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Stability Analysis of Drives Excavated in Paste-filled Stopes for Underhand Mining

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ABSTRACT: This paper evaluates the stability of drives excavated in paste-filled stopes that have been previously mined out. Stability of the drives is important as the vibrations generated during the drilling and blasting processes affect the stability of the drives in low-strength paste. The practical implementation of the process has been carried out at an underground lead-zinc mine in India. A similar detailed study for such a mining practice in India has not been conducted in the past. Simulation for effect of blasting vibrations and subsequent excavations of the drives on the paste-filled stope is carried out through dynamic numerical analysis in FLAC^{3D}. Rayleigh damping conditions were applied to the model along with the application of dynamic loading conditions. Dynamic response of the blasting and excavation process is studied to evaluate displacement magnitudes and strength-to-stress ratio for the excavated drives. The numerical model is calibrated using the peak particle velocity data of blast vibrations obtained from the field test. The numerical results are in accord with the field observations in the mine. Limited damage to the drives is observed and the dynamic model confirms the same due to the effect of blast loads. Future scope of the study is to understand the stability of drives with changes in stress conditions as the mining advances to greater depths. It may also help to modify the blasting parameters to control the vibrations affecting the drives in paste-fill.

1. INTRODUCTION

The stability of underground mine excavations subjected to drilling and blasting vibrations has been a major concern. Different mining methods are employed based on different mining conditions and method of ore extraction. Preparation of stopes using drilling and blasting is a common practice. However, the safety of personnel and mining machinery are given importance at the same time the production is optimized. The problem of safety of underground structures subjected to blasting vibrations has been addressed by Drake and Little (1983), Kumar et al. (2016), Saharan et al. (2008) and many authors in the past. Fractures generated in pillars subjected to blasting vibrations could compromise the safety of the mine on a local or global scale. The paper evaluates the effect of blast vibrations on the stability of drives excavated in paste-filled stopes in an underground lead-zinc mine in India. The ore was previously being extracted using overhand mining method but due to mine stability issues, the mine management decided to switch to underhand mining method with paste backfill. To undergo extraction, drives are excavated in the already mined-out stopes filled with paste, to drill downward boreholes. The boreholes are drilled downwards from the crown level of the underhand stope to prepare it for extraction. These drives in paste-fill are excavated using drilling and blasting operations.

Blast vibrations affect the stability of the backfilled paste which possesses low strength compared to host rock and ore rock. Therefore, it is imperative to study the stability of these drives until the underhand stope is prepared for extraction. Finite difference modeling tools such as Fast Lagrangian Analysis of Continua (FLAC^{3D}) can be used to analyze the stability of the underground excavations. The dynamic modeling features in FLAC^{3D} software can simulate the dynamic blast load imparted to the structure. The model is framed using the rock and material properties that were measured using the in-situ geotechnical tests and laboratory testing. The model is calibrated using peak particle velocities generated during some of the test blasts that were carried out in the mine. The peak particle velocities at different points with reference to the blast location are recorded and identified as an effective parameter to study the effect of blast load imparted to the drives in the mined-out and paste-filled stopes. Assessment of stability of the excavated drives has been provided to understand the effect of blasting during excavation in the underground lead-zinc case mine.

2. DYNAMIC MODELING IN FLAC^{3D}

Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC^{3D}), developed by Itasca Consulting Ltd., is used to carry out numerical simulations. This program is based on an explicit finite-difference method for computational purposes. This is helpful in studying the dynamic instability of the mined-out zones and drives caused by the blasting vibration load and stress re-distribution after excavation. Effect of blasting vibrations in a mining environment has been studied by many researchers. Lilley et al. (1998), Gool et al. (2004), Xu et al. (2006), and Wei et al. (2007) studied the effects of blasting on paste-filled stopes using numerical modeling tools. In this study, the stability analysis of the excavations in paste-filled stopes is made possible due to the coupling of inbuilt formulation codes and mine model in FLAC^{3D}. The three most important aspects considered for simulation of the suggested model in FLAC^{3D} are- (1) dynamic loads due to blast pressure; (2) blast wave transmissions through the model; and (3) mechanical damping. All these factors characterize the generation of dynamic loads due to low-peak amplitude and high-frequency dominant blast waves, the response of drives to dynamic loads generating due to the blast waves, and the energy losses in a natural system.

This paper also integrates the dynamic computations with the excavation simulation reflecting the mining method that is being implemented in the mine. The lead-zinc underground mine where the practical implementation of this study is carried out adopted open-stoping with paste-filling as the primary mining method. The mine management decided to switch to underhand mining from overhand mining method as the latter was creating ground control problems. One of the main problems was the rock material crumbling down due to the presence of a shear zone passing through the steep ore body. The reasons for the instability problems are not discussed in detail as they are not in the scope of this study.

