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STABILITY ANALYSIS OF THE PILLARS OF THE UNDERGROUND MINE CHAABET EL-HAMRA, ALGERIA BY ANALYTICAL AND NUMERICAL METHODS

Purpose. Analysis of the current and proposed room and pillar exploitation technique of the Zinc mine (Chaabet El-Hamra) by two different approaches, the tributary area (TAM) for analytical method and numerical method (Finite Element Method FEM) through PLAXIS 3D software.

Methodology. In this work, the stability analysis of the room-and-pillar of the Chaabet El-Hamra mine was performed. Firstly, the safety factor for both conditions was calculated by TAM: 1) the current operation using 8.0 m wide rooms with 4.0 × 4.0 m pillar sections; 2) the proposed technique using 9.0 m wide rooms with 3.0 × 3.0 m pillar sections. Secondly, the numerical method was used to analyze pillar stability and total displacement of the proposed technique through the PLAXIS 3D software.

Findings. Using more than one method in underground mining for analysis of the existing or proposed technique is the best solutions for achieving reliable results.

Originality. The originality of this work is to use two different methods – TAM and numerical method (FEM) – for analyzing the rooms-and-pillars stability design at a mine and proving the accuracy of this method in mining engineering field

Practical value. The results of the chamber and pillar stability analysis indicate a safety factor of 1.38 for the proposed technique. In addition, the maximum displacements are 0.259 mm. Thus, the proposed operating technique of the layer will not cause stability problems. The production ratios show that the extraction rate of the current technique is 89 % and for the proposed technique it is 93.75 %, so these results show that the proposed technique is advantageous and more practical. The stability studies confirm the fact that geotechnical research with computer applications (numerical methods) in underground mining can make a significant contribution to developing safer and more economical stopping methods with greater health responsibilities, security and environment.

Keywords: *mines and mining, productivity, stability, rooms-and-pillars, factor of safety, FEM, Chaabet El-Hamra Mine*

Introduction. The method of exploitation by rooms-and-pillars is a method that started in the mining field. This method applies to all types of deposits, but mainly to formations of sedimentary origin (e.g. Coal, Potash, Salt, Iron, Bauxite, and Zinc), whose dip does not exceed 30°. Rooms-and-pillars are an ideal method for extracting flat deposits over a wide and shallow area (up to a few hundred meters).

Mine pillars are blocks of ore (natural support) abandon in place between two or more production excavations. Their function is to provide support to minimize the movement of the rock mass in the area of the excavation influence. However, when sizing the pillars, we must choose the minimum amount of ore to leave in place. This quantity in the pillar must allow the minimum support necessary to ensure the stability of the excavations while ensuring the highest rate of extraction possible (Luo, Y. 2015).

Pillar stability is one of the most complicated and extensive problems in rock mechanics for underground mining and strata control. Although these problems have been studied by several researchers including Wael A. (2015), John L. P., et al. (2013), Yang Y., et al. (2017), Vidal F. N. T., et al. (2011) and Nakache R., et al. (2015), the issue of using many different methods such as analytical and numerical methods, to date, does not find accurate results to eliminate the risk of collapse and subsidence.

The rooms-and-pillars stability analyses were applied to the Zinc Mine (Chaabet El-Hamra). The current operation uses 8.0 m wide rooms with 4.0 × 4.0 m pillars, while the proposed technique suggests 9.0 m wide rooms and 3.0 × 3.0 m pillars.

The stability analysis of the rooms-and-pillars of these two situations was performed by two different methods, analytical method and finite element computer model and a Mohr-Coulomb failure criterion, applying the PLAXIS 3D software. During these simulations, a discussion of the stability of the rooms-and-pillars using safety factors and the extraction ratio were performed.

The objective of this work is concerned with stability analysis study of the current and proposed room and pillar exploitation techniques of the zinc mine (Chaabet El-Hamra) by two different approaches, the tributary area for the analytical method and numerical method (Finite Element Method FEM) through PLAXIS 3D software.

Site Description. ***Location and Topography***. The Chaabet El-Hamra deposit is directly located, about

250 km southeast of Algiers and 50 km south of Setif, in the Chouf-Bouarket region 4.5 km from Ain-Azel and 12 km southeast of the Kherzet Youssef mining complex (Fig. 1, *a*). Its approximate geographical coordinates are 35° 45′N and 5° 30′E. The altitude of the site varies from 950 to 1200 meters.

