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Geotechnical modeling of the method for mining cobalt deposits at the Bou Azzer Mine, Morocco

Anas Driouch[1*], Latifa Ouadif[1], Abdelaziz Lahmili[1], Mohammed Amine Belmi[1], Khalid Benjmel[2]

[1] *Mohammadia School of Engineers, Mohammed V University, Rabat, Morocco*
[2] *Faculty of Sciences Ain Chock, Hassan II University, Casablanca, Morocco*
**Corresponding author: e-mail anasdriouch@research.emi.ac.ma*

Abstract

Purpose. The Bou Azzer Mine encounters difficulties during cobalt mining. In order to select the optimal mining sequence with the least geotechnical stability problems, one possible variant is the cut and backfill mining method used in the Bou Azzer East area at a depth of 540 m.

Methods. This paper presents a methodology for selecting a sequence of the cut and backfill mining method using 2D geotechnical numerical modeling, taking into account the morphological characteristics, geomechanical properties of the ore and the surrounding rocks.

Findings. The sequences of mining with rock backfill and rock-cemented backfill show that the high principal stress (Sigma 1) is in the range of 10-153 MPa, and the safety factors are in the range of 0.63-1.89. Therefore, mining sequences with cemented backfill and under cemented backfill have a principal stress (Sigma 1) in the range of 10-112 MPa and acceptable safety factors.

Originality. In this study, the bottom-up mining sequence with a cemented backfill is proposed for the case of low-quality serpentine footwall. This mining sequence aims to achieve good cobalt mine production and provides a safe environment for miners.

Practical implications. In the mining industry, the choice of mining method using 2D or 3D geotechnical numerical modeling is important to ensure the safest and most operational mining sequence in the mine lifetime.

Keywords: *Bou Azzer East, cobalt, mining method, finite elements, geotechnical engineering*

1. Introduction

The recently discovered shaft VI ore body in the Bou Azzer East area is currently the most important deposit of the Bou Azzer Mine in terms of morphology and grade (Fig. 1). The selection of the mining method is one of the most important activities in mining engineering, which requires the consideration of many technical, economic, political, social, and historical factors [1]. This research aims to select an appropriate mining method for this new cobalt ore deposit at a depth of 540 m, which presents a geotechnical complexity in its serpentine footwall with very poor geomechanical quality (Fig. 2). Thus, it is necessary to select the safest sequence in terms of geotechnical stability and adequate backfilling.

Several more practical methodical approaches were suggested by a group of mining scientists, such as [2]-[5], but were not sufficient for the automatic selection of a mining method. The numerical scoring approach for evaluating mining methods was first suggested by Nicholas [6], based on the geometry and grade distribution of the deposit and rock mass strength (ore zone, hangingwall, and footwall).

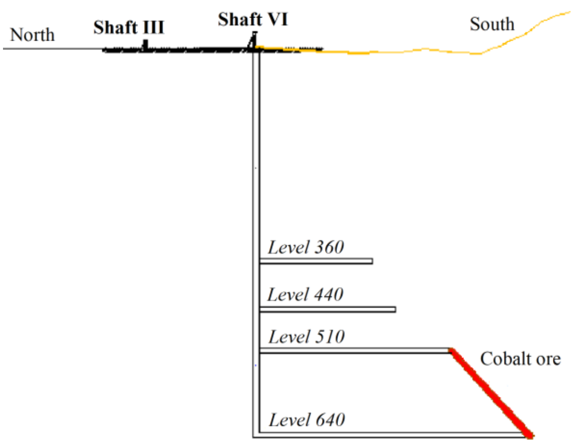

***Figure 1.** Cross-sectional view and development scheme of the cobalt mine in the Bouazzer East area*

For some time, researchers have been developing innovative decision support tools such as [1], [7]-[12] for the use of software technology based on multi-criteria approaches of numerical systems for the assessment of the suitability of a mining method for a particular ore.