Initial balance state is determined after defining the computational mode, constitutive model, and boundary conditions. The excavation of drives and stope plugs is simulated using static computational analysis. After analyzing the static results, the dynamic mode is set active along with dynamic boundary conditions mentioned later in this study. After applying dynamic loads simulating the blasts to excavate the drives in paste-fill, the dynamic analysis is carried out and results are assessed. To carry out simultaneous excavations and blasting, the program is designed to toggle between the computation schemes. For dynamic analysis, the damping of energy generated through the system reproduced the magnitude and form the energy losses in the original mining conditions when subjected to dynamic loading. This is ensured by calibration of important parameters which is discussed further in a separate section.

3. GENERATION OF MODEL IN FLAC^{3D}

3.1. Model geometry

The constructed model geometry is a similar representation of the dimensions of underground structures at the mine. The stopes where the excavation and blast simulations are conducted, lie roughly 580m below the surface as depicted in Figure 1.

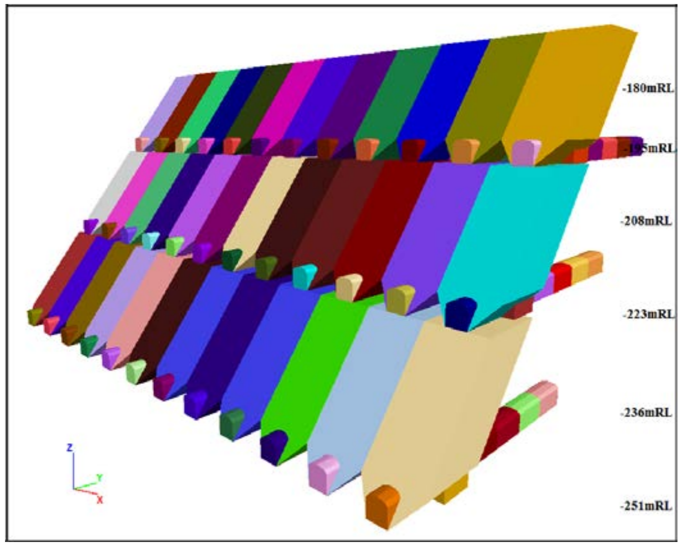

Figure 1. Discretized model of the stopes and drives.

The level in which the excavation and blasting process is simulated lies between the -195 mRL and -223 mRL, which is the middle level in Figure 1. Each stope has dimensions measuring approximately 15 m x17 m x25 m as shown in Figure 2.

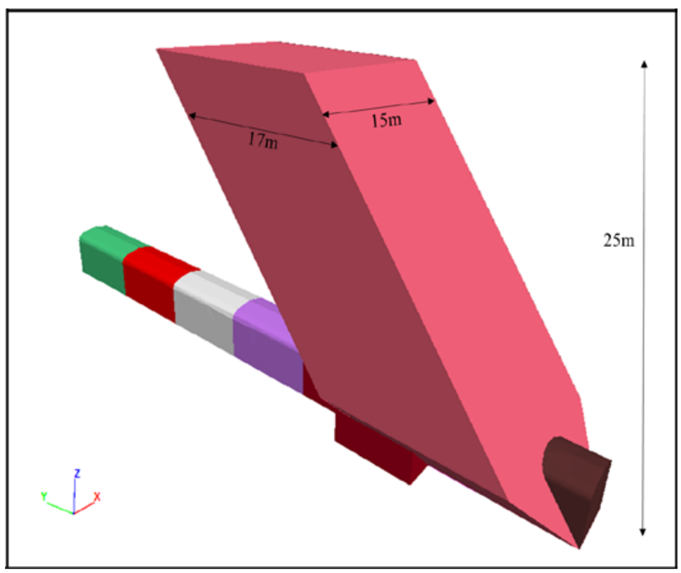

Figure 2. Model geometry of an individual stope and drive.

The stopes are simulated as already extracted and paste-filled stopes in which the drives are to be excavated. These drives will be used for preparing the ore containing stopes below -223 mRL for extraction by drilling long-holes for blasting.

Table 1. Physico-mechanical properties of different intact rock materials.

