A numerically based geomechanics risk assessment of the cut and fill underground mining method

Kamilya Omirzhankyzy, Ali Mortazavi
School of Mining & Geosciences, Nazarbayev University, Astana, Kazakhstan

ABSTRACT: The study of rock pillar stability is a common concern in mining engineering. It is critical to enhance predictive research of the mining effect and improve design to avoid catastrophic failures in mines operating at great depths. This results in the creation of pillars that must be retrieved during subsequent phases of excavation, typically under conditions of extreme stress. The purpose of this work is to examine the geomechanical parameters affecting pillar stability and behavior under the complicated nature of the rock mass in-situ, boundary conditions, and operational complexities associated with the cut-and-fill mining method at great depths. To evaluate the pillar deformation mechanisms, a comprehensive Finite Element Analysis was conducted. The obtained results are discussed and presented in terms of pillar stress and displacement fields. A parametric analysis was conducted to compare and determine the significance of geomechanical design parameters on pillar behavior, stability, and bursting potential.

Keywords: Geomechanics Design, Pillar Stability, Risk Assessment, Cut and Fill method.

1 INTRODUCTION

Rock that is in its natural state between two or more underground excavations is referred to as a pillar. For this reason, the extraction of ore from underground mines always involves the use of pillars, whether they are temporary or permanent. The cut-and-fill method is employed most frequently in steeply dipping vein deposits as well as huge deposits that have an irregular shape. The most significant aspects of pillar design are knowledge of the pillar strength and the estimation of the needed safety factor for a specific loading scenario. Empirical and computational methods can be used to evaluate the pillar load; however, the in-situ pillar strength is typically unknown and significantly more challenging to ascertain. In South African coal mines, Salamon (1970) was the first author to offer an empirical and semi-statistical method for the determination of pillar strength. The subject of pillar analysis and pillar design has been investigated by many authors.

The use of numerical methods, as advanced design tools, allows considering a variety of complicated boundary conditions and material behaviors. The complex nature of rock mass at in-situ scale makes it a difficult material from a mathematical representation point of view. Regarding the non-linear behavior of rock pillars at high stress levels associated with deep mining conditions, numerical methods may be utilized to examine the mechanisms involved in rock pillar behavior. The primary objective of this paper is to investigate, under 2D conditions, the pillar behavior under different stress conditions and varying geomechanical design parameters. In this research, the behavior of heavily stressed sill pillars was simulated using the finite element analysis method. The primary objective is to investigate the effect that material strength parameters on in-situ behavior of pillars.

2 METHODOLOGY

2.1 *Modelling strategy and input data*

In this research, a 2D finite element model of a typical cut-and-fill mining method condition, employed in narrow vein mining conditions, was constructed using the RS2 code (Rocscience, 2020) for an orebody that is dipping at an angle of 75 degrees. An analysis domain of 300 m × by 400 m was considered for the model. The overall view of the constructed model, the employed boundary condition, and a magnified view of the orebody geometry is shown in Figure 1. The orebody thickness (width) is 15 m, height H is 100 m, and H_s (the height of the sill pillar) is 7.5 m, H_l which is the thickness of the layers or cuts used to excavate the underneath stope and equals 3 m. The mining depth is 1000 m.

Stress change in the sill pillar as a function of mining was monitored to describe the mechanisms involved. A series of measuring points were considered within the sill pillar in the horizontal and vertical directions (Fig. 1b). Mining was conducted symmetrically on both sides of the pillar to better observe the mining effect on stress change in the sill pillar, hanging wall, and foot wall. A linearly variable vertical stress variation was considered within the model and various horizontal-to-vertical stress ratios (k = 0.5, 1, 1.5, and 2) were considered during the analyses. A Mohr-Coulomb material model was used in all analyses.

The input data to the model were taken from the Norilsk Region, Russia (Neverov, 2014). Norilsk is in the Russian High Arctic, 2800 km north of Moscow, and is one of the world's largest nickel and palladium producers and copper suppliers. Norilsk's copper-nickel-PGM deposits lie between 500 m and 1500 m below a flood basalt and sediment sequence. A combination of intact rock data and rock mass data was used within the RocData software environment to determine rock mass design parameters as input to the model. A summary of the physical and mechanical properties and the determined rock mass data which was used in the numerical analysis is presented in Table 1.

