Stability analysis of an abandoned deep metal mine using numerical analysis tool: A case study

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Abstract. In the recent years due to rapid urbanisation, the key focus has been shifted to development of rural and remote areas. Abandoned mine sites are being evaluated for land reclamation with remediation measures as part of the development program. The abandoned mines come with inherent risk like unpredictable potential future subsidence and sinkhole formations on the surface. The identification of these potential risk areas stands as a major challenge for remediation. The inaccessibility to site makes it even more difficult to study the current geo-mechanical stress conditions for stability evaluation. Despite these limitations, it is essential that abandoned mine sites could be evaluated to atleast give an indicative understanding of current scenarios with regard to safety.

Using numerical analysis tool, it is possible to simulate a model similar to that of the abandoned mine, to identify the potentially stressed zones and assess the stability of the underground excavation. The finite element method is used to develop a numerical model using GTS NX software. The software aided in evaluation of stress distributions and stability of the closed mine since the mine presents a hydro geological problem. The model analysis has proved to be very helpful in observing the mechanical behaviour of materials, modelling of rock systems and understanding the deformations in the rockmass.

Three case conditions of varying the input parameter of peak ground acceleration (PGA) with a minimum PGA value of 0.06g to a maximum PGA value of 0.22g was used in the model studies of Champion Reef mine (3.2km deep gold mine). The vulnerable zones of seismicity were identified to be concentrated at a depth below 1500m from the surface and the maximum peak ground accelerations observed at the surface was found to be 0.1g to 0.22g. The model developed and approach used in this study is an attempt to present the overall view of the probable stability condition for a rough risk assessment study of the deepest Champion Reef metal mine in Kolar Gold Fields.
1. Introduction
Due to mining, the virgin and intact rock is being disturbed by excavation leading to redistribution of stresses. The redistribution of stresses around the excavations at deeper levels during active mining and post-mining are major concerns causing threat to the residents and safety of surface structures above. As the depth of mining increases, the associated risks of instabilities within the mine also increases. The probability of risk increases when the deep mine is closed due to reasons of resource depletion. Upon closure of a mine, it is assumed that the state of equilibrium may be attained over a period of time. The chances of a deep closed mine with large mine voids, inundation of water, failure of supports and weakening of rockmass over a period of time makes it vulnerable to instabilities added with the changing rockmass stress conditions and regime.

The geo-materials of such mines may comprise of rock mass, soil cover and geological discontinuities presenting a highly non-linear behaviour. The process of evaluation for stability requires data related to exact location of the mined-out spaces, layout of the mine, inundated water level and geological details of the mine which are some of the major technical challenges posed by abandoned mines. In such situations, numerical techniques are proven to be feasible tools to analyse the behaviour under loading conditions. Empirical methods are available for evaluation of mining induced seismicity but seem to have limitations with regard to mined-out sites with voids partially or fully inundated. Numerical techniques are better equipped to consider relevant parameters for the assessment of mining-induced seismicity and its effects on surface structures.

The geometry and geology of an underground mine is very complex. The representation of the geo-mechanical stress condition, considering the non-linear behaviour of the rockmass with mined out spaces, inundated water level and current mining-induced seismicity makes the analyses an even more complex model. Discretization of such geometry without many approximations/manipulations is important to understand the overall behaviour of the mine. Among the many methods of numerical simulation, the finite element method (FEM) with implicit dynamic integration was found to be more appropriate to serve the required purpose. In case of FEM, modelling of complex geometries and irregular shapes for finite elements are available for discretization/meshing of domain. Different types of boundary conditions can also be easily incorporated in FEM for basic and complex problems. In the case of implicit time integration condition, the solution in each discrete time step is unconditionally stable because global equilibrium is achieved at each iteration. Since equilibrium is always maintained, the step size may be chosen without many restrictions. It is an implicit solution and can be used for accurate results involving small number of time steps.

Considering the safety of human settlement and structures, an attempt is made to understand and make a quick assessment of the stability of this underground gold mine. The objective is to identify the potential zones of vulnerability.