Properties	Host Rock	Ore	Paste
Density, ρ, kg/m^3	2800	3400	1800
Uniaxial Compressive Strength, σ_{ci}, MPa	52	60	1.5
Cohesion, c, MPa	2.41	2.11	0.85
Friction Angle, ϕ, degrees	43.02	40.44	47.01
Tensile Strength, τ, MPa	0.62	0.16	0.79
Poisson's Ratio, ν	0.30	0.30	0.24
Bulk Modulus, K, GPa	6.19	25.50	0.14
Shear Modulus, G, GPa	5.23	11.80	0.065

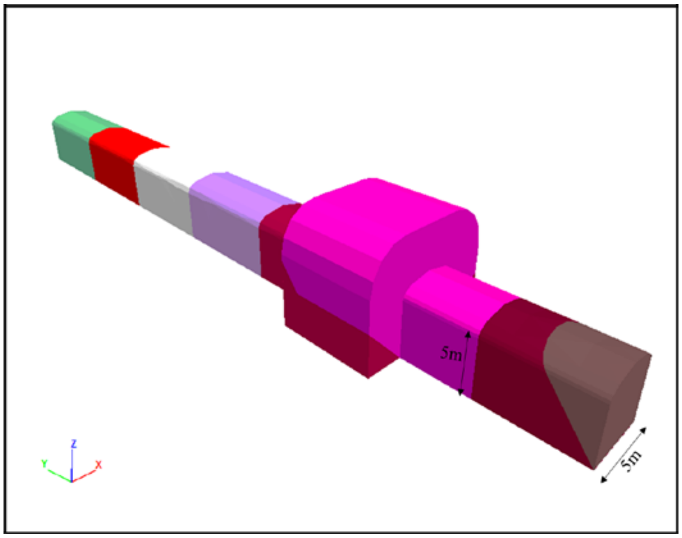

Figure 3. Model geometry of a drive and stope plug.

The crosscut drives leading in the stopes have a typical 5 m x 5 m profile shown in Figure 3. A cement plug, as shown in Figure 3, is constructed to block and prevent spillage of backfilled paste in the excavated hollow stope from the above level. The stopes in the level above -195 mRL are also treated as the post-extraction paste-filled stopes. This is done to have an insight into a scenario where blasting in future drives in paste-fill are affected from the above paste-filled stopes.

3.2. *Insitu stresses and physico-mechanical properties*

The rock mass and geotechnical properties for all the materials used in the numerical model were measured by the mine management using geotechnical borehole measurements and laboratory testing. The equations for calculating the in-situ stresses with depth in the underground mine in the study are estimated to be:

$$\sigma_H = 0.034\ z + 5.65 \quad (1)$$

$$\sigma_h = 0.017\ z + 2.82 \quad (2)$$

where 'σ_H' is the maximum horizontal stress in MPa; 'σ_h' is the minimum horizontal stress in MPa; and 'z' is the depth below the surface in meters. The surface of the mine is marked as 392 mRL. The major horizontal stress, which is also the major principal stress, aligns 82^o east from the north and is assumed to act in the horizontal plane. The minor horizontal stress and vertical stress directions are taken orthogonal to the major horizontal stress.

The sequence of rocks, as examined from hanging wall to footwall can be broadly grouped as under Garnet-biotite-sillimanite gneiss with intermittent bands of pegmatites. The ore minerals (mainly sphalerite and galena with sulfide gangue, pyrite, and pyrrhotite) are present in the schistose matrix of quartz, potash feldspar, sillimanite, graphite, and various micaceous minerals. The Mohr-Coulomb constitutive model represents the plastic or yielding rock behavior in the numerical model. The physico-mechanical parameters for the intact host rock, ore rock, and paste-fill material are provided by the mine management as listed in Table 1.

3.3. *Boundary conditions*

Like any other FLAC^{3D} model, this numerical model of a discretized finite region is enclosed within artificial boundaries. The boundaries have to be large enough so as not to affect any forces within the area of investigation, yet not so large to increase the burden on computational speed and time. For dynamic analysis, viscous or absorbing boundaries are used which prevents reflection of outward propagating waves back in the model. These boundary conditions are applied at the bottom and four side faces. No boundary is applied to the top face as it represents the free surface. Rayleigh stiffness damping is applied which is independent of dynamic frequency. The parameters for the application of Rayleigh damping is discussed further in the next section.

4. CALIBRATION OF DYNAMIC MODEL

4.1. *Rayleigh damping parameters*

For dynamic systems, vibration energy within the system faces some degree of damping. This prevents the system from oscillating indefinitely when subjected to forces (Itasca FLAC^{3D} Manual). In this study, Rayleigh damping is implemented in the numerical simulation to reproduce the energy losses in the dynamic system when subjected to dynamic blast loads. A damping matrix, C, could be used to represent classical Rayleigh damping and is related to mass (M) and stiffness (K) matrices as:

$$C = \mu M + \lambda K \quad (1)$$

where μ is the mass-proportional damping constant and λ is the stiffness-proportional damping constant. Rayleigh damping is also considered to be frequency-independent over a fixed range of frequencies which makes it suitable to apply for low-peak amplitude and high-frequency dominant blast waves. For this study, these constants are determined with the help of calibration of modeling results with field data. The peak particle velocity (PPV) values estimated with the help of numerical modeling are matched using those obtained during test blasts in the field. The calibration results are used to arrive at the suitable parameters including Rayleigh damping constants and dynamic loading conditions. These parameters are required to study the response of drives in paste-fill to dynamic loading due to blast pressure.