Table 1. The rock mass data used as an input in the analysis.

Material	ρ (MN/m^3)	Poisson 's Ratio	GSI	Deformation Modulus (MPa)	Tensile strength (MPa)	Friction angle (deg.)	Cohesion (MPa)
Host Rock	0.027	0.22	67	26246	0.88	44.4	5.3
Ore	0.04	0.25	70	19324	0.47	39.8	5.6

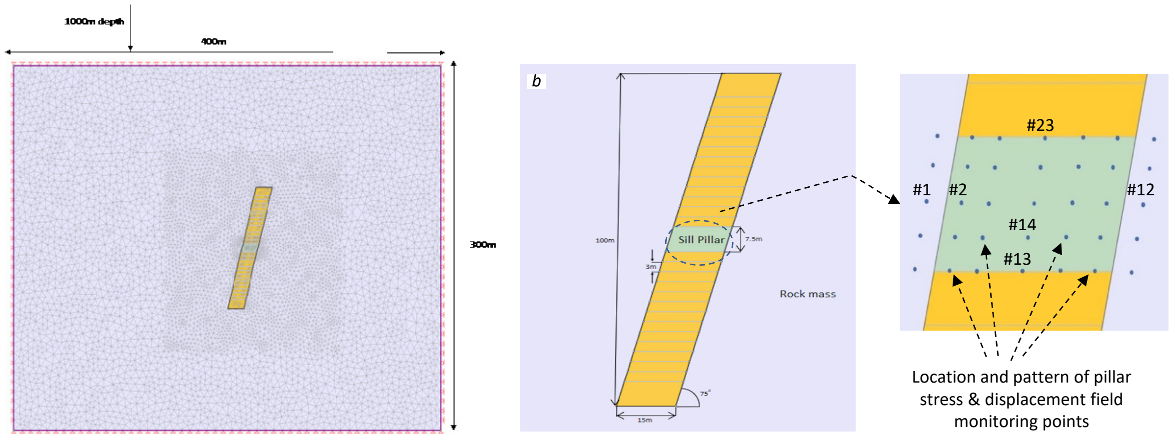

Figure 1. The overall view of the constructed model: a) model discretization and boundary condition, b) Magnified view of the orebody and pillar geometry.

2.2 *Sensitivity analysis*

The concern was to study the behavior of the sill pillar as large-scale rock convergence and sudden release of strain energy occur as the final dimensions of the pillar and excavated area are approached. The cut-and-fill mining process was simplified to demonstrate the mechanisms involved in stress change and redistribution as a function of mining. The data were gathered from 35 monitoring points (Fig. 1b) with a consequent parametric and statistical analysis of the key geomechanical parameters which were varied by ±5%, ±10%, and ±15%. A total of 72 independent analyses were carried out. The sensitivity analysis was performed by monitoring the stability behavior with respect to changes in different variables in the model. Some key results obtained from the analysis are presented in the next section.

3 NUMERICAL SIMULATION RESULTS

3.1 *Base Model Simulation*

In the base run model, the data determined and reported in Table 1 were used as input. It is generally agreed upon that the failure of the pillars begins on the sides and, in the absence of confinement, spreads inward toward the center of the pillar. Since the goal of this study was to have a detailed analysis of the load distribution and change within the pillar while the excavation process was being carried out, the excavation process was carried out simultaneously on both sides of the pillar. Accordingly, the pillar was loaded symmetrically, and this enabled a better observation of change in pillar stress and displacement fields. This made it possible to evaluate the behavior of the pillar under loading as a function of the strength and deformability of the pillar. Throughout the process of excavation, the vertical stress was continually measured, and the locations of monitoring points were chosen in such a way that it was possible to analyze the influence of pillar end effects as a function of change in pillar strength parameters. A change in the pillar stress field as a function of mining cuts is shown consecutively in Figure 2. In this run, the pillar width-to-height ratio is 2 and the ratio of horizontal to vertical stress was assumed to be 2. As can be seen from the figure, mining of each cut leads to an increase in the stress level within the pillar which eventually may lead to a pillar burst if not controlled. Figure 3a illustrates the variation of pillar maximum principal stress along the pillar width and as a function of mining steps for horizontal to vertical stress ratio of 2. Moreover, this diagram illustrates the magnitude of the pillar stress build-up at various stages of excavation. As can be seen from the figure, as excavation begins on both sides of the pillar, elastic stresses begin to build up along the edges of the pillar, and stress concentration rises at these places due to the pillar compressing by the horizontal stress field. This is followed by the failure of the edge of the pillar, which causes the stress concentration to move into the core of the pillar. When elastic–perfectly plastic models are used, the confinement of the pillars is overestimated, which leads to an overestimation of the pillar strength. It is realized that the strain-softening constitutive law is the most accurate model to use when attempting to define the behavior of pillars but due to lack of data, usage of this model was not possible in this work. A second set of runs was conducted assuming a hydrostatic field (k = 1). Similarly, the change in pillar stress as a function of the mining step is shown in Figure 3b. Comparing the two simulation results, it is visible that in a hydrostatic field, the pillar benefits from the unified confining stress provided in-situ, and thus a higher stress build-up in the pillar is observed.

