Production Sequence Analysis of an Overhand Cut-And-Fill Mine in a Narrow-Vein Type Orebody Using Numerical Modeling

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ABSTRACT: Excavation-induced stresses have the potential to trigger instabilities around underground openings due to disturbance of the pre-mining stress field. Production sequence is a critical aspect in underground mining as it controls the stress distribution in the rock mass. The cut-and-fill mining method requires consideration of the mining sequence to mitigate the instability risk due to excessive stress concentration in stopes scheduled for production. This study covers the effects of production sequence on the crown pillar and the global mine stability using numerical modeling. A transition from open pit to underground mining in Western Türkiye was investigated. The orebody is a long-narrow vein type steeply dipping metallic mineralization that has three uniformly striking sub-sections. 2D and 3D elastoplastic models were used to examine the crown pillar deformations in alternative production scenarios. Large-scale effects of producing the orebody sub-sections in various orders were studied considering the global mine stability.

Keywords: Underground mining, production sequence, open pit underground transition, numerical modeling.

1 INTRODUCTION

Transition from open pit to underground mining is a common practice in metal mining. Although geomechanical restrictions are vital, the economy is also a dominant factor to set the limits of the surface operation. The crown pillar is an essential structure and a portion of the orebody that is left in place to sustain the stability of underground openings. Xu et al. (2019) studied the full recovery of a crown pillar by simultaneously replacing it with an artificial pillar. There are various studies on the determination of crown-pillar thickness using empirical and numerical methods (Chen & Mitri 2021, Dintwe et al. 2022 and Xu et al. 2018). Whittle et al. (2018) established a mathematical method to determine the pillar geometry with no regard for geotechnical stability. Afum et al. (2020) published a similar attempt with a mixed integer linear programming approach. Karian et al. (2016) stated that prevention of stope failure is a crucial aspect of maintaining pillar stability. Some recent studies consider destressing techniques for the reduction of stress concentration on the pillar body (Vennes et al. 2020). Despite the comprehensive research on crown pillar design methodologies, there is no attempt to investigate the production sequence on the crown pillar stability regarding the orebody type and geometry.

This paper focuses on the effects of production sequence in an overhand cut-and-fill mine by considering the local and global geotechnical aspects. On the local scale, the relation of the crown pillar stability with the most critical underground production sequence was studied. The global study investigated the effects of various production phases on the stope, crown pillar, and global mine stability. 2D and 3D numerical codes were used to simulate different extraction scenarios. Study outcomes have the potential to contribute to the geomechanical assessment of the transition from open pit to underground mining for long, narrow vein-type orebodies.

2 STUDY AREA

The research area involves an open pit at the feasible depth of a narrow vein-type metallic orebody in Western Türkiye. Transition to an underground operation was assessed regarding the viable production method for the remaining orebody. The ultimate pit limits extend to approximately 160 m around the center and the long axis has a length of 730 m. The ultimate pit depth is 90 m. Deviation of strike on the ore-bearing zone divides the orebody into three sub-sections named North, Middle, and South veins. The average strike is N45°W with a dip of 70°-80°. The vein thickness varies between 1.5 m to 12 m and it is 4 m on average. The thick section takes place in the Middle vein. The open pit and the locations of the cross-sections taken for modeling purposes are provided in Figure 1.

