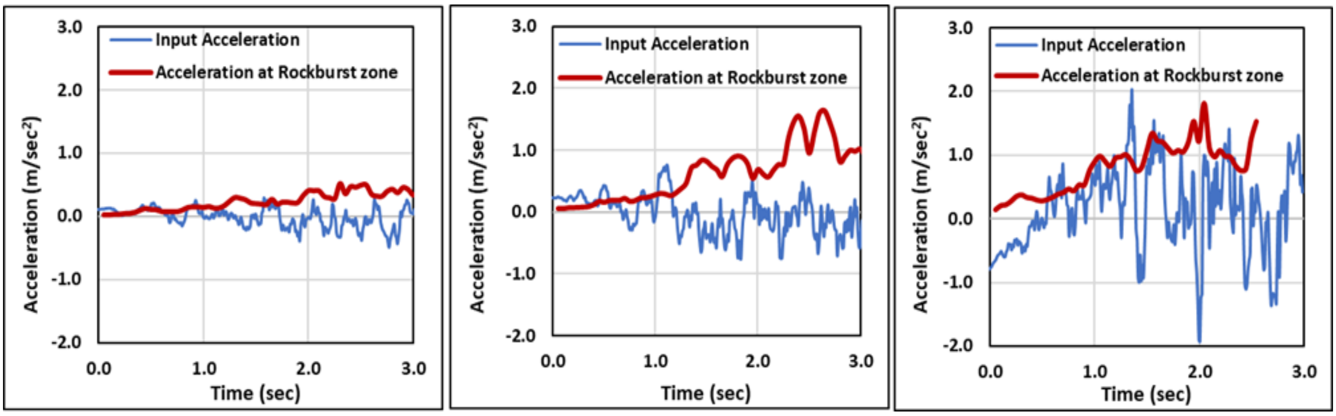
The accelerations observed at the ground surface are not considerably amplified when assessed with input acceleration till the violent failure of the rock mass has taken place. A violent failure of rock mass indicates instability being introduced and redistribution of stresses leading to further failure of the stressed rock masses. Further analysis needs to be carried out to study the effect of seismic load on deeper levels and identification of vulnerable zones post failure of rock masses using Discrete Element Method.

The outcome of the model analysis is as follows:

a) The vulnerable zones were found to be concentrated up to a depth of 1500 m from the surface.
b) The vulnerable zones were also found to be concentrated at a depth of 2100 m to 3200m.
c) The maximum peak ground accelerations observed at the surface are found to be 0.071g to 0.266g.
d) The maximum peak ground velocity was 0.38 m/sec and the maximum peak ground displacement was 5.0 cm.

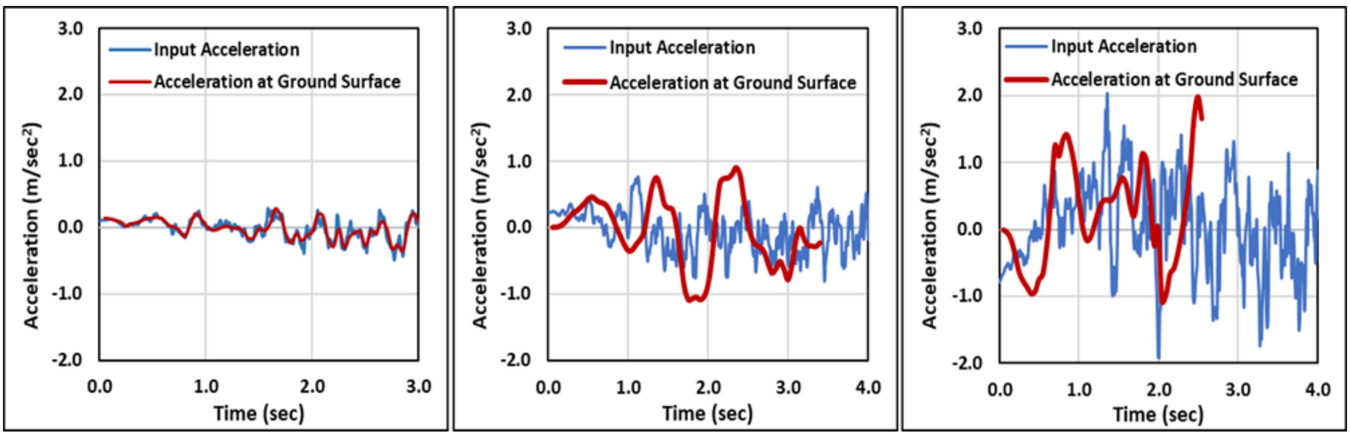
The field observations and analysed data of recorded seismic events from seismic monitoring systems are as follows:

