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Parametric Study on the Stability of Crown Pillars Considering Multi-Variate Regression and K-Cross Validation Techniques

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***Abstract* -** The role of crown pillar between two main levels in any underground metalliferrous mine plays a pivotal role in maintaining the stability of extracted open stopes in each level. Thus, the dimension of the crown pillar left intact between the main levels in the underground should be competent enough to withstand the induced stresses developed as a result of extraction as well as blasting, especially in large scale production methods such as large-diameter blasthole stoping method. In addition to the crown pillars in adjacent levels, a barrier crown pillar of sufficient thickness is also left intact between the ultimate pit bottom and the first level of extraction. These horizontal pillars are of utmost importance as it is one of the deciding factors in determining the stability of the existing underground structures throughout the life of mine. The present study focuses on the stability of a crown pillar left intact between two main levels existing below an open pit mine operating simultaneously with the underground mine. The targeted proposed production of the underground mine is around 5 million tonne per annum. In this paper, a total of 135 finite element models of the underground mine have been analyzed considering elasto-plastic material model. The simulation models are assessed in terms of plastic damage index with variation in material properties, crown pillar thickness, stope-extraction sequence and depth of mining. Based on the results obtained, some useful conclusions have been drawn considering both multi-variate regression and k-cross validation models.

***Keywords*:** Crown pillar stability · Plastic damage index · multi-variate regression · Artificial neural network · *k*-fold cross validation

1. Introduction

Pillars are essential structural units of most underground mines, used to ensure safety and economically maximize the extraction of the ore body [1]. The primary purpose of the pillars is to provide safe access to working area and to support the load of overlying strata and overburden between adjacent underground openings temporarily or permanently. The Pillars are the "in-situ rock between two or more underground openings" [2] which is also be termed as the natural pillars. The intact left-over natural pillars in underground metalliferous mines includes the rib pillar, sill pillar, crown pillar, barrier pillar, shaft pillar, and post pillars. The role of pillars is to maintain the local stability around individual excavations and more general control of displacements in the mine near-field domain. Thus, the economic and safe design of the pillar support system should fulfil the essential requirement of assuring the global stability of the mine structure [3]. The dimension of crown pillar in metal mines plays a crucial role in determining the stability of surrounding rock structures especially when dealt with large-scale production methods such as large diameter blasthole (LDBH) stoping method. An under-designed pillar may not sustain the induced stresses developed during stoping and may lead to the collapse of both crown and rib pillars. On the other hand, ores are locked in an over-designed crown pillar and hence, it reduces the ore recovery. Very few studies have been carried out so far to determine and predict the thickness of the crown pillar in an underground; however, the study is only limited to surface/barrier crown pillar with longitudinal method adopted for extraction of stopes [4]. There exists no literature to determine and predict the thickness of crown pillar considering transverse method of stope extraction with thick orebodies.

The present study focuses on stability of crown pillars in an underground copper mine with transverse method of stope extraction using three-dimensional non-linear finite element (FE) analyses using ANSYS Workbench Version 2023 [5]. Elasto-plastic constitutive plasticity model has been used to simulate the stress-strain response of rock mass. The analyses result obtained from the numerical simulations are evaluated in terms of a plastic damage index 'η' as proposed by Mohanto and Deb [6]. Parametric study is also carried out varying parameters such as material properties, stoping sequence, crown pillar thickness and depth of working to determine the significance of each parameter with η. Multi-variate regression (MVR) and k-cross validation models have also been developed considering the mentioned input parameters. From this study, it is quite evident that the methodology adopted in this paper can be applied in similar geo-mining condition as there is hardly any literature reported for crown pillar stability with transverse method of stope extraction.

2. Three-dimensional Numerical Modelling of the Underground Mine

Figure 1 shows the underground mine model geometry below a surface mine, considered for this study. Transverse method of stope extraction is carried out owing to the thicker ore deposit, i.e., stope extraction across the strike direction. The surrounding rock mass includes the orebody (OB) surrounded by waste rock (WR) with intrusion of basic dyke (BD). Five working levels have been considered for the present study with level interval of 60 m for the first level followed by 75 m level interval for the subsequent lower levels. Out of the six stopes in a particular level, two active stopes are operating in each level to meet the production target of the underground mine. A surface/barrier crown pillar of 40 m thickness is maintained below the ultimate pit bottom; thereby, providing overall stability to the underground mine. The crown pillar extends throughout the entire stope length across the strike between two main levels. It is assumed that the all the stopes in a particular level are backfilled before undergoing stope extraction in the lower levels.

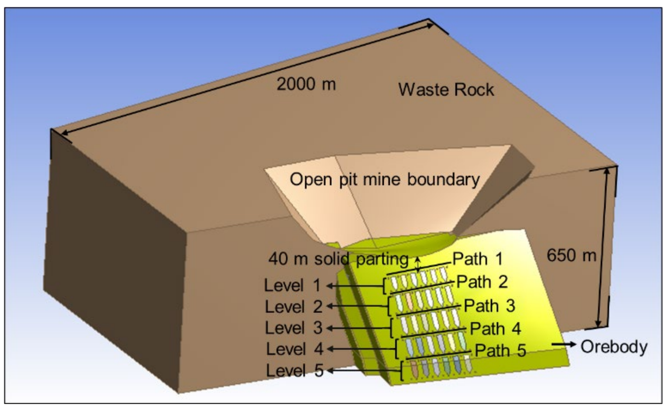

Fig. 1: Three-dimensional underground mine model considered for the study.