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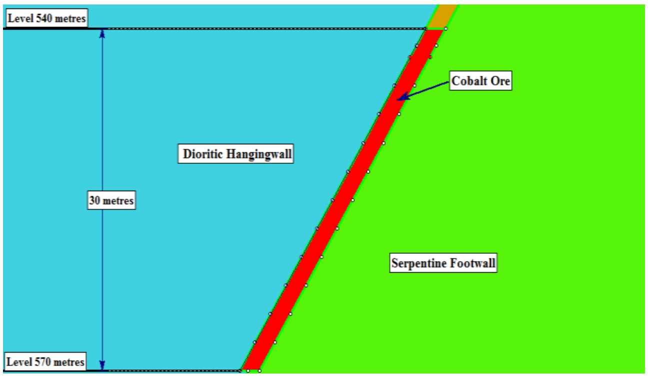

Figure 2. Cross-section represents the cobalt ore vein with its dioritic hanging wall and the serpentine footwall in the Bouazzer East zone

Geotechnical numerical modeling is an extremely strong tool for examining numerous complicated problems of underground mining excavations with a wide range of geological, geotechnical, and geometrical constraints. Moreover, it analyzes the sequences of mining methods according to the desired backfill. Currently, several research works use numerical modeling as a means of stability analysis in the mining industry context, such as [13]-[17]. Generally, the most used criteria for a geotechnical analysis evaluation are major principal stress, minor principal stress, and safety factor. This work presents a methodology for the selection of a suitable variant of the cut and fill mining method through 2D geotechnical modeling, using finite element software RS2 [18], representing the morphological and mechanical characteristics of the ore and its host to select the most advantageous variant and provide a safe environment for the miners in terms of geotechnical stability, the durability of operation, technical feasibility.

2. Mineralogical context

The Bou Azzer district of Cobalt, Nickel, and Arsenic is located west of the Precambrian Bouazzer-El Graara inlier, which lies in the central part of the Anti-Atlas. This inlier-oriented WNW-ESE marks the major accident of the Anti-Atlas "AMAFZ". Hydrothermal vein-type mineralization of Bou Azzer are spatially and genetically related to the serpentine rock mass. Thus, the hydrothermal alteration of these serpentines allowed the release of Cobalt, which is controlled by Pan-African tectonic processes [19]. We distinguished two types of mineralization by taking into account their morphological criteria and their geometric relations with the surrounding rocks [20] (Fig. 3).

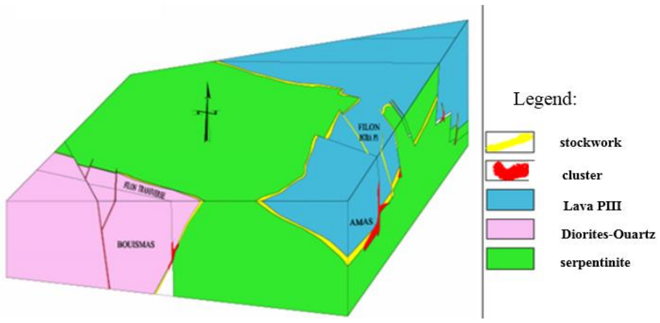

Figure 3. General morphology of mineralization at the Bou Azzer mine [20]

Two types of mineralization:

– the "cluster" mineralized bodies extended parallel to the contact between the serpentines and other rocks;

– transverse-type mineralized bodies correspond to vein-type on the tectonic contact of serpentine massifs with diorites-quartz.

In terms of texture, these mineralization are either disseminated, massive, or banded in quartz, carbonate (calcite and dolomite), talc and chlorite gangues.

3. Methods

3.1. Data collection

3.1.1. Geomechanical classification of rock masses

Geomechanical characterization of rock masses: diorites-quartz, cobalt ore, serpentinite, carried out by surveys of drill holes at a depth of 510 m. The most used classifications for quantitative evaluation of rock mass quality in this research are the RQD of Deere [21], the Q-system of Barton and al. [22], and the RMR of Bieniawski [23]. Thus the geological strength index (GSI) developed by Hoek and al. [24] is based on the evaluation of the lithological structure and the state of the surfaces of discontinuities in the rock mass and is extended by [25].

Table 1. Geomechanical classifications of rock masses (cobalt ore, diorites-quartz, serpentinite)

Parameters	Ore (cobalt)	Hangingwall (diorites-quartz)	Footwall (serpentinite)
RQD	55-60%	70-80%	20-30%
RMR	60	69	25
Q-system	7.59	13.72	0.20
GSI	55	60	40
Quality	medium	strong	very poor

Table 1 depicts the geomechanical classification of rock masses (cobalt ore, dioritic hangingwall, serpentine footwall) at the Bou Azzer mine, indicating that the cobalt ore is of medium quality and the serpentine footwall is of very poor quality. As a result, hangingwall dioritic is of good quality.

3.2. The choice of the mining method

In 1981, Nicholas suggested for the first time a numerical approach for mining method selection, based on a numerical scoring system for each extraction method obtained by adding the scores of the classes: geometry and grade distribution of the deposit and rock mass strength (ore zone, hangingwall, and footwall) [6]. The higher the rating, the more suitable the mining method. One of the problems of this approach was that all selection criteria had the same relevance. A recent modification involves weighting various categories, such as that ore geometry, ore zone, hangingwall, and footwall [26].