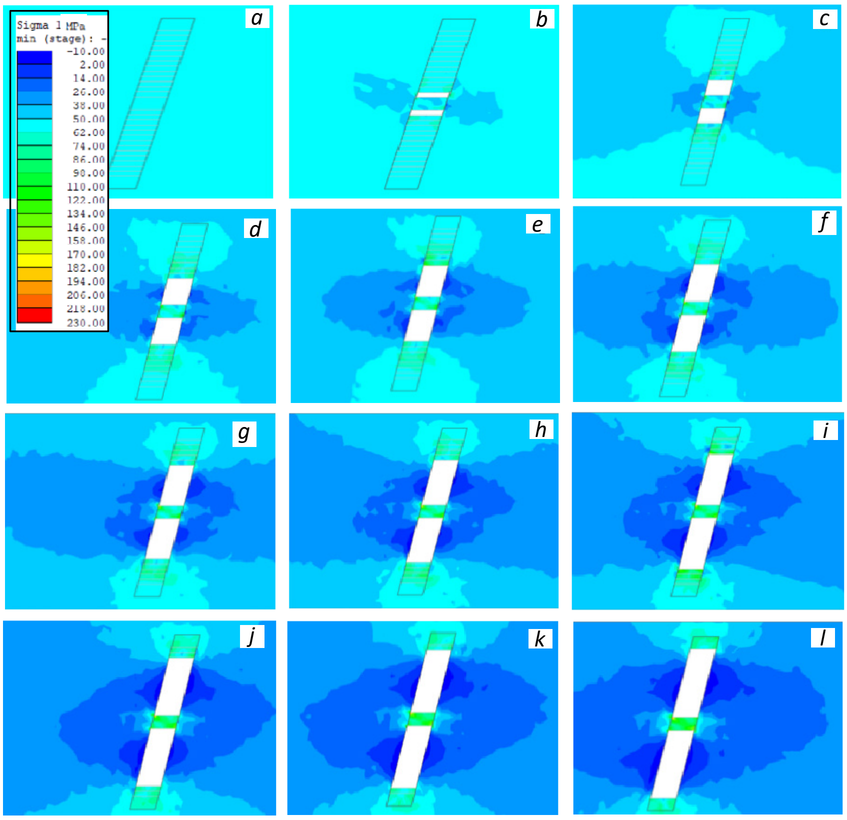

Figure 2. Principle stress distribution in sill pillar and surrounding host rock as a function of the mining step: a) In-situ (no mining), b) Step 1, c) Step 4, d) Step 6, e) Step 7, f) Step 8, g) Step 9, h) Step 10, i) Step 11, j) Step 12, k) Step 13, l) Step 14.