2.1. Rock Mass Properties considered for the study

The core rock samples collected from the case study mine are tested in the laboratory to determine their mechanical and elastic properties. To incorporate the field conditions, parameters such as geological strength index (*GSI*) and degree of disturbance (*D*) are used to determine the rock mass properties. To reduce the geo-mechanical properties of the intact rock, RocData User's Manual Version 4.0 is used. Table 1 shows the material properties of the rock mass considered for the study; where M1: weak rock mass, M2: moderate rock mass representing field conditions and depicting average value of strength values and *GSI*, and M3: strong rock mass.

Table 1: Material Properties considered for the numerical analyses.

Material Properties	Material M1			Material M2			Material M3		
	OB	BD	WR	OB	BD	WR	OB	BD	WR
GSI	60	60	60	65	65	65	70	70	70
σ_{cm} (MPa)	7.9	7.3	12.8	13.8	9.9	17.5	20.9	13.7	23.8
E_m (GPa)	5.2	6.9	8.8	8.5	8.7	11.1	11.8	10.6	13.5
ϕ_m (deg.)	51.3	49	55	54.7	50.7	56.4	57.5	52.2	57.8
c_m (MPa)	2.9	2.7	3.6	3.6	3.0	4.0	4.4	3.4	4.5

σ_{cm}: Uniaxial compressive strength of rock mass, E_m: Youngs modulus of rock mass, ϕ_m: Angle of internal friction of rock mass and c_m: Cohesion of rock mass

2.2. Loading and Boundary Condition

The maximum and minimum principal horizontal stresses are applied onto the side faces according to the depth of mine model; whereas, the opposite faces are constricted in respective directions. To incorporate the in-situ stresses, gravity loading is applied in vertical direction to the underground model shown in Figure 1.

2.3. Input Variables for Parametric Study

A parametric study is carried out to determine the plastic damage index η based on the variation of four independent variables, i.e., material ratio MR (3 variations: M1, M2 and M3), crown pillar ratio CPR (3 variations: 10 m, 12 m and 15 m), stope sequence ratio SSR (3 variations: P-R-P, P-R-S-R-P and P-R-S-R-S-R-P; where P: Primary stope, R: Rib pillar and S: Secondary stope) and depth ratio DR (5 variations for 5 different levels). All the input parameters are made dimensionless as ratios for better comparisons of the results in this study. The terms MR, CPR, SSR and DR are defined as:

$$\text{Material Ratio (MR)} = \frac{\sigma_{cm}(\text{M}i)}{\sigma_{cm}(\text{M2})} \tag{1}$$

$$\text{Crown Pillar Ratio (CPR)} = \frac{\text{C}i}{\text{C2}} \tag{2}$$

$$\text{Stope Sequence Ratio }(\text{SSR}) = \frac{\text{Extracted/Stope Volume}}{\text{Total Volume}} \tag{3}$$

$$\text{Depth ratio (DR)} = \frac{\text{Depth of a particular level from the open pit bottom (m)}}{\text{Depth of the last level from the open pit bottom (m)}} \tag{4}$$

where i is the number of variations of that particular parameter.

3. Results and Discussions

The numerical simulation results are assessed along pre-defined paths 1-5 as shown in Figure 1 in terms of plastic damage index η. Figure 2 (a) – (b) show the influence of parameter MR on the average η value for different values of SSR and DR considering crown pillar thickness of 12 m. It was observed that plastic damage index η value increases linearly with decrease in material ratio MR, decrease in crown pillar ratio CPR and increase in stope sequence ratio SSR. However, it varies in a non-linear fashion with an increase in depth ratio DR for the different variations of the other independent variables.

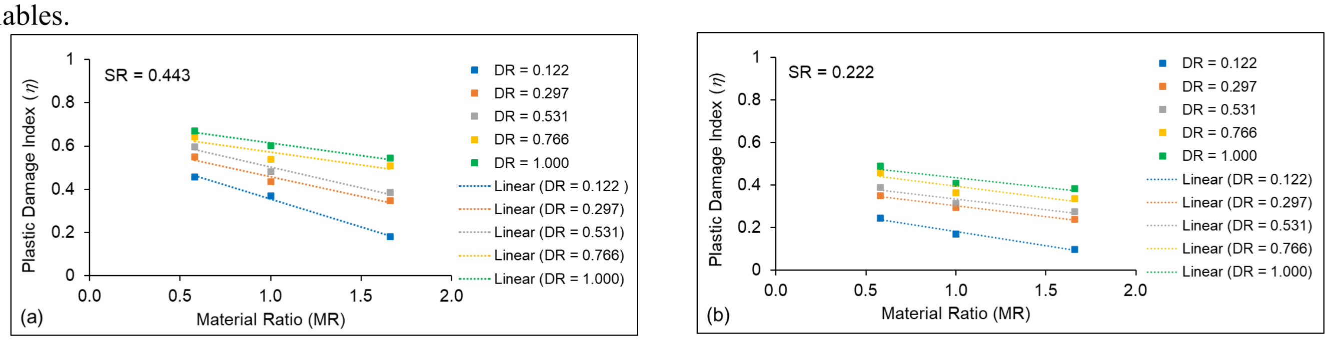

Fig. 2: Variation of average η with change in MR for (a) P-R-P, and (b) P-R-S-R-P sequence of extraction