a) The Kolar Gold Fields mine has experienced rock bursts up to a depth of 1500m from surface and at a depth of 2500 m to 3200m. Figure 2 shows the longitudinal section of Kolar Gold Fields – spatial distribution of rock burst during mining at deeper levels.
b) During the period 2006-2012, the maximum acceleration recorded ranged between 0.0006g to 0.10g with duration of event ranging between 0.3 sec to 2.5 sec.[10]
c) The maximum peak ground velocity was 0.01037 m/sec and the maximum peak ground displacement was 0.0298 cm.



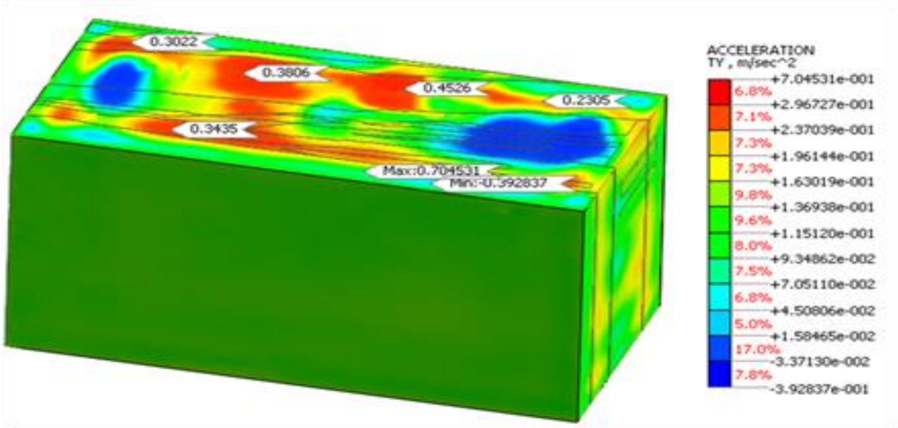
(a) (b) (c)

Fig. 6: Acceleration time histories at rock burst zone (a) Case 1 (b) Case 2 (c) Case 3

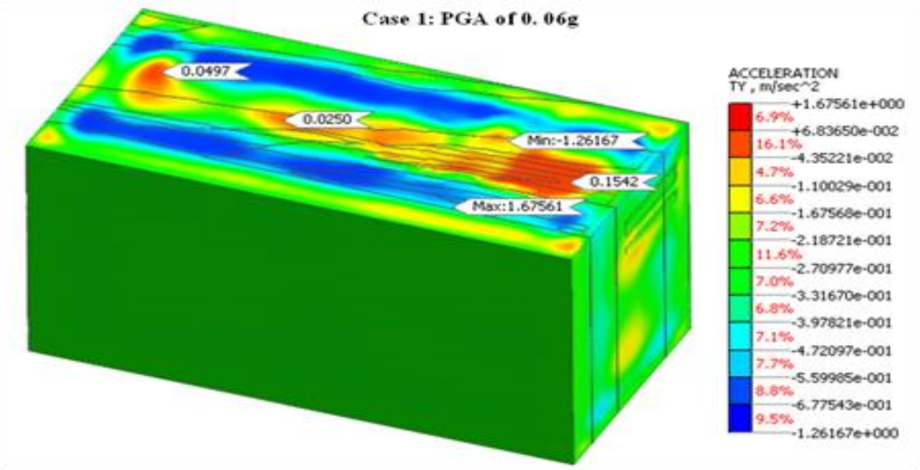


(a) (b) (c)