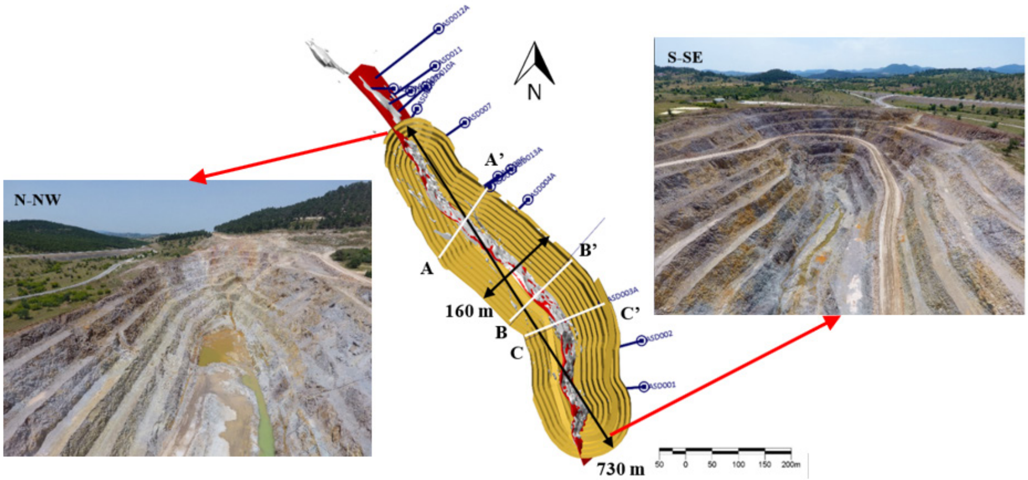

Figure 1. Overview of the open pit and the uniformly striking sub-sections of the vein.

3 METHODOLOGY

A complementary simulation scheme was adopted to assess the mechanical response of the transition from open pit to underground mining. The locally-thick vein in the middle section was considered to be the most critical part in terms of the crown pillar stability as a maximum of four stope extents that will be produced alongside. In this region, the effect of the production sequence was analyzed using a plane-strain based 2D Finite Element code. Due to the deviating strike of the orebody, conventional 2D simulation techniques are insufficient to observe the global effects of production. Therefore, a 3D Finite Difference code was used to determine the best production sequence. Mohr-Coulomb strain softening model was used in simulations. Considering the hydrogeological studies and observations, half-saturated material properties were assigned. The field stress ratio was taken 1.0.

The geomechanical properties of the rock mass domains were calculated with the Generalized Hoek & Brown Failure criterion (Hoek et al., 2002) based on the laboratory test results and geomechanical classification of the drill cores. Table 1 summarizes the numerical model input parameters for rock mass domains and the cemented-fill material. A fill mixture comprising of 6–8% cement + waste rock, or cement + tailings was selected based on lab scale trial tests. Filled stopes will serve as pillars during the production of side stopes after sufficient curing time. 'Overburden' (O/B) represents the slope mass of the open pit mine and the quality is considered to be better than the 'Ore Zone', which has the lowest rock quality. 'Hanging Wall' (HW) is only slightly better and 'Foot Wall' (FW) has the best score according to rock mass classification.

Table 1. Model input parameters for the rock mass domains and the cemented fill.

Rock Mass Domains		O/B	HW	Ore	FW	Fill
GSI (peak)		45	40	35	55	-
GSI (residual)		25	23	22	26	-
Unit Weight (kN/m^3)		23.9	24.3	24.4	24.1	24.0
Modulus of Deformation (GPa)		0.83	1.09	1.54	7.20	0.60
Poisson's Ratio		0.12	0.16	0.11	0.13	0.30
Mohr-Coulomb Parameters	Tensile Strength (MPa)	0.20	0.17	0.52	0.67	0.20
	Internal Friction Angle (°)	37	36	39	41	30
	Cohesion (kPa)	381	334	408	950	400
	Dilation Angle (°)	4	3	2	6	0

4x4 m cut and fill stopes were designed on a single row on each level for the thin veins on the North and South. Because the vein thickness reaches up to 12 m in the middle section, four stopes may operate alongside. The stope length was planned to reach up to 50 m regarding the structural condition of the rock mass. The stope plans are presented in Figure 2 for the critical cross-sections. According to the Q tunneling index, the suggested support system is grouted split sets of 2.0 m length with a 1x1 m pattern in and out-of-plane and 12-15 cm shotcrete with wire mesh at the roof and sidewalls.

For the open pit to underground mine transition, the scaled span method (Carter & Marinos, 2014) and the numerical simulations proved that a 10 m thick crown pillar provides a safety factor of 1.5.