Based on the results obtained from the numerical simulation, a multi-variate regression and a multilayer perceptron ANN model considering 9-fold cross validation evaluation technique are developed for the present study; where, the dependent variable is plastic damage index η and independent variables are MR, SSR, CPR and DR. Figure 3 (a) shows the variability of the predicted η obtained from regression analysis and the observed η from FEM analysis. The R^2 for the regression analysis of the crown pillar stability between observed and predicted η is found to be 0.94. Figure 3 (b) shows the importance and normalized importance of independent variables obtained from the ANN model for crown pillar stability;

where, normalized importance is defined as the ratio of importance value to the largest importance value and is expressed in terms of percentage. It was inferred from both the models that SSR has the strongest positive influence on plastic damage index η and there exists a linear relationship between them. The second most contributing parameter is depth of working; but it resembles a non-linear relationship. The third most influencing parameter is material properties followed by crown pillar thickness. However, the effect of CPR on plastic damage index η is so small that it can be neglected for all practical purposes.

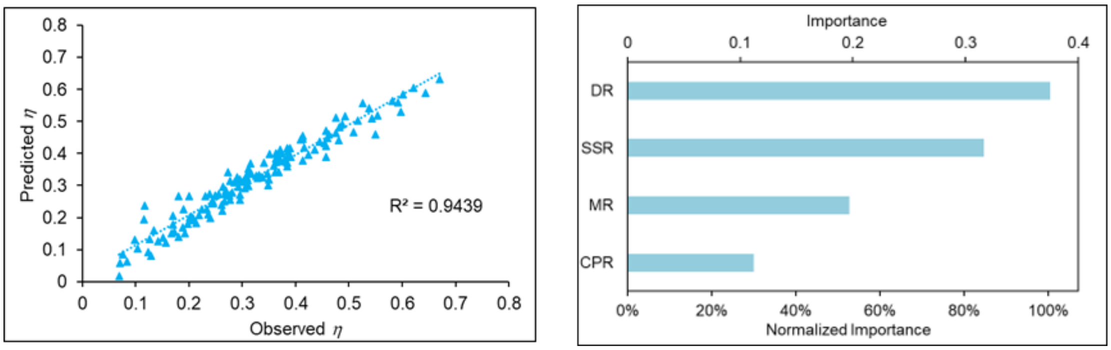

Fig. 3: (a) Comparison of observed η (FEM) with predicted η (MVR) and (b) Normalized importance of variables for ANN model

4. Conclusions

Maintaining the stability of crown pillars at different levels in an underground metal mine is one of the major challenging issues when dealt with large scale production scenario. Three-dimensional FE analyses have been performed to simulate the stability of crown pillar in an underground mine with transverse method of stope extraction. The results obtained from numerical simulations are analyzed in terms of plastic damage index η. Parametric studies have also been carried out to develop a multi-variate regression (MVR) and k-cross validation models for prediction of plastic damage index η, based on the different variations in material properties, crown pillar thickness, stoping sequence and depth of working. This study has led to the inference that stoping sequence has the strongest influence on plastic damage index, followed by depth of working, material properties and crown pillar thickness. The methodology adopted in this paper may be applied in several other applications in underground mine stability analysis considering different variations of mentioned parameters and also including variations of other parameters such as rib pillar width and stope height.

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References

[1] M. Ahmad, N. A. Al-Shayea, X. W. Tang, A. Jamal, H. M. Al-Ahmadi, and F. Ahmad "Predicting the pillar stability of underground mines with random trees and C4. 5 decision trees." *Applied Sciences* 10.18 (2020): 6486.

[2] D. F. Coates. Rock mechanics principles. In *Geoscience Abstracts*; American Society Photogrammetry: Bethesda, MD, USA, 1966.

[3] B. Brady and E. Brown. Pillar supported mining methods. In: *Rock Mechanics for underground mining*. Springer, Dordrecht. 2007.

[4] T.G. Carter. A new approach to surface crown pillar design. in *Proceedings of the 16th Can. Rock Mechanics Symposium*. Sudbury. 1992, pp. 75-83.

[5] ANSYS Workbench User's Manual. Version 17.0. Pennsylvania. United States

[6] S. Mohanto and D. Deb. Prediction of Plastic Damage Index for Assessing Rib Pillar Stability in Underground Metal Mine Using Multi-variate Regression and Artificial Neural Network Techniques. *Geotech Geol Eng*. 2020:38, pp:767–790.