The parameters that must be examined when choosing a mining method include [6]:

1) geometry and grade distribution of the deposit;

2) rock mass strength for the ore zone, the hangingwall, and the footwall;

3) mining costs and capitalization requirements;

4) mining rate;

5) type and availability of labor;

6) environmental concerns;

7) other site-specific considerations.

In the first stage, a primary classification of mining methods is used to determine which are the most applicable. Based on the geometry, grade distribution, and rock mechanics qualities in the East Bouazzer area (Table 2).

Table 2. Cobalt deposit characteristics in the Bouazzer East area according to the approach of [6]

General shape	Ore thickness	Plunge	Depth below surface	Grade distribution
Irregular: dimensions vary over short distances	Narrow: < 10 m	Steep: >55°	540-570 m	Erratic: grade values change radically over short distances and do not exhibit any discernible pattern in their changes

Table 3 presents the results of the mining methods based on the application of the Nicholas numerical approach. The most appropriate mining methods are cut-and-fill and square set, with higher scores according to the order of priority.

After narrowing the recommended mining methods to two, cut and fill is a mining process in which each slice of rock is taken after blasting and then filled with some form of fill material (rock, paste, or hydraulic fill), allowing space for the next slice to be mined [6]. As a result, the traditional square set method is quite different, in which timber squares are created to replace the mined rock and to support the surrounding rock [6].

In the second stage, based on an evaluation report of cobalt ore productivity, labor availability, and mining experience above the depth of 540 m in other regions at Bou Azzer mine by the cut and fill mining method with the rock fill sequence. These parameters show that the cut and fill mining method is more advantageous than the square set method in terms of annual cobalt ore productivity. In addition, the square set method is slow, costly, and requires highly skilled miners and supervisors. Because one small block of ore is taken and replaced with a "set" or cubic frame of lumber that is instantly set into place in square set mining, there are also transportation and fire risk issues [27]. Selecting the cut and fill mining method is the most efficient and economical. This method can be used where the ore and wall rocks are weak, and hence the opening size and permitted period between ore removal and excavation filling are carefully regulated [28].

Table 3. Ranking results of different mining methods according to the approach of [6]

Mining method	Total points
Cut & Fill	35
Square Set	35
Room & Pillar	33
Shrinkage Stoping	30
Sublevel Stoping	29
Sublevel Caving	-26
Top Slicing	-26
Block caving	-29
Longwall	-84

3.3. The description of the Cut and fill mining method

Cut and fill mining (Fig. 4) removes ore in horizontal slices, starting from the bottom undercut and advancing upward. Ore is drilled and blasted, and muck is loaded and removed from the stope. When the stope has been mined out, voids are backfilled with hydraulic sand tailings or waste rock. The fill supports the stope walls and provides a working platform for equipment when the next slice is mined [29].

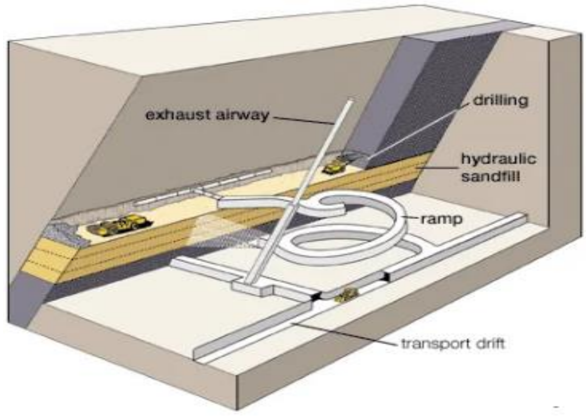

Figure 4. Cut and fill stoping [29]

The development for cut-and-fill mining includes [29]:

– a haulage drive along the footwall of the ore body at the main level;

– undercutting the stope area with drains for water;

– a spiral ramp in the footwall with an access drive to the Undercut;

– a raise connecting to levels above for ventilation and filling material.

3.4. The different variants of the cut and fill mining method

The cut and fill mining method is particularly adaptable and recommended in the case of irregular vein-type mineralization of Bou Azzer, with a very poor quality serpentine footwall. The mining cycle of the different variants starts with each slice of rock being removed after blasting, then a backfill that will secure the operation of the next slice, and so on. The cycle repeats until the planned ore depletion [30].

The extraction sequences of the cut and fill mining method used in this study are as follows:

– bottom-up sequence with backfill (rock, cemented, rock-cemented);

– top-bottom sequence under cemented backfill.