Regional Geology. The area is located within the Hodna district, located at the junction of three geological zones (Tellian Atlas, the Sahara Atlas, and the high plains). The high plains overlay a carbonate platform, which remained shallow during the Mesozoic times. The carbonate platform was unstable and subsiding from the Upper Triassic to Albian (Lower Cretaceous). It comprises more than 2300 m of sediments, terrigenous and carbonates (including dolomitic series). Several dolomitic series are characterized by their important mineralization, mostly on the northern and southern margins of the platform (Fig. 1, *b*).

A tectonic of horst and graben has caused asymmetrical folding, occasionally with diaper developing in the cores.

The mineralization is flat dipping sitting in an anticline and extends over 500 meters strike length, 150 m across strike, and is ranging from 100–160 m below the surface and is open at depth. The thickness of mineralization ranges from 1 to 20 m. Ore from the Chaabet El-Hamra mine was trucked to Kherzet Youcef for processing into zinc concentrate.

Access to the mineralized zone is through an inclined shaft (decline), which is located at the lowest point in the region, at Hill 1020, over a length of 830 m

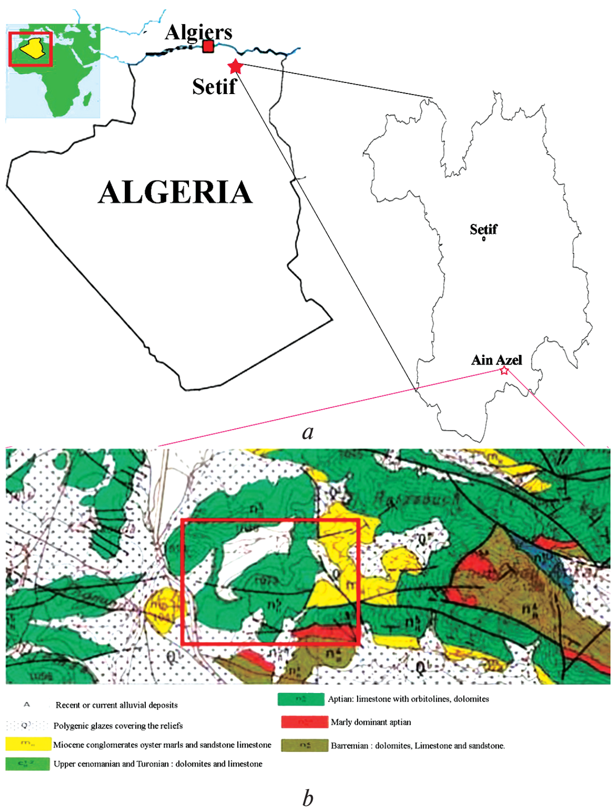


Fig. 1. The area studied. Location and topography (a) and geology map (b)

in the waste rock. It is used for the circulation of personnel, equipment and for the evacuation of ore. It also serves as a fresh air intake to underground mining. This decline is preceded by a trench access, a length of 113 m, from the coast 1034 to that of 1025, but a slope contrary to the slope of the descent, is of the order of 6 %.

Analysis Methods. The diagnosis of stability of an underground mine and its monitoring is based on various methods of observations and measurements, now being well under control (deformation measurements, constraints, ultrasonic auscultation, various geophysical methods, and others).

These methods are applicable in principle to all types of complex mines or not. On the other hand, the computation of the stresses to evaluate the conditions of stability is likely to be difficult in the complex mines. In this paper, two methods of calculation have been used: the most well-known analytical methods of calculation and numerical methods of calculation.

Analytical Methods. Tributary Area Method (TAM). The analysis of the stability of the pillars are based on the theory of the tributary area method (TAM) which is well adapted to the underground mines exploited by the method of rooms-and-pillars stopped, located at shallow depth (H. R. Renani, 2018).

The TAM is the simplest method for determining the load of a pillar. This method makes it possible to quickly evaluate the stability of the pillars.