2. Location details

2.1. Geology
The area of monitoring is part of the Archean complex of Southern India and falls in the Kolar Schist belt of the Archean greenstone belt of Karnataka. The Kolar Gold Fields (KGF) mines area is at the southern tip of the schist belt and consists of two system of rock formations, the Dharwar schist (Horneblende Schist), metamorphosed from basic igneous rocks, and the peninsular gneiss series, formed by the granite intrusion from beneath. It falls part of the highly metamorphosed schists belt which runs 80km North–South and 4 kms East-West. The KGF mines consists of seven gold bearing lodes and in general there are mainly two types of lodes viz., gold quartz lodes and sulphide lodes. The host rock for gold is hornblende schist of lower Dharwar age accompanied with pegmatites and Champion gneisses. The auriferous quartz veins strike nearly N–S, parallel to the general geological
The trend of the schist belt. The schists are folded and faulted with intrusion of dolerite porphyry dykes and pegmatites. The fold dips westward from 30° near the surface to 85° in the deeper working mines.

The mining area is located between 12.92N-12.98N and 78.24E-78.27E, at an altitude of 900 m above the mean sea level (MSL) as shown in Figure 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 (Srinivasan et al., 2013; Praveena Das et al., 2016).

2.2. Mining Method and Support System
The predominantly used method of mining in Kolar Gold Fields mines was the long hole open stopping method. With increasing depth and for stabilisation of the stope, mechanized cut and fill (CAF) method was adopted as the main mining method in all the production levels till the closure of the mines. The CAF stopes were considerably large and occupied the widest part of the ore body/zones. The stopes were filled by using sand/cement fills. In the last stages, the pillars were mined and backfilled with rock waste. Swellex rock bolts were used as regular support and grouted anchors in critical locations. For long term stability, extensive cable bolting was done.

2.3. Study area
The Kolar Gold Fields mine lie on the Kolar schist belt spreading over an area of 8 km long in the North-South direction and about 4 km in width along the East-West direction. The longitudinal (north-south) section through Kolar Gold Fields mine (Srinivasan et al. 1997) showing spatial distribution of rockbursts along the mined-out stopes and shafts is shown in Figure 2.
Figure 2. Longitudinal section of Kolar Gold Fields mine showing spatial distribution of rockbursts

Considering the mining area of 6 km (N-S) x 3 km (W-E) x 3.5km (D) comprising of shafts and 1400 km of tunnel work with 70 percent stopped out area, it becomes exceedingly difficult to model the entire stretch considering all the geological, geotechnical, and hydrological parameters.

In this study, an area of 1km (N-S) X 2 km(E-W) X 3.5 km (D) section of the deepest champion reef mine is taken for analysis as shown in Figure 3. The area covers the 3.2 km deepest (113 level) mined out section, Mysore North fault along with the Tennant’s fault and the railway line with champion railway station. The major structures in the study area include old British type bungalows (stone walls and tiled high roofs), houses built of masonry walls with asbestos / sheet roofs and few houses with asbestos walls with tile/ sheet roof. The area is identified as a zone with previous and recent rockburst activity.

Figure 3. Champion reef mine area identified as location for analysis

3. Numerical Model

3.1. 3D model
The area between Carmichael’s shaft and beyond Garlands shaft lying between 12.935N-12.944N and 78.246E- 78.264E with the initial stopped out workings (mine voids) are considered for modelling. 3D Finite Element tool GTS NX is used for the analysis. The generated 3D model of the deepest Champion Reef mine showing the geology, faults (Mysore North Fault and Tennant’s Fault) and the mine voids as shown in Figure 4. The dimension of the modelled area is 2 km x 1 km x 3.5 km. The geological details are from geological plan of Champion Reef mine from Survey Dept. 1956.
The rock materials are modelled as equivalent continuum using Generalized Hoek Brown Constitutive behaviour to study the stability of the model for different seismic loads. This material considers the stress decrease phenomenon as per jointed rock mass. The non-linear Generalized Hoek-Brown criterion for rock masses provides input data for the analyses required for the design of underground excavations in hard rock. The criterion defines material strength in terms of major and minor principal stresses as:

$$\sigma_1 = \sigma_3 + \sigma_{ci} \left( m_b \frac{\sigma_3}{\sigma_{ci}} + s \right)^a \quad \sigma_1 \geq \sigma_2 \geq \sigma_3$$

where

- $\sigma_1$ and $\sigma_3$ are the major and minor effective principal stresses at failure
- $\sigma_{ci}$ is the uniaxial compressive strength of the intact rock material
- $m_b$ is a reduced value of the material constant
- $m_b, s$ and $a$ are parameters related to the geological strength index (GSI) and the disturbance factor (D).