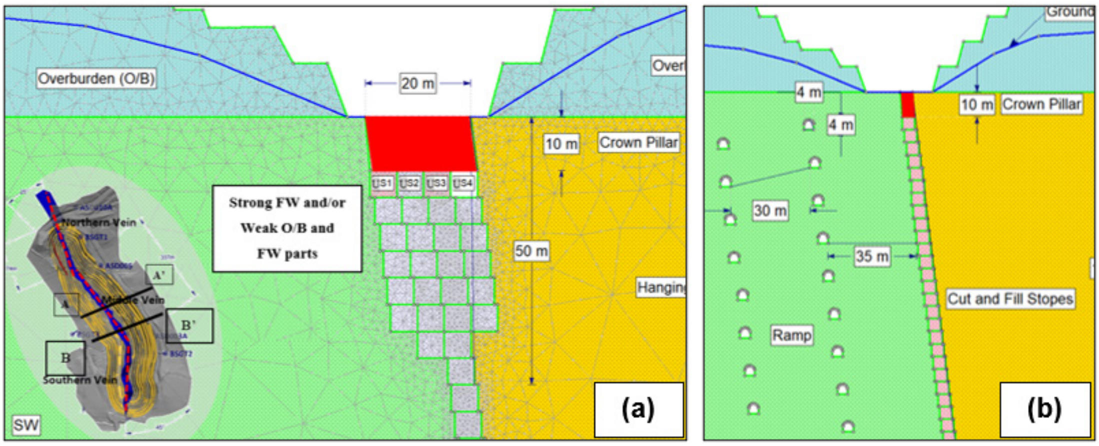

Figure 2. Stope plan for the thin (North & South) and thick (Middle) veins.

4 RESULTS AND DISCUSSION

The numerical study was based on two parts; the first part investigates the effect of production sequence on the most critical production stage, which is the extraction of the top-most stopes at the middle vein. The second part examines the macro effects of various production sequences considering the sub-sections on the North, Middle, and South veins. Numerical simulations were used to study various scenarios and the results are presented in the following section.

4.1 *Effect of Stope Sequence on the Crown Pillar Stability*

2D elastoplastic models were computed with various production sequences of the thick vein with four alongside stopes to represent the most critical scenario. The model represents the last production stage in which all the lower levels were produced and filled but only the top-level remains. The four stopes were numbered between 1 and 4 starting from the footwall side. Each sequence is mentioned with a four-digit code comprised of the stope names in order of production. Figure 3 shows the yielded elements for five of the most-common production sequences. The red color indicates that 100% of the elements were yielded. Failure is assumed to occur when the yielded elements span within the whole crown pillar extent that is from stopes to the pit bottom.

Although the same mine design is kept 1234 and 1324 shows no critical deformation on the crown pillar. However, 1423, 2314, and 2413 indicate extensive deformations on the HW side, which may lead to local failures on the roof. Considering the pillar extends to 300 m on the third dimension, such a recursive pattern may cause crown pillar instability on the HW side. Another outcome is the pillar instability in sequence 1423 and 2413.

