Effect of Parameters on the Surface Crown Pillar Stability in an Underground Mine considering Regression and Artificial Neural Network Models

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Abstract

Natural pillars including surface crown, crown, rib and sill pillars play a vital role to deal with the instability issues encountered in any underground metal mine. Therefore, especially in large-scale production methods, these pillars should be strong enough to endure the generated stresses generated by extraction and blasting. For the final design, more thorough techniques like numerical modelling must be utilized; empirical and analytical methods hold viable for the preliminary design. This study looks into the stability of a 40 m surface crown pillar below the ultimate open-pit bottom at a copper mine with a steeply dipping orebody.

A total of 54 finite element models have been analyzed for underground mines considering elastic-constitutive material model. The evaluation of results obtained from simulation models is carried out using safety factor as a function of variation in material properties, crown pillar thickness, rib pillar thickness and stope extraction sequence. It is observed that for the considered geo-mining conditions, the surface crown pillar is safe for the different parametric variations.

Keywords: Artificial Neural Network, Finite Element Method, Multivariate Regression Model, Surface Crown Pillar.

Introduction

Extraction of ore embedded in the earth crust is the prime purpose of mining. Both surface and underground mining techniques are viable options for extracting the mineral out from the earth. The controlling parameter which determines the mining technique to be used, whether surface or underground, depends on stripping ratio. Once the ultimate open pit bottom is reached, the surface mining method is transformed to underground considering land and environmental related constraints[11,16]. A nearly horizontal rock strata is left intact behind throughout this transformation to ensure the safety and stability of the underground mining operations. This leftover rock from the open pit bottom, i.e. the surface crown pillar separates the direct surface ground from the subterranean[5]. The subsurface structures such as the surface crown pillar not only protect the underground mine from ground movement but also from material inflows. Thus, analysing the behaviour of rock mass in this surface or barrier crown pillar is of utmost importance considering overall stability of the underground mine.

One of the popular mining techniques used for extracting large, tabular deposits with sharp dips is large diameter blasthole (LDBH) stoping employed for mass production in underground mines. If the thickness of the orebody is within 25 m, longitudinal method of extraction is carried out, whereas, if the orebody thickness exceeds 25 m, transverse method of extraction is employed. The stopes extraction in either of the methods leaves behind huge voids, leading to stress concentration around the natural pillars left intact in the underground mine. A nearly horizontal pillar, sometimes referred to as crown pillar, is left intact between two adjacent level of extraction to guarantee the stability of these stopes[14].

Pillar stability is largely dependent on variables including depth, excavation size, rock mass characteristics, backfilling, reinforcing, horizontal load and dipping[8-10]. Thus, optimizing the thickness of underground pillars is an important concern in any underground mine. Very few studies have been carried out for determination of crown pillar thickness in underground mines; however, the literature is restricted only to surface/barrier crown pillars with longitudinal method of stope extraction[3]. Thus, determination of stability of surface or barrier crown pillar is of utmost importance considering field and laboratory investigation as well as numerical simulation.

Before the advent of numerical methods, the analytical and empirical methods were widely used by for determining the thickness of pillars in underground mines. According to Mohanto and Deb[14], numerical methods can effectively handle issues with complex geometry and site-specific factors. In the recent decades, numerical modeling has been extensively used to investigate the stability of subterranean openings in static as well as dynamic conditions[1,6,7,19]. Nowadays, soft computing techniques including artificial neural networks (ANNs), fuzzy inference systems (FISs) and radial basis function neural networks (RBFNNs) are extensively used with field study, laboratory tests and numerical methods to cater to the geotechnical issues in underground[12,13,15,17,19].

The present study focuses on three-dimensional finite element analysis of underground metalliferrous mine operating below an open pit mine with transverse method of stope extraction. Large diameter blasthole stoping method of extraction with ring hole drill and blast pattern is adopted to extract the ore from underground. Below the ultimate pit bottom, a 40 m thick solid surface crown pillar is left intact. A total of 54 numerical models have been developed to analyze the behaviour of surface crown pillar subjected to massive ore extraction in the first level.

Numerical simulation results are assessed in terms of safety factor and principal stress concentration. Parametric sensitivity study is also carried out with variations in material properties, thickness of rib pillar, thickness of crown pillar and sequence of stope extraction. The study has been further extended and multivariate regression (MVR) as well as artificial neural network (ANN) models are also developed. From the simulation results, it can be concluded that the 40 m surface crown pillar is safe considering the variation in above mentioned parameters.