The Geological Strength Index (GSI) is a system of rock-mass characterization for reliable input data of rockmass properties required for numerical analysis or closed form solutions. This index helps in considering a rock mass as a mechanical continuum without losing the influence of geology and its effect on the mechanical properties. The GSI is based on combination of two parameters: the blockiness and the discontinuities within the rockmass.

$D$ is a factor that depends on the degree of disturbance that the rock mass has been subjected to, based on both blast damage and stress relaxation. The geological strength index (GSI) and disturbance factor (D) for jointed rockmass are used for estimation of the material constants and used as input data for numerical analysis (Hoek et al., 2002). The equations for the material constants (Hoek and Brown, 2019) are expressed as
\[ m_b = m_i \exp \left( \frac{GSI - 100}{28 - 14D} \right) \]

s and a are constants for the rock mass, where s = 1 and a = 0.5, for intact rock.

\[ s = \exp \left( \frac{GSI - 100}{9 - 3D} \right) \]

\[ a = \frac{1}{2} + \frac{1}{6} \left( e^{-GSI/15} - e^{-20/3} \right) \]

where

GSI is Geological strength index

m is intact rock material property

D is Disturbance factor (D=0 for undisturbed rock masses, D=1 for very disturbed rock masses)

The basic input physico-mechanical material properties used are elastic modulus, unit weight, uniaxial compressive strength, triaxial properties. The properties are laboratory tested values of Kolar Gold Fields mine location (study area) from Geological Survey of India (GSI) report (Panduranga et al., 2009). Based on laboratory test results, the GSI and intact rock parameter were decided referring to Hoek and Brown, 2019 (Latest Edition for guidelines for GSI calculation). Table 1 shows the elastic and non-linear properties defined in the model.

**Table 1. Material properties defined in the model**

| Material properties | Uralite Diabase | Amphibolite | Porphyritic type | Uralite Basalt | Hornblende Schist |
|---------------------|-----------------|-------------|------------------|----------------|------------------|
| Elastic Modulus x 10^7 (kN/m²) | 8.54 | 8.40 | 6.82 | 9.36 | 8.26 |
| Unit Weight (kN/m³) | 28.63 | 29.40 | 26.68 | 29.61 | 29.62 |
| GSI | 40 | 40 | 45 | 40 | 30 |
| Intact Rock Parameter | 7 | 25 | 30 | 17 | 29.62 |
| Disturbance Factor | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| m_b | 0.196810 | 0.702891 | 1.135860 | 0.477966 | 0.062015 |
| s | 0.000113 | 0.000113 | 0.000240 | 0.000113 | 0.0000248 |
| a | 0.511368 | 0.511368 | 0.508086 | 0.511368 | 0.522344 |
| Uniaxial Compressive Strength (kN/m²) | 87377 | 196133 | 166713 | 294200 | 152199 |
| Damping Ratio | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

**3.2. Seismic Load**

To generate the seismic load, an Artificial Earthquake Generation approach (Housner & Jennings, 1964) has been considered in the study. This method uses the power spectral density of design spectrum as expected maximum response. Taking the parameters of the highest magnitude seismic event to have experienced over the mining area to simulate a real earthquake with parameters equal to that of the seismic event. A subsequent 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 of Kolar Gold Fields is shown in Figure 5.
The response spectrum is converted to acceleration time history. The minimum, intermediate and maximum accelerations of 0.06g, 0.10g and 0.22g are being considered based on the previous ground motion studies (Gupta 2010). The obtained acceleration time histories used in the present study are shown in Figure 6.

Due to the seismic load, both body and surface waves develops and travel over an infinite medium. So, in order to simulate infinite medium, viscous boundaries are considered in the current study. This viscous boundary would help in eliminating the reflected waves and help in generation of infinite medium. The damping constants and stiffness of the viscous springs are calculated as per Lysmer & Kuhlmeyer, 1969 and modulus of subgrade reaction approaches, respectively.