4.2. Calibration of peak particle velocity

The calibration of the numerical model is important to provide accurate results which reflect the response of excavated drives to blasting vibrations. In the numerical model, after the blast pressure is applied, the time history of peak particle velocities in the three principal directions are obtained. For this study, the peak particle velocity (PPV) in the vertical direction is used to calibrate the numerical model. These values were measured in the field using Micromate vibration monitors. Only vertical PPV is considered to be an important direction for the propagation of blast waves because of a considerable degree of freedom for material to move in that direction. Figure 4 shows a representation of the blast location and monitoring locations with respect to the paste-filled stope.

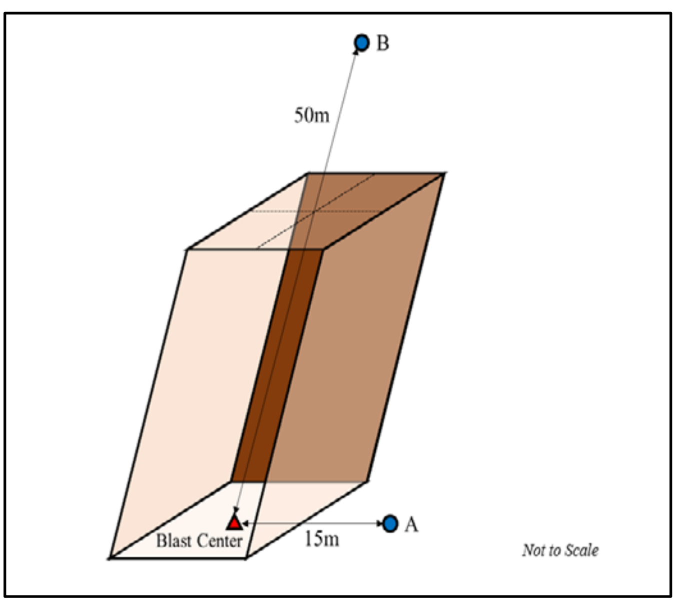

Figure 4. Data monitoring locations with respect to the blast location in the test stope.

Vertical PPV's are observed at two locations namely A and B located at a radial distance of 15 m and 50 m from the blast center, respectively. Table 2 shows the field blast vibration data obtained from conducting a blast in a stope no. 112 located below the -130 mRL. Using the field data, the PPV may be calculated using the equation given by Kumar (2015). As stated by the author, the equation is established based on studies conducted by various researchers and is given as:

$$v = \frac{f_c^{0.642} * D^{-1.463}}{\gamma} \tag{3}$$

where v = peak particle velocity (m/s); f_c = uniaxial compressive strength (UCS) of rock (MPa); and

$$D = \frac{R}{\sqrt{W}} \tag{4}$$

where, D = scaled distance ($m/kg^{1/2}$); R = radial distance from blast center (m); W = charge weight (kg).

Since the blast cannot be explicitly simulated in $FLAC^{3D}$, a free field pressure created by the blast is applied normal to the boundary of the drives and plug which is uniformly distributed along the blast region. The dynamic loading condition along a drive are uniform at its boundary along the axis passing the center of the drive. The equation given by Bulson (1997) is used to calculate the free field pressure at the drive and plug boundary and written as:

$$P_o = \rho c v \tag{5}$$

where, P_o = peak pressure (MPa); ρc = acoustic impedance (MPa.s/m); c = seismic velocity (m/s); and v = peak particle velocity (m/s).

Calibration is done to arrive at suitable values for the Rayleigh damping constants and dynamic loading conditions. Figure 5 shows the history graph for vertical PPV vs. time step for the calibrated model in $FLAC^{3D}$.

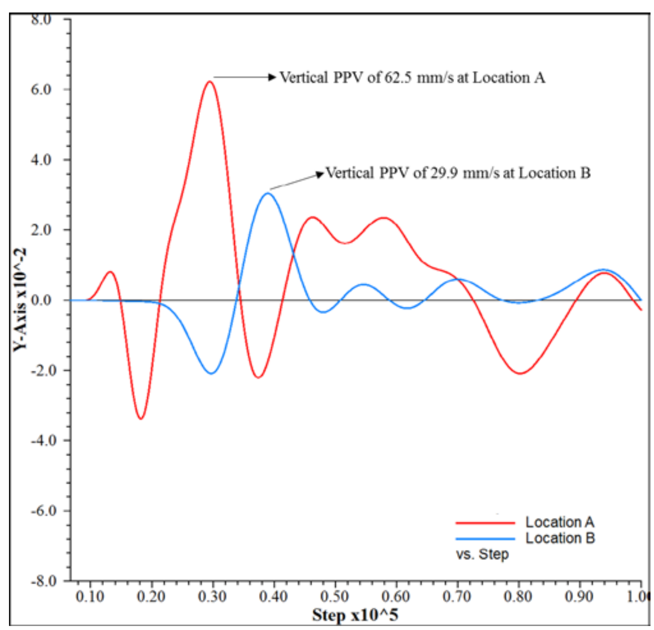

Figure 5. Calibrated model graph of vertical PPV magnitude (Y-axis) vs. time step (X-axis).