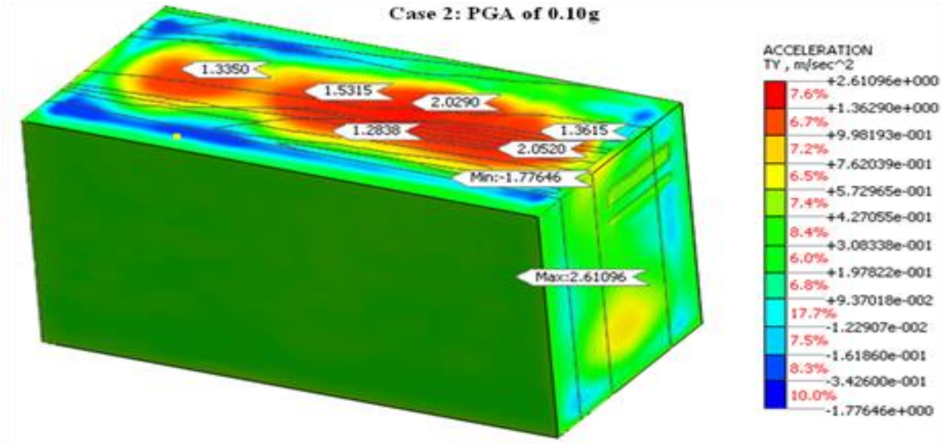
Fig. 7: Acceleration time histories at ground surface (a) Case 1 (b) Case 2 (c) Case 3



Case 1: PGA of 0. 06g



Case 2: PGA of 0.10g



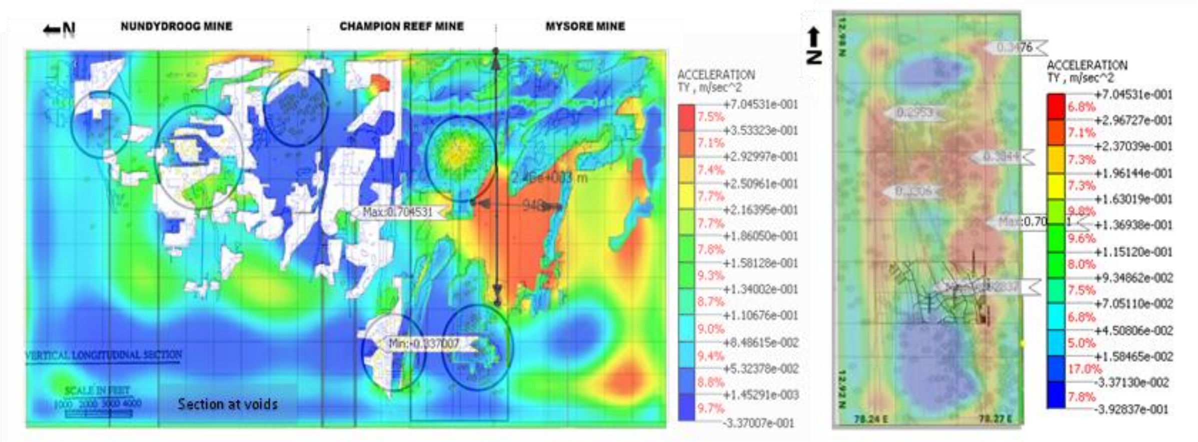
Case 3: PGA of 0.22g

Fig. 8: Accelerations observed at the ground surface for all three cases

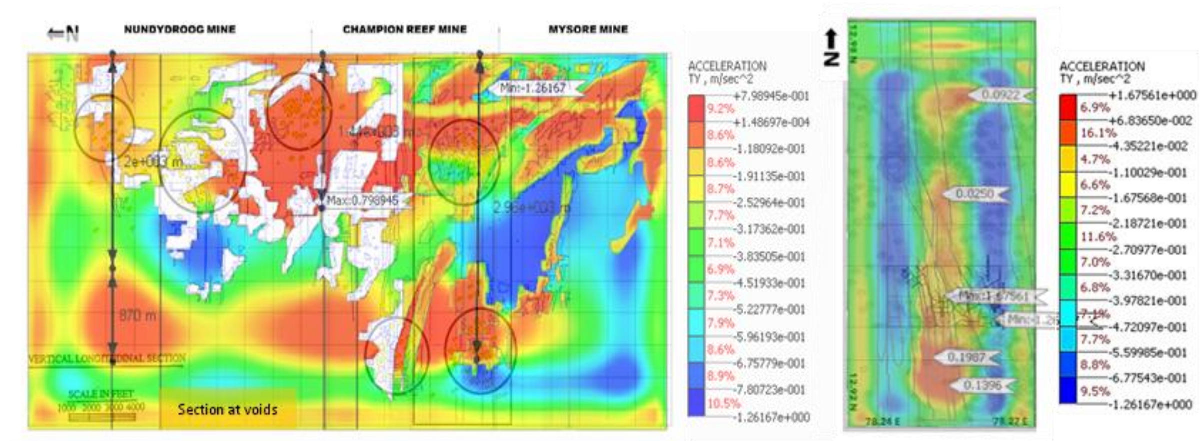
The simulations carried out for all the three cases were validated with field observations (data of seismic events) (Fig. 9). The observations were correlated with the model studies and it has been observed that:

a) Most of the locations of vulnerable zones as identified through field data analysis were identified through model simulation studies also.
b) The gradual increase in the PGA values as the simulated seismic load increased, is well demonstrated through model studies.
c) The results for case (iii): PGA=0.22g being simulated through model studies show similarities in the location of vulnerable zones and the maximum intensities at the failed zones along with the depth of occurrence.
d) The vulnerable zone locations identified at the surface through model simulations also indicate similarities in location and intensity of occurrence with that of field studies.

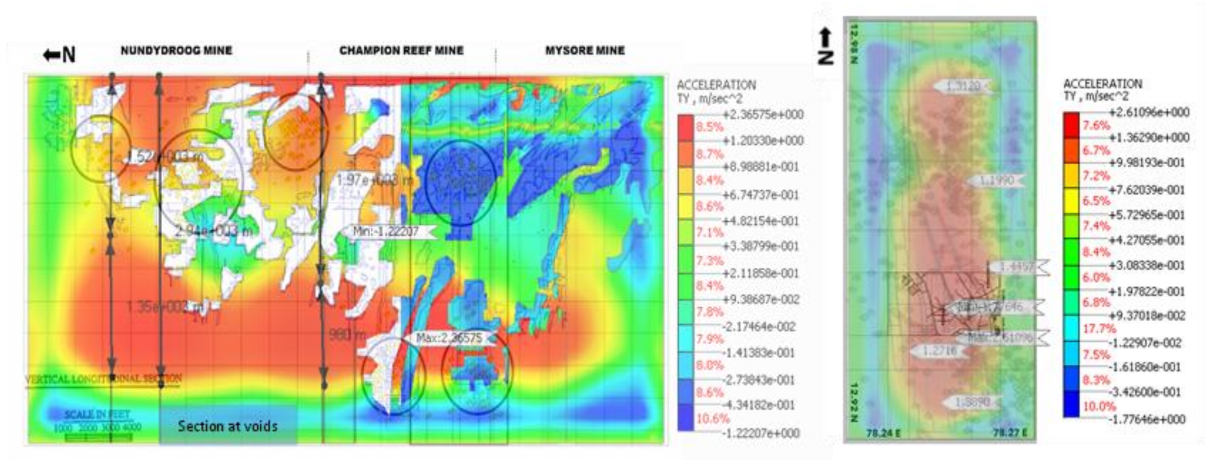
A recent short term seismic monitoring study in 2018-19 on occurrence of rockburst was carried out in this mined out area, the outcome shows the occurrence of low intensity rockbursts at a depth of 1000 m to 3000 m. The maximum peak ground acceleration recorded was 0.005g to 0.010g[1].



Case 1: PGA of 0. 06g



Case 2: PGA of 0.10g



Case 3: PGA of 0.22g

Fig. 9: Zones of failure at void section and at surface w.r.t. field observations for all three cases

One of the major observation was that the events were found to concentrate along both sides along the prominent Mysore North fault. To further study the effects of the Mysore North fault, a section was chosen in the entire mined out area comprising of Mysore North fault, the champion railway line with the railway station and a zone with previous and recent rock burst activity. The major structures in the study area were old British type bungalows (stone walls and tiled high roofs), houses built of masonry walls with asbestos / sheet roofs. The location details and the geological details of the section taken for simulation studies are given in fig. 10.

Analysis was carried out for this section and the model was run for two cases separately: section analysis considering the prominent Mysore North fault and section analysis not taking the existence of the fault, only geology was considered.