Considering the stopes are filled with water from a level of 500 m from the surface till the deepest mined out level of 3.2 km. To study the hydrodynamic fluid-rock interaction, water is modelled as a continuum linear material with Poisson’s ratio equal to 0.49. The section comprises of two faults that are traversing through the modelled area. To establish the fault behaviour, interfaces are assigned at the fault location. Viscous boundary is modelled at the boundaries of the model to absorb all the waves (no reflected waves) generated because of the seismic load.

4. Analysis and Results

Material damping plays a significant role in the energy dissipation in the case of earthquakes. Hence Rayleigh damping approach is implemented in the model. Eigenvalue analysis is run prior to the nonlinear time history analysis to calculate the mass participation and frequencies (f1 & f2) of the model. It is observed that 73% of the mass is participating and the first two predominant frequencies of the model are 1.4786 & 1.5987 cycles/sec. These frequencies are being used to calculate the Rayleigh damping coefficients alpha (mass proportional coefficient) and beta (stiffness proportional coefficient) in the subsequent seismic analysis.
Taking all the available data as inputs, a parametric seismic – nonlinear time history analyses is carried out for Peak Ground Accelerations of 0.06g (Case-1), 0.10g (Case-2) and 0.22g (Case-3) applied as a ground acceleration at the bottom of the model, at 3.5 km from the ground surface (deepest champion reef mine). In all the three cases, the initial stress in the rock is calculated using K0 condition and seismic analysis is carried out.

A seismic activity in an abandoned mine not only affects the stability of stopes but also the overlying structures above the surface. Rockbursts are the outcome of changes in stress conditions in deep hard rock mines. The model was helpful in identifying the vulnerable zones close to the surface. The vulnerable zones in all the three cases seem to have been identified at 1500 to 3000m from the ground surface. It is observed that the vulnerable zones are zones of high shear stress concentration and nearing plastic state as shown in Figure 7. The plastic state of the vulnerable area presents an insight into the yielding of rock mass at those zones.

Figure 7. Spatial distribution of shear stress and plastic zone for all three cases
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 has aided in the identification of vulnerable zones and the effect of event of such magnitudes can bring about on the surface. It can be further observed, that as the input acceleration at the bottom is increased, the acceleration at the vulnerable zones also have increased indicating zones of high seismicity (rockburst). The acceleration has triggered the failure of rockmass at these zones. The acceleration in these models at the indicated zones respectively have triggered rockburst in all the three cases at different time periods. The acceleration time history plots aids in better visualising the effect of acceleration with time and shown in Figure 8.

Figure 8. Acceleration time histories at rockburst zones (a) Case-1 (b) Case-2 (c) Case-3

The waves get amplified as it moves towards ground surface. And these induced earthquakes result in plastic failure due to tension at the marked vulnerable zones as shown in the Figure 7. These plastic failure zones are the vulnerable zones and the tensile stresses resulted in failure (rockburst). The tensile failure in the materials was identified and the same has been in shown in the legend of Figure 7 itself. Also, over a period of time from the closure of the KGF mine, several rockburst events have occurred in the same location as shown in Figure 2. In order to understand the spatial distribution, two lines (Line A and Line B) have been considered similar to Ma et al., 2019 as shown in Figure 9.

Figure 9. Lines considered for extraction of spatial distribution of PGV
Figure 10. The spatial distribution of PGVs of the vertical motion (Z component) and the horizontal motion (vector sum of the X component and Y component) of tensile failure source (PGA of 0.10g) along Line A and Line B.

From Figure 10, it is observed that the spatial distribution of the ground motion along Line A and Line B represents a tensile failure source (similar to Ma et al., 2019). The ground motion spatial distribution can be analyzed and used to understand the type of failure.

Finite element numerical solution only allows continuum modelling and any sort of events such as rockbursts may result in the divergence in the solution. Hence the analysis got terminated for all the three cases when the rock at the vulnerable zone has failed.