It may be observed that the PPV's at location A and B are 62.61 mm/s and 29.9 mm/s respectively. This suggests an error of 0.2% and 16% when compared to field test data obtained at both locations A and B, respectively.

Table 2. Field blast monitoring data for calibration of the numerical model

Location of Blast	Monitoring Location	Total Explosive, kg	Radial Distance, m	Vertical PPV, mm/s
Stope 112 Panel Level -130mRL	A	4254	15	62.61
	B		50	25.03

When comparing the numerical simulation data as shown in Figure 5 and the field data as shown in Table 2, it may be observed that the dynamic model parameters were calibrated effectively.

5. ANALYSIS OF SIMULATION RESULTS

The numerical modeling analysis comprised of two processes, which are static or excavation analysis, and dynamic analysis. The static analysis includes excavation of drives in paste-filled stopes. The objective of static simulation is to reach a balanced or equilibrium state of the mined-out zone after the excavation. On the other hand, dynamic analysis is based on the outcome of the static analysis. It includes the application of dynamic loads on the excavation, created due to the blast pressure for a certain dynamic time step followed by computations. Figure 6 shows the four stopes for which the simulations are carried out. The excavation and blasting process in the real mine happens in an alternate primary-secondary stoping manner and is replicated in the numerical model.

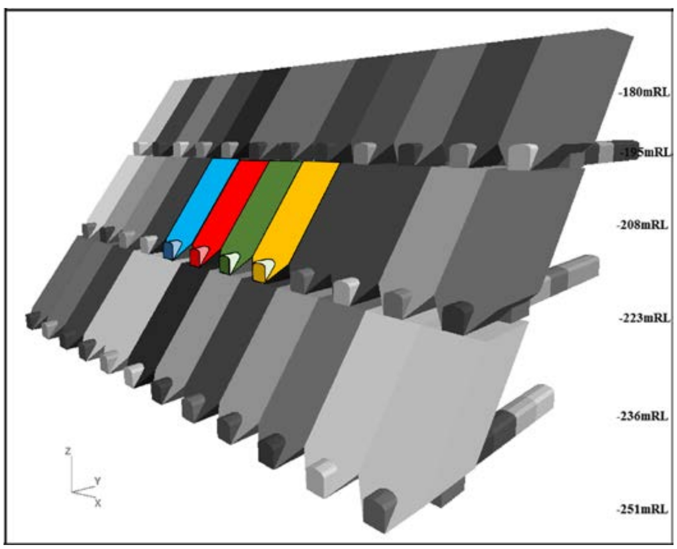

Figure 6. Simulated stopes in the model shown in color

5.1. *Analysis of strength-to-stress ratio*

The strength-to-stress ratio contour plots before the excavation and blasting process are shown in Figures 7, 8 and 9. Figure 7 and 8 show the front view of the contour plots before and after the excavation and blasting process is completed, respectively. It is observed that the paste-fill provides local stability to the mined-out zone.

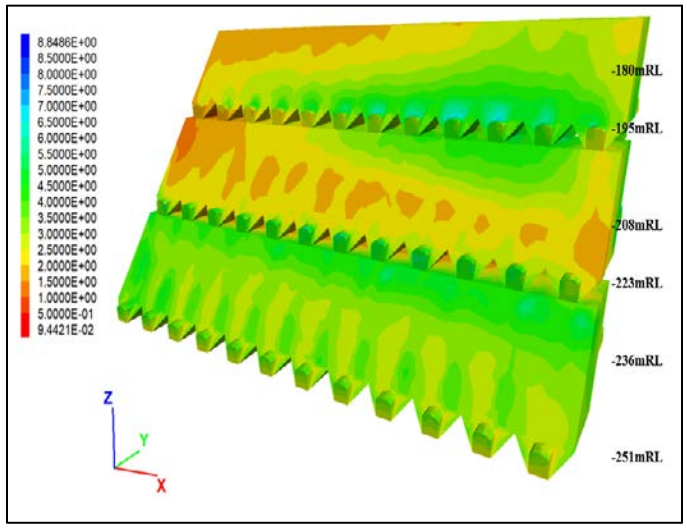

Figure 7. Strength-to-stress ratio contour pre-excavation of drives (front view).