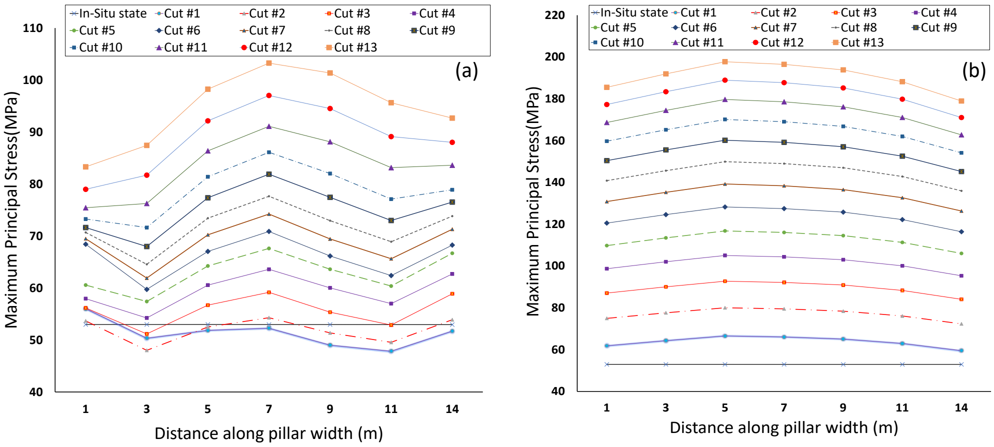

Figure 3. The pillar stress change measured at monitoring points as a function of mining step: a) k=2, b) k=1.

3.2 *Parametric study of the effects of pillar design parameters*

In the conducted parametric study key mechanical and strength parameters of the pillar were changed and the pillar stress field was determined. In total 72 independent analyses were conducted and only some of the obtained results are presented here due to space limitation. As an example, the effects of a 10% increase in rock mass friction angle and a 10% decrease in rock mass deformation modulus were simulated separately and the obtained results are presented in Figure 4. The maximum principal stress distribution was measured and presented in an identical format to the base run results.

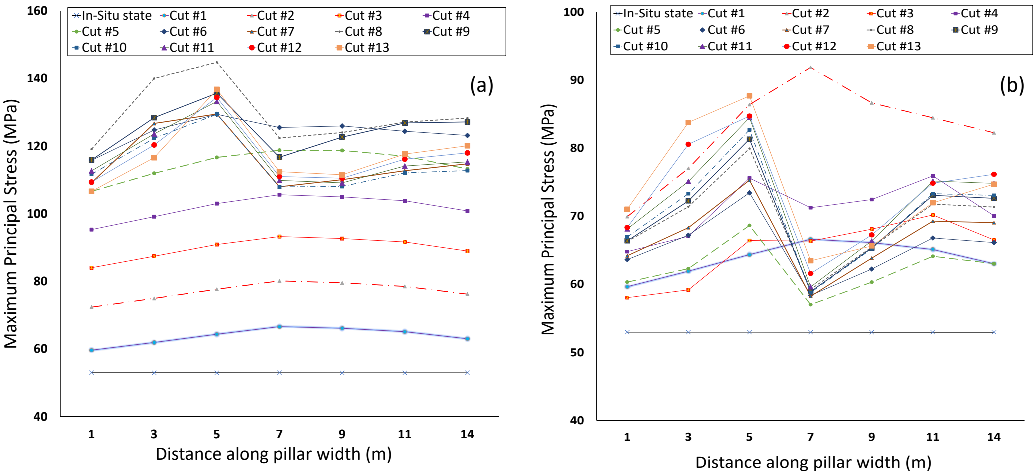

Figure 4. The pillar stress change measured at monitoring points along the pillar width as a function of the mining step: a) Rock mass friction angle was increased by 10%, b) Rock mass modulus was reduced by 10%.

With regard to the findings shown in Figure 4a, the rock mass strength parameters (cohesion and friction angle) both play a key role in determining the ultimate pillar strength. Looking at Figure 4a, we see that the load-bearing capability of the pillars dramatically increases when the friction angle rises. Due to the increase in strength, the pillar core will benefit from higher confining stresses provided by the pillar-host rock interface, which will ultimately increase the pillar's stability. These frictional forces developed at the pillar-host rock interface have a constraining and restraining impact on the pillar, especially at the top and bottom portions of the pillar. Figure 4b shows the effects of a reduction in pillar deformation modulus on the pillar stress field as a function of the mining step. Compared to the base run, in this case, a 10% reduction in pillar modulus leads to the development of lower stress magnitudes along the pillar in particular at the core region. With an increase in deformability, the pillar deforms gradually as mining proceeds and, thus, no significant stress build-up is observed which implies less burst proneness for the pillar. Based on field observations, when pillars are loaded, they will go through the following stages during the loading process as outlined by many authors (Salamon, 1970; Van der Merwe, 1998; etc.): in-situ conditions, stress rising at pillar edges, pillar edge failure, and stress rise in the core, pillar core approaching yield conditions and the side fracture zones become larger, and destressing of ground surrounding pillar.