Material and Methods

The case study mine considered for this study is 546 m above sea level and is situated in Malanjkhand, north-east of Balaghat district of Madhya Pradesh. Production from the underground mine began in 2022, as the open pit mine has reached its ultimate pit bottom. The strike of the orebody extends to a distance of 2.2 km with orebody dipping at 65°. However, because to aplite intrusion, the orebody is split into two parts: North and South mine. The orebody has an average thickness of 60 m; hence transverse stoping method is adopted to extract the orebody.

In order to preserve the overall stability of the underground mine, a 40-meter-long surface crown pillar is preserved just below the final pit bottom. Large diameter blasthole (LDBH) technology is used to recover copper ore, using ring-hole/fan pattern as method of extraction. The stope width is maintained at 20 m with rib pillar thickness of 20 m between two stopes. The two mines are expected to produce approximately 5 million tonnes annually.

Three-Dimensional Finite Element Underground Mine Model: Figure 1a shows the three-dimensional underground metal mine model considered for the present study considering ANSYS Workbench User's Manual Version 2023[2]. It shows the five different levels of 60m level interval each and crown pillar thickness of 12m. To meet the production requirement of 5 million ton per annum, two stopes will be in operation at any instant of time. Assumption has been made that the production from the lower levels will be carried out only after backfilling of the subsequent upper levels is completed. A 40 m thick surface crown pillar is kept intact between the ultimate open pit bottom and roof of first level stopes. Figure 1b shows the predefined path-1 along which the results are assessed in terms of factor of safety where path-1 lies 1m above the first level stopes.

Material Properties considered for this study: Using RocData version 4.0[18], the rock mass properties i.e. Young's modulus of rock mass (Ei) is determined from the intact rock properties obtained from laboratory experiments. Table 1 shows the rock material properties of material MP1 (weak), MP2 (moderate) and MP3 (strong) considered for the present study (OB: Orebody; WR: Waste Rock).

Loading and Boundary Conditions: Figure 2 shows the loading and boundary conditions applied on the underground mine model. *In situ* stresses are applied to the side faces of the mine model, with maximum (σ_{Hmax}) and minimum horizontal stress (σ_{Hmin}) respectively. The *in situ* stresses are varied based on depth from the ground surface. The σ_{Hmax}/σ_v and σ_{Hmin}/σ_v are taken as 1.62 and 0.94 respectively[14]. In order to limit movement in the z direction in the Cartesian coordinate system, displacement boundary condition has been considered at the bottom face. Gravitational force is applied to the model for incorporating the body force.

Results and Discussion

The numerical simulation results are evaluated along path 1 in terms of safety factor as shown in figure 1b. All the independent variables (MP, RPT, CPT and SE) considered for this study are made dimensionless so as to better interpret the results as well as perform multivariate (MVR) and artificial neural network (ANN) analyses. The parameters considered in this study are defined as given in equation 1 to 4:

$$\text{Material Property Ratio MPR} = \frac{GSI\ (\text{M}i)}{GSI\ (\text{M2})} \tag{1}$$

where *i* = 1,2 and 3 and corresponds to GSI values of 50, 60 and 70 respectively.

$$\text{Rib Pillar Ratio RPR} = \frac{\text{RPT}i}{\text{RPT2}} \tag{2}$$

where i = 1 and 2 and represents rib pillar thickness (RPT) of 15 m and 20 m respectively.

$$\text{Crown Pillar Ratio CPR} = \frac{\text{CPT}i}{\text{CPT2}} \tag{3}$$

where i = 1, 2 and 3 and represents crown pillar thickness (CPT) of 10 m, 12 m and 15 m respectively.

$$\text{Stope Extraction Ratio SER} = \frac{\text{Extracted stope volume}}{\text{Total stope volume}} \tag{4}$$

The simulation results obtained from numerical modelling showed that average value of SF varies linearly with variation in MPR, RPR, CPR and SER for all values of individual independent variables respectively.