The objective is to choose a variant well adapted to the local conditions of the deposit in terms of geotechnical stability to control the deformations and the state of stresses to ensure the necessary security for employees, with a coupling of the installation of artificial support.

3.4.1. The bottom-up extraction sequence

The different variants of the cut and fill method with rock fill, cemented backfill, and rock-cemented fill, following an extraction sequence of the stopes, would progress in an ascending manner slice by slice inside the stopes. In the upper part of the ore deposit, an ore pillar was left inside the stopes to maintain stability [30]. The different variants of the bottom-up sequence of the cut and fill method are illustrated in Figure 5.

3.4.2. The top-bottom extraction sequence

The extraction sequence of the stopes would progress in an up-bottom manner from slice to slice (Fig. 6). In the upper part of the deposit, an ore pillar was left inside the stopes to maintain stability [30].

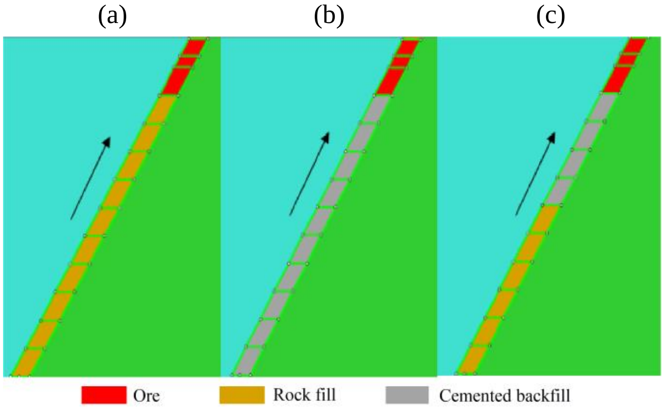

Figure 5. The different variants of the bottom-up sequence of the cut and fill method with the fills used (a) rock fill; (b) cemented backfill; (c) rock-cemented fill

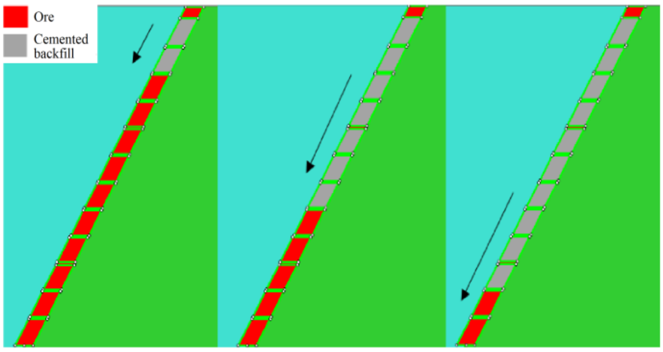

Figure 6. Extraction from the top of the deposit under the cemented backfill

3.5. Geomechanical properties of rock masses

The determination of numerical modeling parameters using the software RocDataV.3.0. [31] (Table 4), based on applying the Hoek-Brown criterion, is most widely used in weak heterogeneous rock masses such as intact rock or strongly broken rock masses [32].

Table 4. Geomechanical properties of rock masses

Parameters	Hangingwall	Ore	Footwall
Hoek-Brown criterion			
m_b	3.721	3.754	0.574
s	0.0048	0.0025	0.0003
a	0.503	0.504	0.511
Rock mass parameters			
σ_{cm} (MPa)	39.718	35.017	2.791
E_m (MPa)	13337.10	10001.41	2271.23
Rock substance strength	2.53	2.19	0.18

*m_b – the reduced value of the material constant; a, s – constants for the rock mass; σ_{cm} – the uniaxial strength of the rock mass; E_m – rock mass modulus of deformation

The necessary input parameters are (σci, mi) intact rock properties, and (D) distur-bance factor, (GSI) geological strength index. The mechanical tests of the intact samples cored at a depth of 540 m in this mine are conducted for the geomechanical parameters, (σci) the uniaxial compressive strength of the rock intact, (Ei) rock intact modulus of deformation, (σt) the tensile strength of the rock intact, and (γr) dry unit weight.

3.6. Geotechnical numerical modeling methodology

Numerical geotechnical modeling of different variants of the cut and fill mining method of the cobalt vein-type deposit at the Bou Azzer mine, using finite element software RS2 [18]. Based on a study approach (Fig. 7) that begins by tracing the geometric shape with an average ore thickness of 2 m and an opening size of 2.5 m, a dioritic hangingwall of good quality and a serpentine footwall of extremely poor quality were identified.