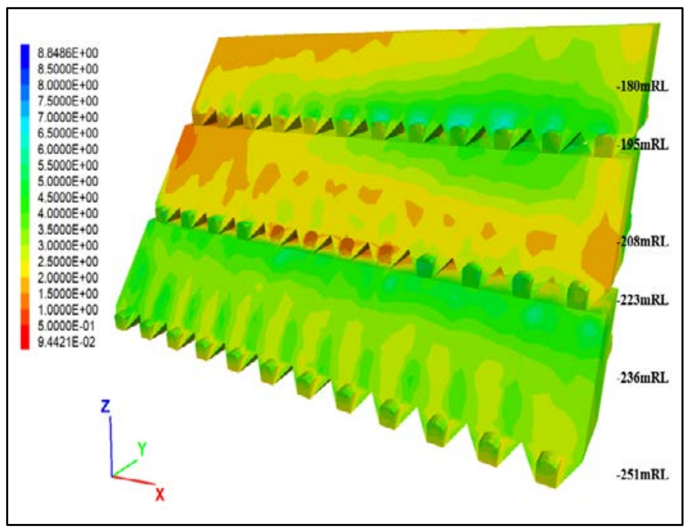

Figure 8. Strength-to-stress ratio contour post-excavation of drives (front view).

It is observed in Figure 9(a) and 9(b) that after blasting and excavation of the drives and blast plug, the factor of safety at many locations near the shoulder and roof of the drives has decreased to less than one. This may be confirmed in cross-section plan views of the drives in Figure 9(c) and 9(d), which show pre-excavation and post-excavation strength-to-stress ratio, respectively. The strength-to-stress ratio contour plots are generated to analyze whether it is safe to carry out further drilling operations from the paste-fill drives to prepare the stopes below for extraction.