The theory of TAM assumes that after excavation, the pillar supports the weight of the land contained in an augmented imaginary prism extending from the level of excavation to the free surface (Wael A., 2015).

The theory of the TAM accepts that the average load of the pillar can be obtained from the following equations.

For a wall pillar, the average axial stress of the pillar is defined by

$$\sigma_p = P_{zz}\frac{(W_0 + W_p)}{W_p},$$

where σ_p is the average axial pillar stress; P_{zz} is the vertical stress of the initial state of stress; W_0 and W_p are the pillar and room widths, respectively.

The area extraction ratio in mining an ore body of uniform thickness is defined by

$$r = \frac{Area\,mined}{Total\,area}.$$

For column pillars with a rectangular cross-section, the extraction rate becomes

$$\sigma_p = P_{zz}\frac{(a+c)(b+c)}{ab}.$$

The area extraction ratio is defined by

$$r = \frac{\left[(a+c)(b+c) - ab\right]}{(a+c)(b+c)}.$$

For the case where square pillars are used, we have $a = b$

$$\sigma_p = \gamma \times H \frac{\left(W_0 + W_p\right)^2}{W_p^2} = \frac{\gamma \times H}{1-r};$$

$$r = 1 - \frac{W_p^2}{\left(W_0 + W_p\right)^2},$$

where γ and H are average unit weight of overburden and mining depth, respectively.

The theory of the TAM has certain disadvantages, however:

1) it neglects the presence of firm edges or undeveloped blocks since it considers that exploitation is infinite. It does not take into account the load on them;

2) the height of the pillars (slenderness) is not taken into account;

3) it assumes constant and uniform static vertical stress and neglects the horizontal stress in the pillars;

4) it does not integrate the discontinuities that affect the rock mass and, in particular, the pillars;

5) it does not take into account the position of the pillars with respect to the closed edges.

Factor of Safety. The pillar stability can be evaluated by determining a factor of safety (F_s).

The safety factor is estimated as given in equation

$$F_s = \frac{\textit{Strength of the pillar}}{\text{average axial pillar stress}} = \frac{\sigma_s}{\sigma_p}.$$

Obert and Duvall (1967) proposed a pillar design method for rocks in general, but mostly based on strong rocks, such as those found in Zinc and Lead mines.

The following equation describes the pillar strength

$$\sigma_s = \sigma_c[0.778 + 0.222(W_0/h)],$$

where σ_c is the compressive strength; h is the pillar height.

Numerical Method. Finite Element Method (FEM). The FEM assumes that the bedrock is continuous. It makes it possible to discretize it into continuous single elements. The FEM also takes into account the geometry of the structure, the boundary and initial conditions, the heterogeneity and the anisotropy of the ground.

At present, the numerical methods are a powerful tool for solving many engineering problems in underground mining. The grounds can be attributed to an elastic or elastoplastic constitutive law or others. From the constraints and deformations obtained, this method is able to globally locate the most stressed or relaxed areas.

Thanks to very powerful computer means, three-dimensional models can be produced (e.g. PLAXIS 3D 2000). Although this method is very efficient in estimating the stresses around underground structures, it does not allow taking into account natural discontinuities in a satisfactory way, although we can introduce particular elements for this purpose (elements of interface and joint elements). This method is more widely used today than before (Chhunla C., 2018).

Plaxis 3D version 1.2 software is used in the modelling of room and pillars stability. The software evaluates the stress analysis and deformation by finite element method (FEM).

Methodology. In this work, the stability analysis of the rooms-and-pillars of the Chaabet El-Hamra mine was performed. Firstly, the safety factor was calculated by TAM for both conditions:

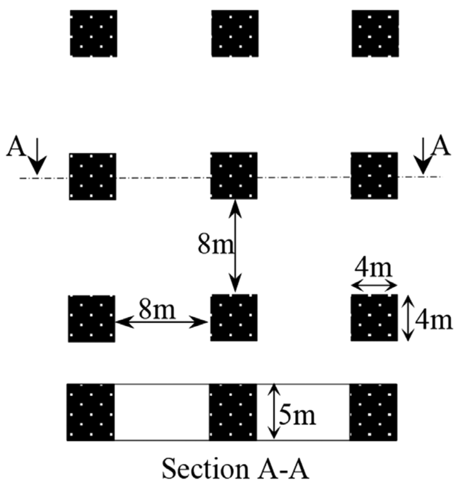
1. For the current operation which uses 8.0 m wide rooms with 4.0 × 4.0 m pillar sections (Fig. 2, *a*).