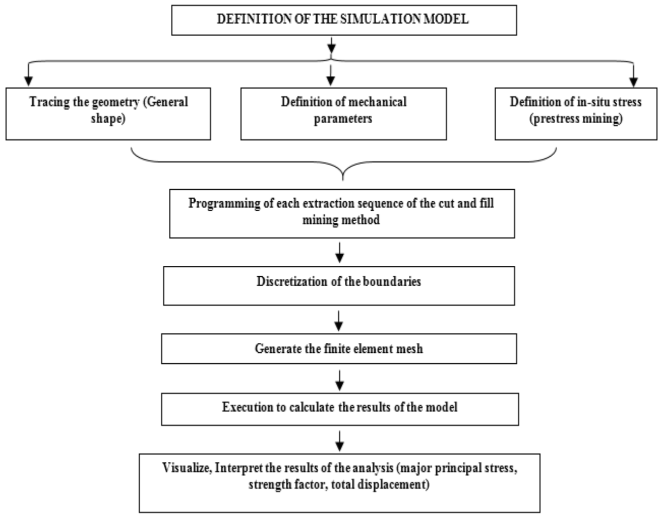

Figure 7. The 2D geotechnical numerical modeling methodology of the ore extraction sequences by the RS2 software [18]

The mechanical parameters of the Hoek-Brown failure criteria will be defined next. Thus, the pre-stress mining, followed by the programming of each extraction sequence for the various study variants, followed by the discretization of the boundaries and generation of the finite element mesh, and finally, the execution to calculate the model results to visualize the data and interpret the analysis results (major principal stress, minor principal stress, safety factor, total displacement).

4. Results and discussion

4.1. The bottom-up extraction sequence

4.1.1. Sequence with the rock fill

During the extraction of ore by sequence 1 with the rock fill (Fig. 8), the major principal stress in the dioritic hangingwall and serpentine footwall varies between 10 and 114 MPa from the first to the last slice, with an average elevation of 8 MPa for each slice. In the crown of the excavation, the major principal stress increased from 40 MPa for the first slice to the last slice at 162 MPa, with an average elevation of 10 MPa for each slice, while the last two slices had higher stress.

After backfilling the slices with rock fill, the major principal stress in the dioritic hangingwall and the serpentine footwall is between 8 and 99 MPa, with an average stress decrease of 7 MPa in each slice. Thus, in the crown of the backfilled excavated slices, the major principal stress decreases with an average of 6 MPa for each slice.

The safety factors during ore extraction vary between 0.95 to 1.6 in the crown of the excavations and the dioritic hangingwall. The serpentine footwall has very low safety factors in the range of 0.32 to 0.95, with very low safety factors in the last two slices.

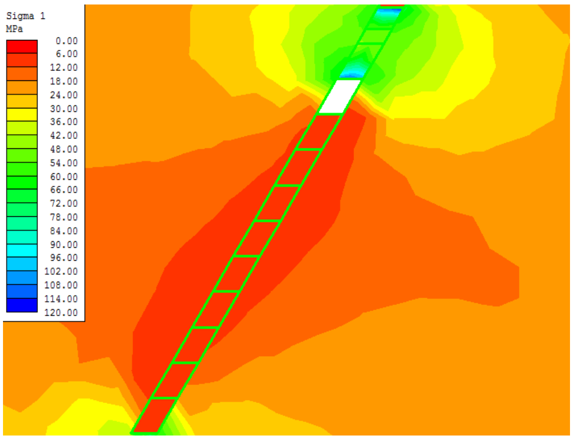

Figure 8. The results of the major principal stress during ore extraction in slice 10

Factors of safety after backfilling the slices range from 1.26 to 1.68 in the dioritic hangingwall and the crown of the slices. Therefore, the serpentine footwall still has low safety factors ranging from 0.63 to 1.

4.1.2. Sequence with cemented backfill

During the extraction of ore by sequence 2 with the cemented backfill (Fig. 9), the major principal stress in the dioritic hangingwall and serpentine footwall from the first to the last slice ranges from 10 to 90 MPa, with an average elevation of 6 MPa in each slice. In the crown of the excavation, the major principal stress increases from 40 to 120 MPa, having an average elevation of 7 MPa for the slice, while the last two slices have higher stress.

After backfilling the slices with cemented backfill, the major principal stress in the dioritic hangingwall and serpentine footwall ranges from 10 to 82 MPa, with an average decrease of 6 MPa for each slice. In the crown of the backfilled excavations, the major principal stress ranges from 35 to 112 MPa, with an average stress decrease of 7 MPa for each slice.