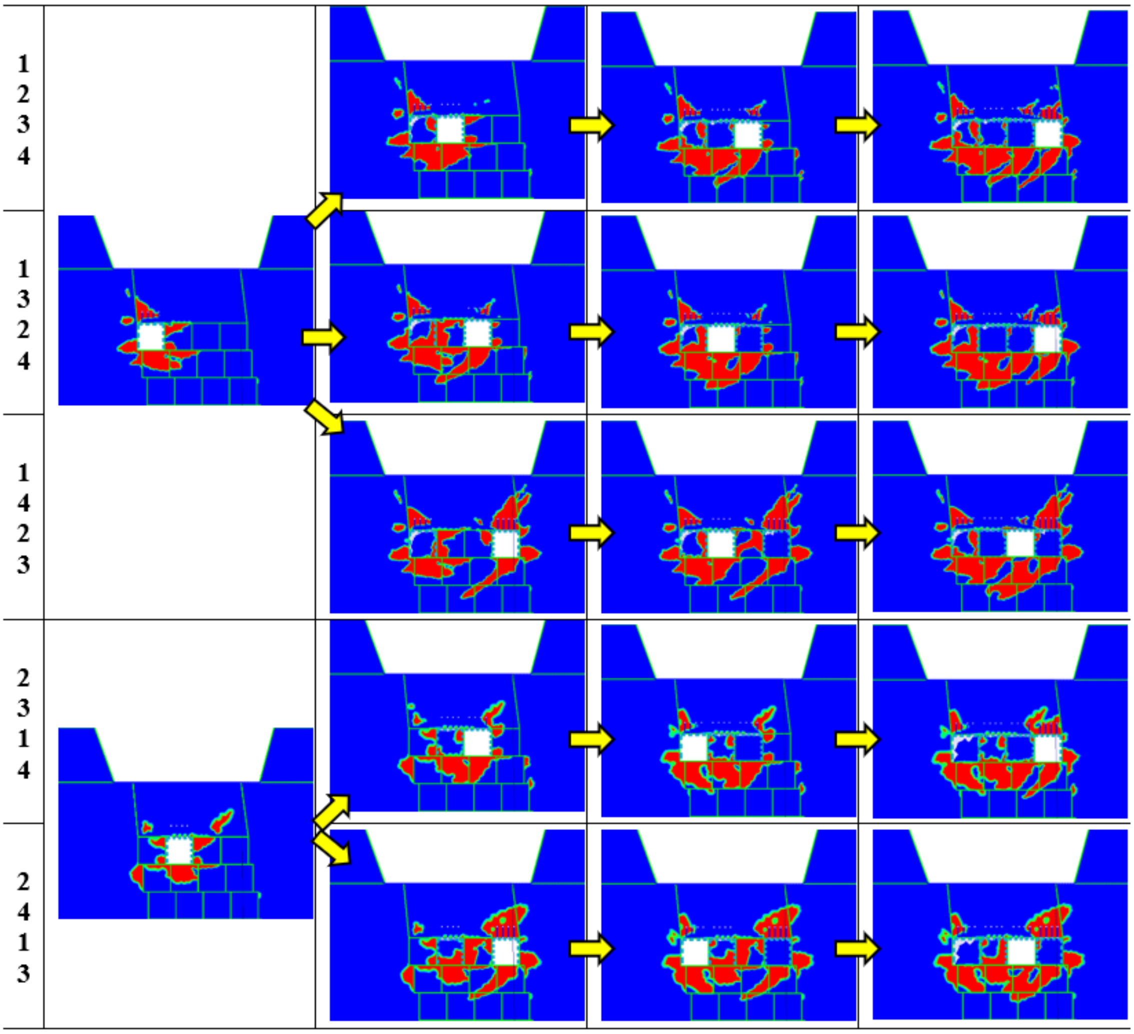

Figure 3. Yielded elements with different production sequences (red color = 100% yielding).

Model outputs point out that no major failure is expected on the crown pillar regardless of the production sequence. However, some sequences may cause minor instability issues on the roof. The significant difference between the geomechanical characteristics of the footwall & hanging wall, and the dip of the vein are considered as the major reasons for the local deformations.

4.2 *Effect of Production Sequence on Large Scale*

The extensive length of the vein-type orebody on the lateral plane creates a challenging condition for mining in terms of the production sequence on the macro-scale. A common approach is to start from the region with high-grade ore concentration. However, an excavation plan is critical in underground mining as uneven stress distribution may cause excessive stress concentration in unmined regions. In the current case, any stress-related instability not only would cause underground mining problems but also carries a risk to initiate slope movements. Therefore, global stability must be ensured at any production phase.

Figure 4 shows the 3D model of the transition from open pit to underground mining. Rock mass involving the open pit was represented by an overburden material. The hanging wall, footwall, and orebody were defined according to the 3D solid models. North, middle, and south veins, divided regarding the critical points of the strike deviation, were shown in different colors. Staged elastoplastic models involve completely extracted and filled sub-sections. Two distinct cases were simulated for mining through the North and South. The objective was to observe the stress concentrations around unproduced sub-sections when any other veins were produced and filled. A horizontal cross-section, as shown in Figure 4, was determined to plot the major principal stress contours from the top view.