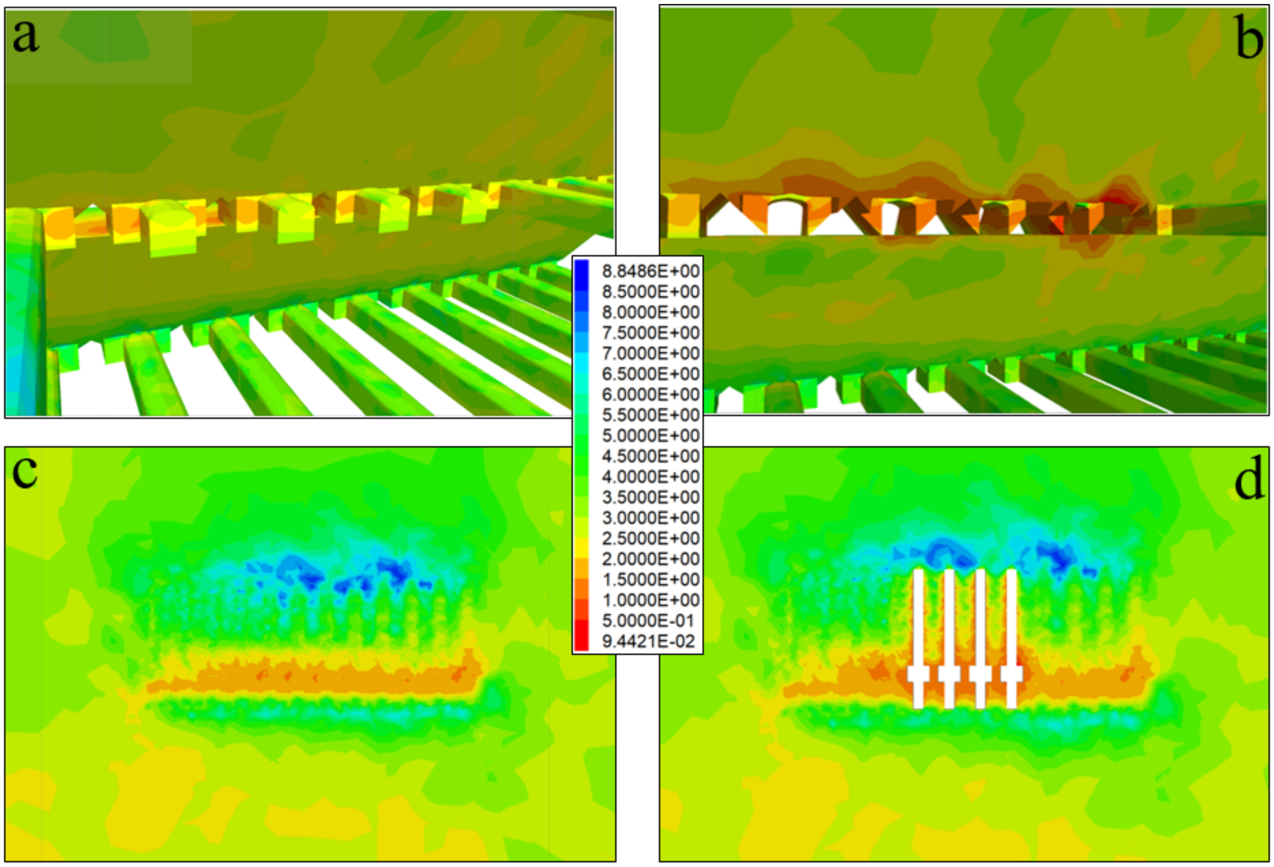

Figure 9. Strength-to-stress ratio contours- (a) pre-excavation of drives (back view), (b) post-excavation of drives (back view), (c) pre-excavation of drives (cross-section view), and (d) post-excavation of drives (cross-section view).

5.2. Analysis of displacement

Figure 10 shows the displacement contour of the four stopes before excavation of drives, whereas, Figure 11 shows the close-up of displacement contours after the excavation of paste-fill drives in all four stopes. By comparing the two, it is observed that a considerable amount of displacement is observed in the roof and floor of the drives. The displacement in the roofs of all four stopes ranges from 30-110 mm, which suggests high displacements due to failure of weaker paste-fill material.

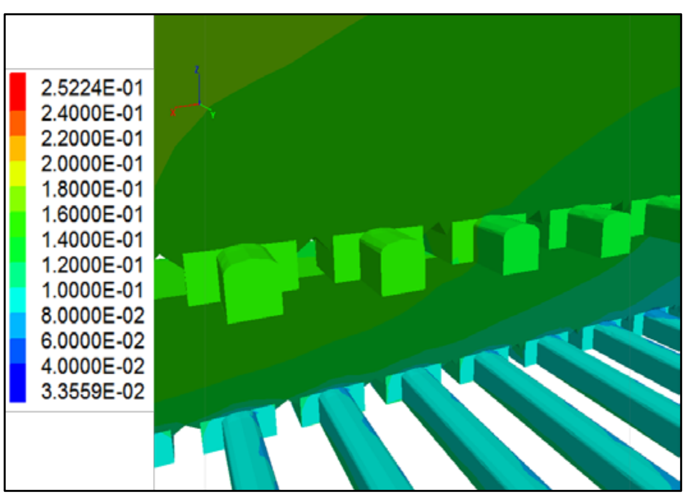

Figure 10. Displacement magnitude contours pre-excavation of drives (back view).

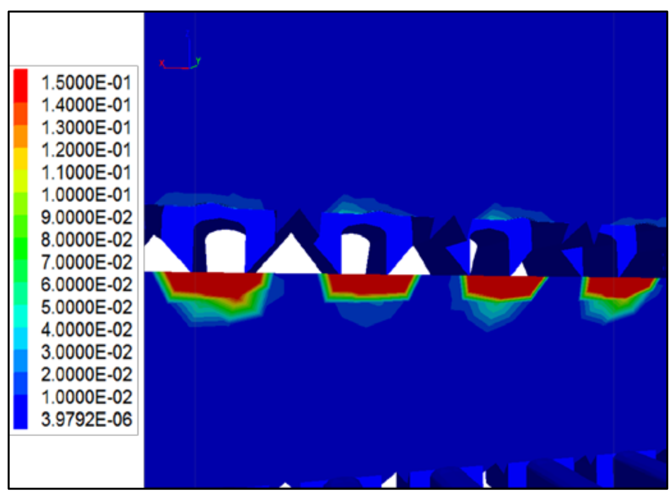

Figure 11. Displacement contours post-excavation of drives (back view).

Figure 12 shows the distribution of displacements during the simulation of excavation and dynamic loading in the four stopes. It may be observed that a primary-secondary order of excavation is followed to simulate the excavation of paste-fill drives. The area of plastic zones in the stopes increases after blasting in adjacent stopes suggesting that blasting vibrations are affecting the previously excavated drives. The contours indicate deterioration of the paste-fill material at many locations in the shoulder and floor of the excavated drives.