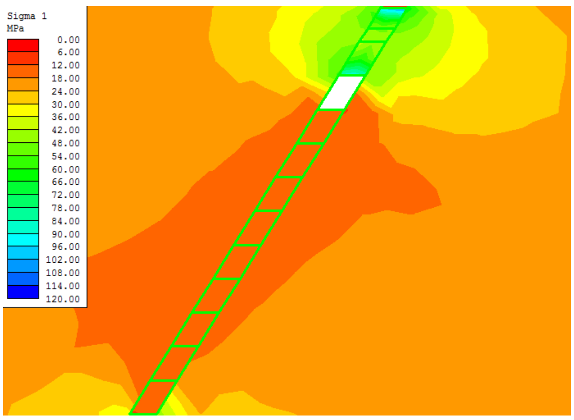

Figure 9. The results of the major principal stress during ore extraction in slice 10

In the crown of excavations and the dioritic hangingwall, the safety factors vary between 1.26 and 1.58, with a low safety factor of 0.95 on the left side of the excavations crown. The serpentine footwall has low safety factors ranging from 0.32 to 0.95, with very low safety factors in the last two slices.

The safety factors are improved after the backfilling of the slices by the cemented backfill, which is between 1.26 and 1.89 in the dioritic hangingwall and the crown of the slices. Therefore, the serpentine footwall still has low safety factors ranging from 0.63 to 1.26.

4.1.3. Sequence with rock-cemented fill

During ore extraction by sequence 3 with rock-cemented fill (Fig. 10), the major principal stress varies from 10 to 104 MPa from the first slice to the last slice, with an average elevation of 8 MPa for each slice. In the crown of the excavations, the major principal stress increased from 40 to 128 MPa, with an average elevation of 7 MPa for each slice, while the last two slices had higher stress.

After backfilling with rock-cemented fill, the major principal stress in the dioritic hangingwall and serpentine footwall ranged from 10 to 96 MPa, with an average stress decreased of 7 MPa. The major principal stress in the crown of backfilled excavations is from 35 to 120 MPa, with an average decrease of 6 MPa.

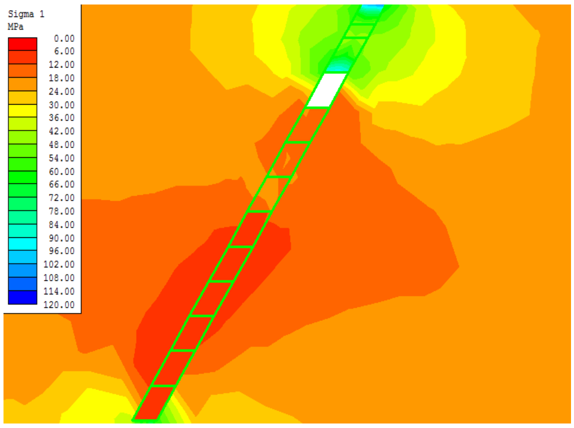

Figure 10. The results of the major principal stress during ore extraction in slice 10

The safety factors presented during ore extraction vary between 0.95 to 1.6 in the crown of the excavations and the dioritic hangingwall. The safety factors in the serpentine footwall are very low, ranging from 0.32 to 0.95, with very low safety factors in the last two slices. The safety factors enhanced by backfilling with rock-cemented fill slices range from 1.26 to 1.89. As a result, the serpentine footwall still has poor safety factors ranging from 0.63 to 0.95.

4.2. The top-bottom extraction sequence

4.2.1. Sequence under the cemented backfill

The extraction of ore by sequence 4 is done by the cemented backfill (Fig. 11). Descending into the stope, the major principal stress in the dioritic hangingwall and serpentine footwall ranged between 15 to 42 MPa, with a small variation of the stresses in all the slices. In the crown of the excavations, the major principal stress varies between 105 and 119 MPa.

After backfilling with cemented backfill, the major principal stress in the dioritic hangingwall and serpentine footwall ranges from 14 to 37.5 MPa, with an average decrease of 2 MPa in all slices. In the crown of the backfilled excavations, the major principal stress varied between 54 and 105 MPa, with a mean decrease of 4 MPa.

The safety factors during ore extraction vary between 0.63 and 1.89 in the dioritic hangingwall and the crown of the excavations. The serpentine footwall has very low safety factors ranging from 0.32 to 0.95.

The safety factors after backfilling are improved and are in the range of 1.26 to 2.5, with low safety factors in the crown of excavations at 0.95. Therefore, the serpentine footwall presents low safety factors ranging from 0.95 to 1.26.