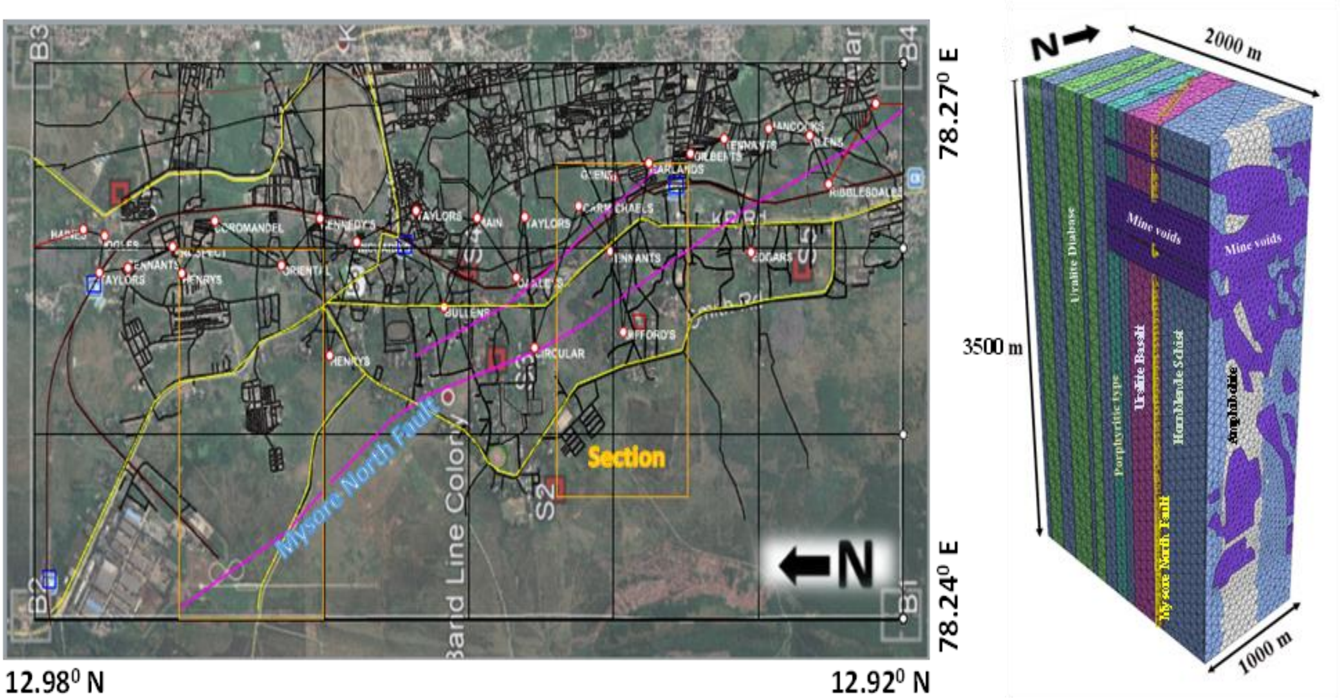


Fig. 10: Location and geological details of section taken for analysis

The analysis clearly indicates that the presence of a fault does make a difference as a zone of weakness is being introduced between the entire mining area. The intensity pattern of peak ground acceleration is being observed on the ground surface for both the cases under the three seismic load conditions (Fig. 11). The observations are as follows:

a) For all three conditions of seismic load applied [case(i)=PGA of 0.6g, case(ii)=PGA of 0.1g and case(iii)=PGA of 0.22g], the vulnerable zones identified on the ground surface are located close to the Mysore North fault.
b) The intensity of the acceleration being experienced on the surface under different loading condition is shown separately for all three cases. For section where fault is considered, the maximum PGA for case (1) =0.107g, for case (2) =0.163g and for case (3) =PGA of 0.228g. For section where fault is not considered, the maximum PGA for case (1) =0.087g, for case (2) =0.130g and for case (3) = PGA of 0.197g.
c) Section analysed without fault effect shows that the vulnerable zones at ground surface are spread over and concentrated in the entire length of the mining area.

Conclusion

The study was carried out to analyse the stability of the closed hard rock deep metal (gold) mine of Kolar Gold Fields. The model analysis aided in locating the potential vulnerable areas in the entire mined-out area for highly stressed and failed zones. The model analysis has been carried out for the entire mined-out area, it has helped in understanding the rock mass behaviour when subjected to various loading conditions and their probable effects on the ground surface.

The model developed has taken into consideration the fault, geology and the stopped out areas for the application of a seismic load equivalent to that of a seismic event to have occurred in the mining area. The analysis carried out has been helpful in identification of vulnerable zones and their trend in occurrence.

The mining region may experience only redistribution of lithostatic stresses in turn build-up of strain energy in the mined-out areas. The sudden and unexpected release of this strain energy shall be the cause for instabilities within the hard rock deep underground mine.