Multivariate Regression (MVR) Model: Parametric sensitivity study was carried out to understand the effect of material property ratio (MPR), rib pillar ratio (RPR), crown pillar ratio (CPR) and stope extraction ratio (SER) on stability of the surface crown pillar. An MVR model was

https://doi.org/10.25303/185da76081

developed based on the obtained numerical simulation results. Equation (5) shows the regression model for safety factor (SF) of surface crown pillar for the range of geo-mining variations considered in this study.

$$SF = 0.2475\ \text{MPR} + 1.292\ \text{RPR} + 0.1395\ \text{CPR} + 0.1245\ \text{SER} \quad (5)$$

The coefficient of determination R2 and F-statistic values are found to be 0.9969 and 4091.7 respectively for the given MVR model. The obtained MVR model is found to be statistically significant (95% confidence interval) with p-value less than 0.05 for all the independent variables except stope extraction ratio (SER). It implies that SER is not significant to explain the presence in the model. Based on the obtained t-statistic value, it is concluded that RPR has the strongest positive impact on the safety factor (SF) followed by MPR, CPR and SER, respectively.

Artificial Neural Network (ANN) Model: In the present study, out of 54 data sets, 69% of the data are used for training the model, 22% of the data sets are used for testing and 9% of the data sets are used as holdout set for validation of the developed ANN model. The hidden layer considered for the present is one with 9 different cases analyzed for the surface crown pillar, varying the number of neurons between 1 and 9 as suggested by Caudill[4].

The performance indices: R^2, mean absolute error (MAE) and root mean square error (RMSE), are used for performance evaluation of all the individual models. The highest performance is found to be with 7 neurons in one hidden layer and hyperbolic tangent as activation function in the neurons of the hidden and output layers (Figure 3). The performance indices i.e. R^2, MAE and RMSE values are found to be 0.96582, 0.02167 and 0.02415 respectively on the test data set.

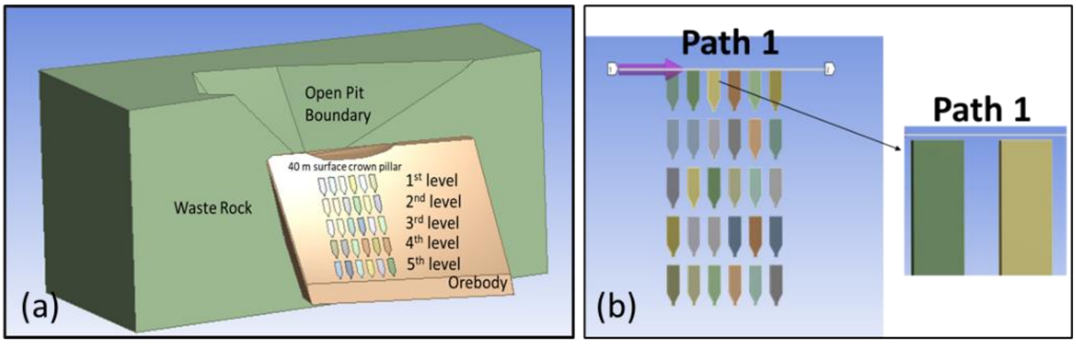

Figure 1: (a) Three-dimensional mine model (b) pre-defined path 1 considered for the study

Table 1
Material properties considered for the present study

Material Properties	MP1		MP2		MP3	
	OB	WR	OB	WR	OB	WR
GSI	60	60	65	65	70	70
Density ρ (kg/m^3)	2690	2700	2690	2700	2690	2700
Poisson's ratio ν	0.16	0.12	0.16	0.12	0.16	10.1
Compressive strength of rock mass σ_{cm} (MPa)	7.9	12.8	13.8	17.5	20.9	23.8
Young's Modulus of rock mass E_m (GPa)	5.2	8.8	8.5	11.1	11.8	13.5