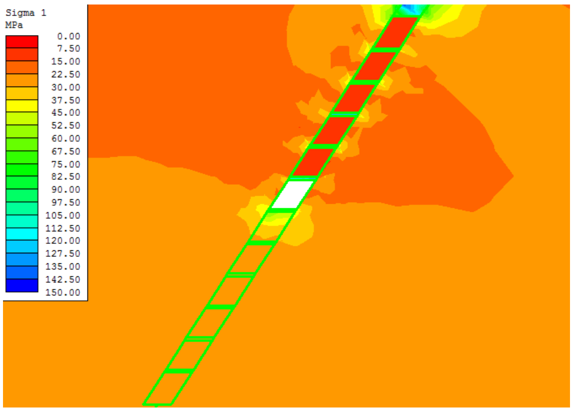

Figure 11. The results of the major principal stress during ore extraction in slice 10

4.3. The choice of the ore extraction sequence

The extraction sequence has the minimum major principal stress and has the highest safety factors. These are the two criteria utilized to select the safest extraction sequence of the cut and fill mining process among the four sequences examined in this study, in order to offer a safe environment for miners in terms of geotechnical stability.

Based on the numerical geotechnical modeling results. Figure 12 presents the variation of Sigma 1 in the serpentine footwall, the dioritic hangingwall, and the ore crown between slice 1 to slice 12 during excavation. The mining sequence 2 with the cemented backfill has an average Sigma 1 of 47 MPa, and the mining sequence 4 under the cemented backfill with an average Sigma 1 of 44 MPa. These two mining sequences have the lowest Sigma 1 in the serpentine footwall, and dioritic hangingwall among the 4 sequences studied. Thus for the ore crowns, sequence 2, with the lowest cemented backfill, shows an average Sigma 1 of 76 MPa.

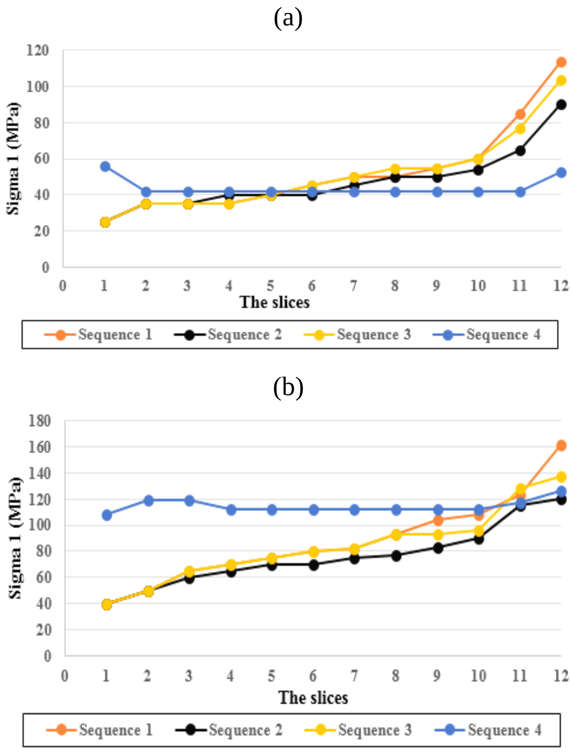

Figure 12. The variation of the major principal stress between slice 1 to slice 12 during excavation in the different mining sequences (a) the serpentine footwall and the dioritic hangingwall (b) the ore crowns

Table 5 presents the criterion of the average safety factors of the 4 ore extraction sequences from slice 1 to slice 12 during excavation. Sequence 2, with the cemented backfill, has the highest average safety factors in the dioritic hangingwall, the serpentine footwall, and ore crowns. Sequence 4 under the cemented backfill has a higher average safety factor in the dioritic hangingwall.

Table 5. Average safety factors in the dioritic hangingwall, ore crown, and serpentine footwall of the different mining sequences studied

	Factor of safety		
	Dioritic hangingwall	Crown of ore	Serpentine footwall
Sequence 1	1.29	0.95	0.66
Sequence 2	1.40	1.05	0.71
Sequence 3	1.29	0.97	0.68
Sequence 4	1.65	0.87	0.61

The quality of the rock mass in the local context of the cobalt mining area at Bou Azzer East is characterized by a serpentine footwall with a low compressive strength of 29 MPa, with a very poor geomechanical quality according to the Q-system and RMR classification. The methodology developed by [33] shows that the serpentine rock mass in the ore mining area is between the depth of 540 and 570 m under the conditions of squeezing grounds. Therefore a dioritic hangingwall has a good geomechanical quality, with a compressive strength of 153 MPa. The choice of the cut and fill mining method for this cobalt deposit is more suitable according to the classification of [6] by integrating geometry and grade distribution of the deposit and rock mass strength (ore zone, hangingwall, and footwall). Hence, cut and fill is preferred for ore bodies having an irregular shape in steeply dipping deposits and scattered mineralization at a high grade. It provides better selectivity than the alternative sublevel stoping mining [29].