During the brittle rock mass failure, the transition takes place from continuum to discontinuum. The rock fractures create discontinuum at the application of load though of low intensities at the initial period itself. The unstable and violent failure of rock mass around the underground opening will be based on elastic here, as the transition from continuum to discontinuum analysis could not be carried out due to the limitations in the software. The effect of seismic load on deeper levels and identification of vulnerable zones post failure of rock masses can be studied using Discrete Element Method.

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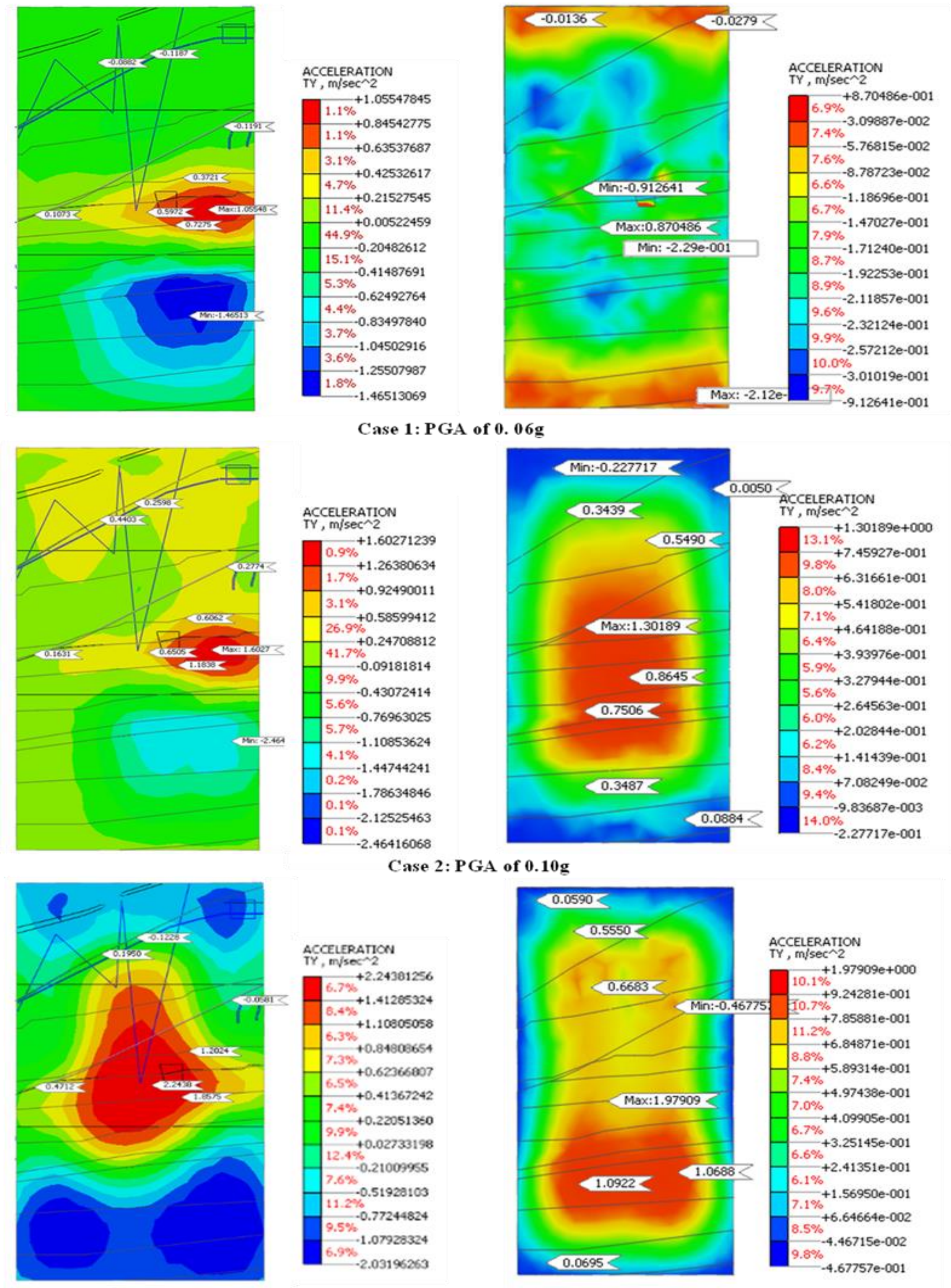

Fig. 11: Vulnerable zones at surface for section with fault (left) and section without fault (right)

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