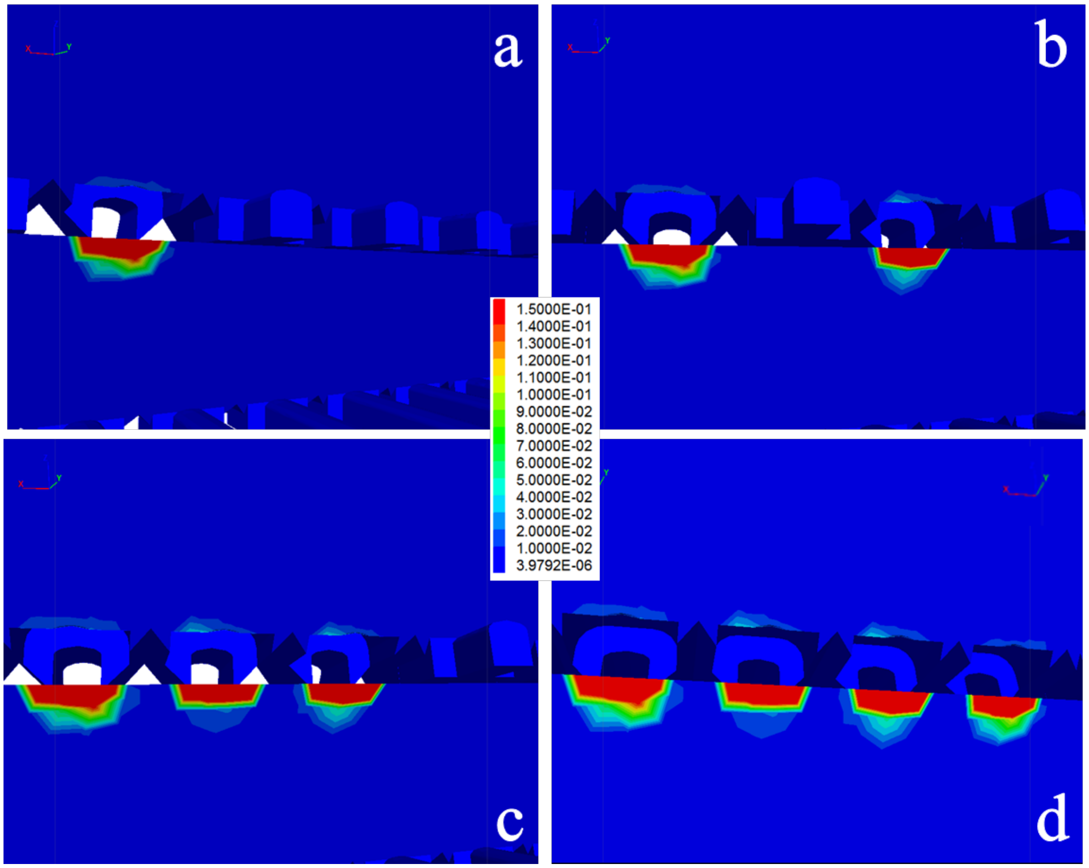

Figure 12. Displacement magnitude contours after blasting for excavation of drives in the four paste-filled stopes.

6. CONCLUSIONS

This study analyzed the effect of blasting and subsequent excavation of drives in paste-filled stopes. This is especially important to assess the stability of the drives for carrying out drilling operations for future stope preparation. The following conclusions can be drawn from this study:

i. The parameters required for this dynamic modeling study are acquired from the geotechnical investigations and blast monitoring data obtained from the test blasts performed in the case mine. An effort is made to keep the model parameters and geometry as accurate to the mine conditions as possible. The Mohr-Coulomb constitutive model is used to represent the rock mass behavior.

ii. Calibration is done using field data of peak particle velocities of the blast vibration waves and those estimated from the model. It was done to calibrate the dynamic damping parameters which are useful to apply dynamic loading conditions and arrive at accurate numerical modeling results.

iii. The simulation results show damage to the shoulder and roof of the drives due to blasting and excavation. The same is confirmed in the field when trial excavation operations were conducted by the mine management in the underground lead-zinc mine.

iv. The drives are found stable enough to carry out further operations of drilling long holes for blasting and extraction of the underhand stope. To ensure the safety of mine personnel and machinery, the mine management decided to reinforce the drives using wire mesh.

v. The damaged area in the roof and shoulder of the drives increased with subsequent blasting in adjacent stopes. This may due to the fact that cumulative damage afflicted by the blast vibrations leads to an increase in the already weak plastic zones of the paste-fill material. However, following an alternate primary-secondary excavation pattern helps in minimizing the damage to the drives when compared to excavation immediately in adjacent stopes.

7. SCOPE OF THE STUDY

The study is useful in analyzing the safety and stability of drives excavated in weak paste-fill material for the underhand mining operation conducted in an underground lead-zinc mine in India. Based on this study, numerous research opportunities may be pursued. It would be useful to study the cumulative effects of blasting on the effect of drives in paste-fill. These drives may prove useful to allow hydraulic filling of stopes below once they are extracted. Also, a parametric study to analyze the sensitivity of the numerical model to dynamic time step, mesh size, damping parameters and physico-mechanical properties of paste-fill material may be conducted. Another useful study would be to analyze the stability of drives and stopes with an increase in working depths which may lead to considerable variations in stress conditions.

8. ACKNOWLEDGMENTS

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