The seismic activity at these vulnerable zones at their corresponding depths of occurrence in turn affect the overlying surface structures. The accelerations observed at the top ground surface is shown in Figure 11. It can be inferred that as the acceleration is increased from 0.06g to 0.22g there is a corresponding increase in ground acceleration at the surface from 0.1g to 0.22g. The maximum peak ground acceleration observed in this modelled area is 0.22g with respect to the boundary conditions as applied for the analysis.
The accelerations observed at the ground surface are not significantly amplified when compared with input acceleration till the violent failure of the rockmass as shown in Figure 12. Since an instability like violent failure of rockmass presents a scenario of instability being introduced at the vulnerable zones and redistribution of stresses should be leading to further failure of stressed rock masses thereby increasing the intensity of vibrations at the ground surface. The effect of the seismic load along with the vibrations due to rockburst on the overlying structures cannot be studied in finite element method. Hence further analysis to study the effect on deeper levels and identification of vulnerable zones post failure of rock masses should be carried out using Discrete Element Method.

The model developed has taken into consideration the geology, the fault system and the stoped out areas for the analysis and application of a known intensity of earthquake equal to the maximum intensity of rockburst experienced in the mine. The analysis conducted has been helpful in identification of vulnerable zones with their corresponding depth of occurrence.
An attempt has been made to co-relate the vulnerable zones identified and zones of actual rockburst at the same location.

The outcome of the model analysis is as follows:

a) The vulnerable zones and zones of seismicity are found to be concentrated at a depth below 1500 m from the surface.

b) The maximum peak ground accelerations observed at the surface are found to be 0.1g to 0.22g and the maximum peak ground acceleration recorded in the mining area was 0.22g.

The simulations were validated with field observations being made from time to time, from the analysed data of recorded seismic events (data from seismic monitoring systems installed at the location). The observations were correlated with the model studies and it has been observed that:

- The Champion Reef mine has experienced rockbursts at a depth of 1500 m to 4000 m, as shown in Figure 2 the longitudinal section of Kolar Gold Fields – spatial distribution of rockburst during mining at deeper levels.
- Closure of deeper levels of mines was done in 1991. Entire mine was completely closed in the year 2001. Post closure of mines, in 2005 rockburst events have occurred with maximum intensity of 0.22g (Srinivasan et al. 2000, 2010). The study further confirms concentration of rockburst events within 1500 m to 3000 m from the surface. The events were found to concentrate along both sides along the prominent Mysore North fault as shown in Figure 3.
- A total of around 1158 rockburst events were recorded for the period 2006-2012. The maximum acceleration ranged between 0.0006g to 0.10g with duration of event ranging between 0.3 sec to 2.5 sec (Srinivasan et al. 2013).

A recent study on occurrence of rockburst was carried out in this mined out area and the outcome show the occurrence of rockburst at a depth of 1000 m to 3000 m. The maximum peak ground acceleration recorded was 0.005g to 0.010g (NIRM unpublished S&T Report) as shown in Figure 13.

The mining region falls in zone 2 of seismological map of India and the tectonic stresses may not be the primary driving force of mine seismicity. Redistribution of lithostatic stresses could be one of the potential factors for the build-up of strain energy leading to the rockbursts in the mined-out area.
5. Conclusions

The study was focused on stability analysis of the closed and abandoned Champion Reef mine in Kolar Gold Fields. The model analysis was carried out to locate the vulnerable areas in the mine for failure and record ground motions (attenuation) at surfaces and failure zones. The model analysis has proved to be very helpful in observing the mechanical behaviour of materials, modelling of rock systems and understanding the deformations in the rockmass.

One of the recent model studies in the abandoned Kolar Gold Fields mine indicate low intensity seismic activity at depths of 1000 m to 2000 m. Three case conditions of varying the input parameter of peak ground acceleration (PGA) with a minimum PGA value of 0.06g to a maximum PGA value of 0.22g was used in the model studies of Champion Reef mine (3.2km deep gold mine). The vulnerable zones of seismicity were identified to be concentrated at a depth below 1500m from the surface and the maximum peak ground accelerations observed at the surface was found to be 0.1g to 0.22g. The model developed and approach used in this study is an attempt to present the overall view of the probable stability condition for a rough risk assessment study of the deepest Champion metal mine in Kolar Gold Fields.

Although, finite element model is able to depict the seismic phenomenon, further studies are required to see the effect of seismic load along with the vibrations due to rock mass failure on the overlying structures. The Discrete Element Method of analysis shall aid in comprehensive and detailed stability analysis taking all the geological, geomorphological and geotechnical inputs.

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