The results of the different sequences of the cut and fill mining method is the subject of this work by a 2D geotechnical modeling according to the extraction sequence and the backfill used. The sequences 1 and 3, and 4, during the extraction of ore present in the excavated slices, higher stresses vary between 10 to 153 MPa. In contrast, sequence 2 with the cemented backfill has the lowest stresses in this study. The various extraction sequences have low to medium safety factors in the dioritic hangingwall and excavation crown. As a result, the serpentine footwall has relatively low safety factors.

After the backfilling of the excavated slices, the two sequences with the rock fill and rock-cemented fill show a decrease in the major principal stress. Therefore, sequence 4 under cemented backfill shows the minimum major principal stress in the stress range between 14 and 105 MPa. The safety factors are improved and acceptable in both sequences with cemented backfill and under cemented backfill because the material used for the backfill of the excavations has good mechanical characteristics and helps to reduce the convergence of the underground excavations. The other two sequences, with rock and rock-cemented fill, show medium safety factors.

The advantages of cemented backfill in the backfilling of excavated slices are controlled safety, good productivity, and less dilution of cobalt ore. The disadvantages are the high costs of mining operations, the stop of production during the backfilling phase, and the important time setting up the operations.

5. Conclusions

The selection of the most operational mining sequence, with the goal of producing good cobalt mine production at the Bou Azzer mine, is critical. Given the ore deposit's geological complexity and the unfavorable geotechnical characteristics of the serpentine footwall with very poor ground quality.

In light of these results, we recommend the extraction of cobalt ore at a depth of 540 m in the mining area at Bou Azzer East by the cut and fill mining method with the extraction sequence 2 of cemented backfill. This sequence shows an average major principal stress of 47 MPa and the highest average safety factors in the dioritic hangingwall, the serpentine footwall, and ore crowns. This provides a safe environment for the miners, with a complementary support system installed during the extraction of ore in the excavations to control the state of induced stress redistribution and deformation.

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Геотехнічне моделювання способу видобутку покладів кобальту на шахті Бу Аззер, Марокко

А. Дріуч, Л. Уадіф, А. Ламілі, М.А. Белмі, К. Бенджмел

Мета. Вибір раціонального способу видобутку для нового родовища кобальтової руди Бу Аззер (Марокко) на глибині 540 м у складних геомеханічних умовах за допомогою двовимірного геотехнічного моделювання із використанням скінченно-елементного чисельного аналізу.

Методика. У статті представлено методологію вибору послідовності методу видобутку підземним способом зі зворотним закладанням із використанням 2D геотехнічного чисельного моделювання з урахуванням морфологічних характеристик, геомеханічних властивостей руди та навколишніх гірських порід.

Результати. Встановлено, що при послідовності гірничих робіт із породним зворотним закладанням та зворотним закладанням із цементованої породи головне напруження (σ_1) знаходиться в діапазоні 10-153 МПа, а показники запасу міцності варіюються у діапазоні 0,63-1,89. Рекомендуємо видобуток кобальтової руди на глибині 540 м у гірничодобувному районі Бу Аззер Схід методом виймання та насипу із послідовністю вилучення 2 цементованого зворотного закладання. Ця послідовність 2 показує середнє значення головного напруження 47 МПа та найвищі середні коефіцієнти запасу міцності у діоритовому висячому боці, серпентиновій підошві та рудних склепіннях.

Наукова новизна. Науково доведено ефективність висхідної послідовності видобутку з цементованим зворотним закладанням для випадку низькоякісної серпентинової підошви. Ця послідовність видобування має на меті досягти високих показників виробництва кобальту та забезпечити безпечне середовище для гірників.

Практична значимість. У гірничодобувній промисловості вибір способу видобутку із використанням 2D або 3D геотехнічного чисельного моделювання є важливим для забезпечення найбільш безпечної та оперативної послідовності видобування впродовж усього терміну експлуатації шахти.

Ключові слова: *Бу Аззер, кобальт, спосіб видобутку, скінченні елементи, геотехнічна інженерія, закладання*