The overall pillar behavior is illustrated in Figure 5. Figure 5b demonstrates the change in pillar load as a function of the mining step for the base run and sensitivity analysis runs. In Figure 5a, considering the monitoring point location and available confining stress, different behavior is observed at different points within the pillar. Figure 5b illustrates the change in minimum pillar principal stress as a function of mining cuts on pillar sides. The pillar stress drops significantly upon mining cuts on both sides of the pillar due to stress relaxation. Mining the subsequent cuts lead to an increase in pillar stress which reaches a peak at cut #7 and then a softening behavior is observed. Accordingly, with an increase in pillar strength parameters, the post-peak behavior of the pillar changes. As illustrated in Figure 5b, the pillar exhibits a stiffer and a kind of hardening behavior in post-peak when strength properties are increased by 10%. The stress–mining step curves presented in Figure 5 provide useful insights that may be used in the design of pillars.

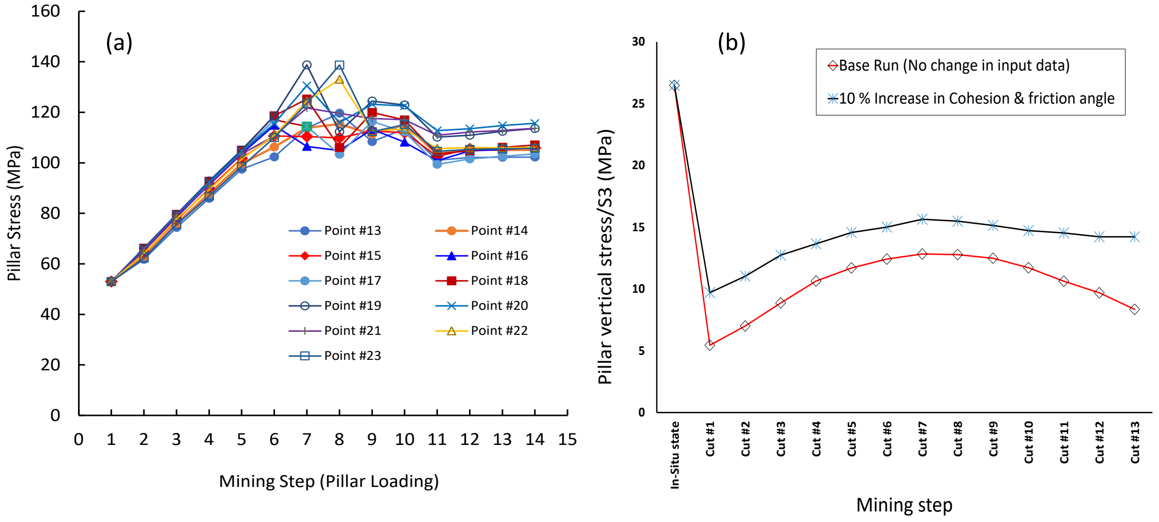

Figure 5. a) Pillar loading history as a function of mining, b) Effects of change in pillar strength properties on pillar in-situ behaviour.

4 CONCLUSION

Numerous authors have provided conceptual and experimental evidence that supports the mechanisms described in this work. In a nutshell, the process by which a pillar fails is a progressive one that begins at the point where the induced stress reaches the peak strength and is then followed by a behavior that is characterized by softening behavior until the level of residual strength is reached. The confinement of the pillar core, the strength of the pillar rock mass, and the mechanical behavior of the pillar–host rock interface are the primary determinants of whether the pillar will fail. To adequately characterize the behavior of the pillars, it is necessary to make use of a suitable constitutive model. The pillar loading history as a function of mining for the increased cohesion and friction angle illustrated that until mining step 7, the normal stress increases steadily, increasing from around 55 MPa (in-situ stress) to over 140 MPa at the 7th step. Hence, the process of cohesion and internal friction angle loss is responsible for the rock mass strain-softening behavior. The employed Mohr-Coulomb model in this study is not fully representative of the pillar post-peak behavior. However, the obtained pre-peak and peak stress levels in this study are in harmony with practical observations of pillar behavior. This is a work in progress and the conducted analyses will be reproduced using a strain-softening constitutive models.

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