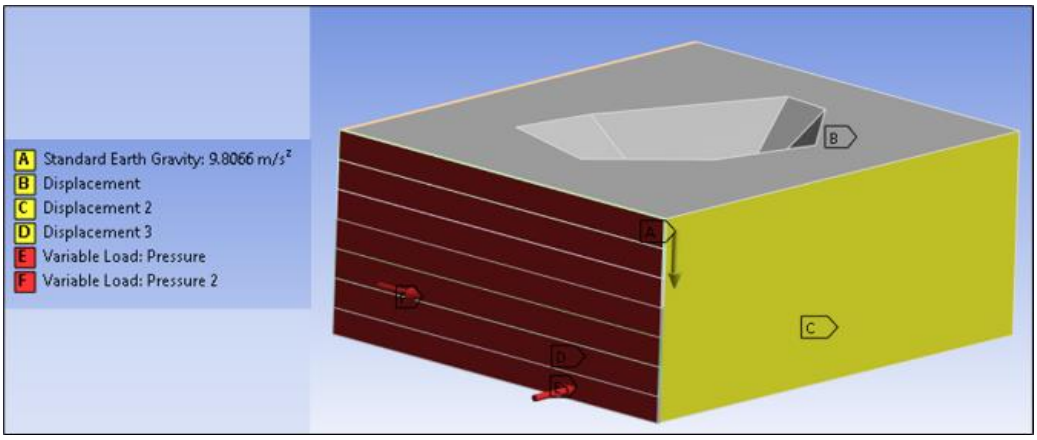

Figure 2: Loading and Boundary conditions considered for the study

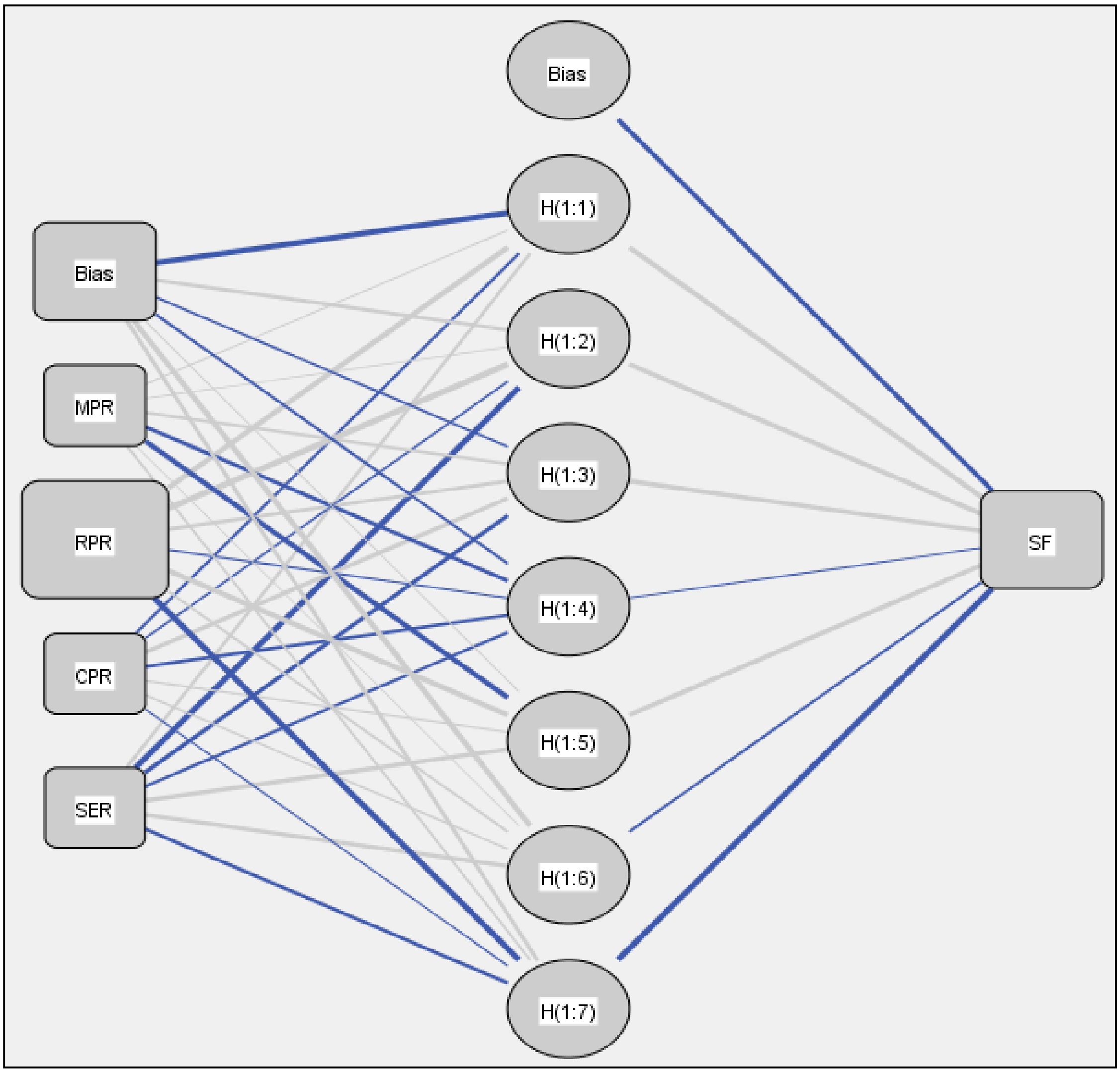

Figure 3: Artificial neural network (ANN) model with 7 neurons in the hidden layer