The expected mechanical behavior was to have stress concentration within unproduced regions because rock mass is stiffer compared to the fill material. However, the observed stress build-up was not considerable. The pit excavation removed the overburden, which used to create a confinement effect, and the free surface on the pit bottom helped relaxation of the unproduced veins to reduce the stress concentration by deformations. Higher stresses on the North and South of the pit prove that the overburden mass is the main reason for loads on the underground mine.

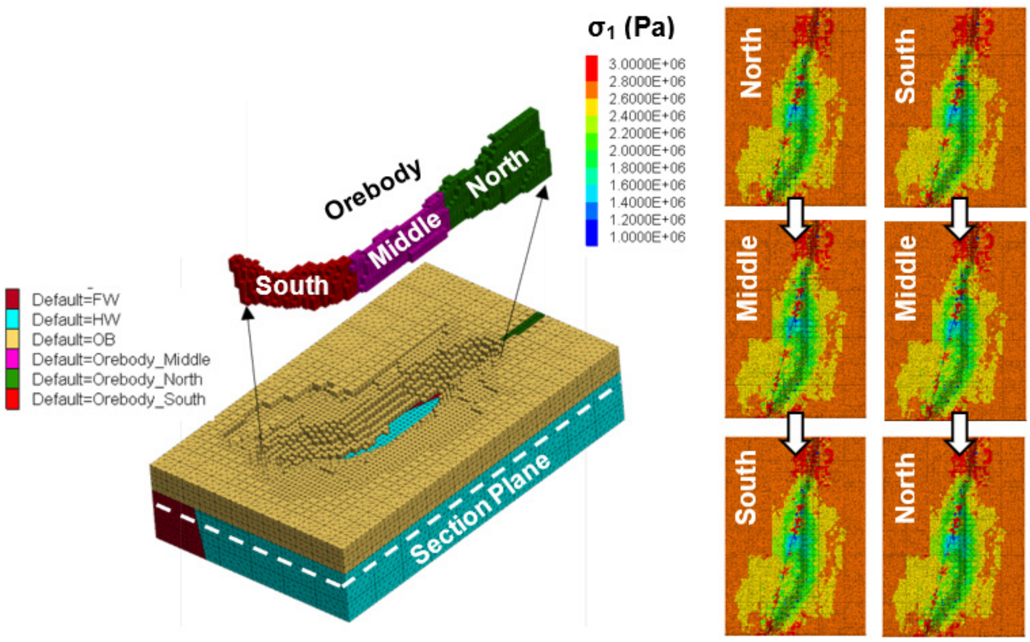

Figure 4. Stresses around the orebody for different production sequences.

It should also be noted that the field stress ratio has a significant control on the model behavior. Currently, hydrostatic loading conditions were assumed for simplification. However, larger horizontal stresses can be expected to increase the stress concentration on unproduced regions. Rock mass quality is another factor. In the simulated case, the orebody had poor geomechanical properties. Higher stress concentration would be observed on a stiff orebody. Finally, the pit depth has the potential to affect the stress distribution.

5 CONCLUSION

This study investigated the effects of production sequence in an overhand cut-and-fill mine. Local and large-scale effects were examined on stope sequence and orebody sequence models. Crown pillar and global mine stability were studied for various production scenarios. In the assessment of the stopes, 2D numerical models revealed no critical deformation on the crown pillar when producing with 1234 and 1324 systems. On the other hand, local roof failure risk was observed due to extensive deformations on the HW side of the crown pillar when using 1423, 2314, and 2413. Pillar instability in 1423 and 2413 was another outcome of the numerical modeling study. Another investigation was made on the effect of production sequence on large scale. Because the orebody strike changes on two critical points and creates three sub-sections, the best operation practice was investigated using a 3D numerical code. No significant stress build-up was observed on unproduced regions that can be associated with any of the two mining directions. The relaxation at the pit bottom related to the overburden removal was considered to be responsible for this effect. However, it was noted that the behavior is likely to change for different field stress ratios, orebody geomechanical characteristics, and the pit depth.

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