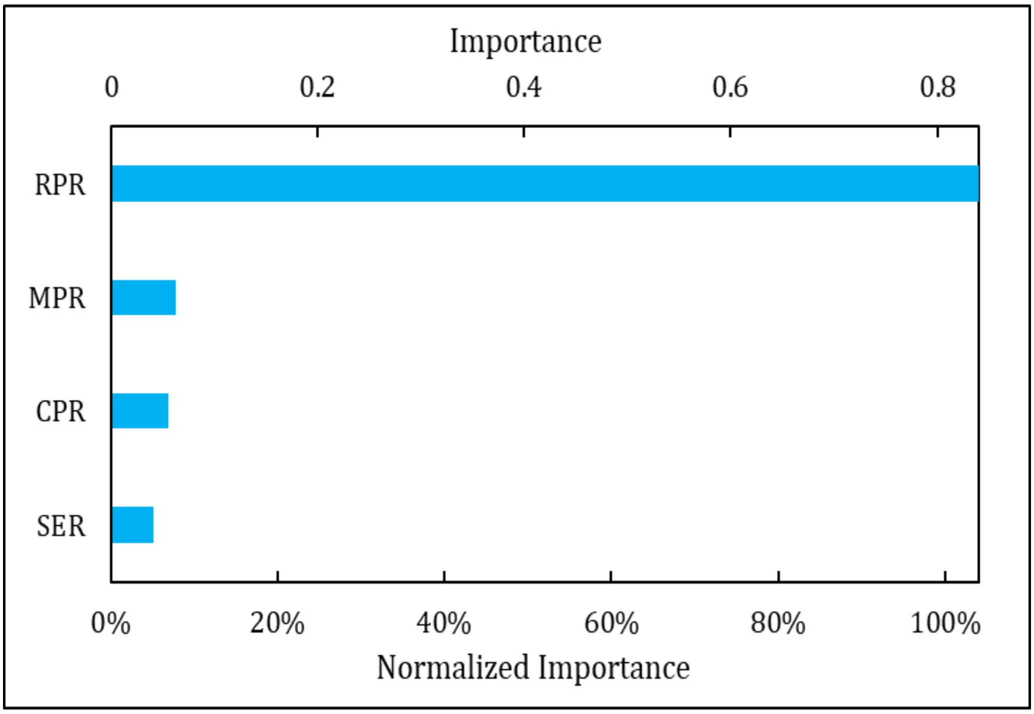

Figure 4: Normalized importance of dependent variables based on ANN model

The normalized importance shows that RPR has the most significant impact on how the ANN model determines safety factor *SF* for the surface crown pillar stability followed by MPR, CPR and SER respectively as shown in figure 4. The coefficient of determination R^2 and F-statistic values are factor *SF* for the surface crown pillar stability followed by and MPR, CPR and SER, respectively as shown in figure 4.

Conclusion

The present study focuses on the three-dimensional finite element analyses of an underground metal mine to analyze the stability of 40 m thick solid surface crown pillar. The findings are:

1. The surface crown pillar was found to be stable with different variations of material properties, crown pillar thickness, rib pillar thickness and stope extraction sequence.

2. A multi-variate (MVR) regression model was developed considering the numerical data obtained from simulation. The MVR model was found to be statistically significant with R2 value of 0.9969. The higher value of R2 can be attributed to the fact that there is insignificant change in safety factor at a height of 1 m above the open stopes from the first level. However, the values may change at different depths from the open pit bottom.

3. An artificial neural network has also been developed for the present study. The normalized importance shows that RPR and MPR have the most significant impact on how the ANN model determines safety factor SF for the surface crown pillar stability followed by CPR and SER. The artificial neural network model shows R2 value of 0.96582 which is less than the MVR model. It can be attributed to the fact that the total number of models are comparatively less; thus, increasing the number of parameters or models may improve the accuracy of the ANN model.

Thus, it can be inferred that the surface crown pillar can be rendered safe for the different variations considered in the geo-mining conditions prevailing in the case study mine site. Both the MVR and ANN models can be used for predicting the safety factor of surface crown pillar under the given range of independent variables. However, further, the study can be extended at different depths from the ultimate open-pit bottom to capture the safety factor close to the proximity above the first level stopes.

Acknowledgement

The authors are grateful to the competent authorities of Hindustan Copper Limited (HCL) for granting the project.

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(Received 22nd January 2025, accepted 20th February 2025)