2. For the conditions of proposed technique which involve the use of 9.0 m wide rooms with 3.0 × 3.0 m pillar sections (Fig. 2, *b*).

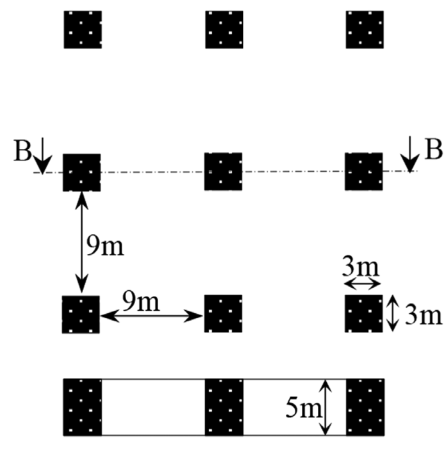
Secondly, the numerical method was used to analyze pillars stability and displacement vertical of the proposed technique through the PLAXIS 3D software (Fig. 3). Finally, a discussion of the stability of the room-and-pillar using safety factors and the extraction ratio was performed.

Fig. 3 shows the model and meshing performed by PLAXIS 3D software. The studied problem is divided into three zones; 110 m of dolomite (roof), zinc layer (e.g., 5 m thickness) and dolomite (e.g., footwall).

The geomechanical and strength properties of rock mass used in this numerical modelling based on field



a



b

Fig. 2. Room-and-Pillar stoping methods. Current method (a) and proposed method (b)

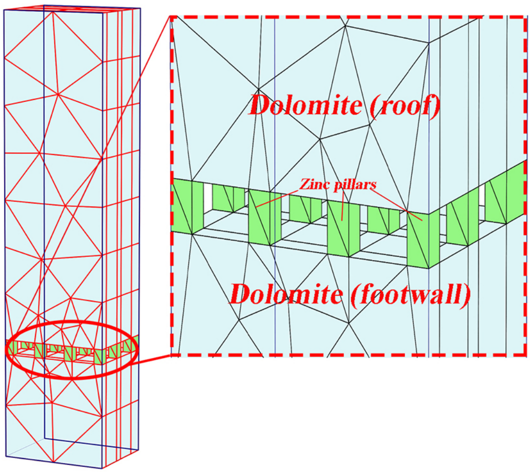


Fig. 3. Plaxis 3D model set up and meshing

measurement and laboratory studies are given in Table 1.

Results and discussion. ***Analysis performed by ATM.*** In the TAM analysis, the safety factor and the extraction rate were calculated through two cases. Firstly, the safety factor value was calculated by the existing parameters in the mine (W_0 = 8 m, W_p = 4 and 110 m depth). Secondly, the safety factor was calculated by the proposed parameters (W_0 = 9 m, W_p = 3 and 110 m depth). The output results are shown in Table 2.

The results obtained by the existing parameters (Fig. 3) show that the mine is stable (F_s = 2.54) with a profitable extraction rate (89 %); on the other hand, the results found by the proposed variants depict that the mine remains stable (F_s = 1.38) with a very high extraction rate (93.75 %).

Table 1

Geotechnical parameters used in the numerical modeling

Materials	E_{ref}	C_{ref}	γ	φ	ν	ψ
	(GPa)	(KPa)	(kN/m^3)	(°)	–	(°)
Dolomite	28	4984	26	51.2	0.32	8
Zinc	45	5192	30	82.73	0.25	8

E: Young's modulus, C_{ref}: *cohesion,* γ: Unit weight, φ: friction angle, ν: Poisson's ratio, ψ: dilatancy angle

Table 2

The safety factor computed by current and proposed pillar sizes

Elements		Pillar size	
		current	proposed
Depth to pillar roof level	H (m)	110	110
Compressive strength	σ_c (Mpa)	72	72
Pillar height	h (m)	05	05
Room width	W_0 (m)	08	09
Pillar width	W_p (m)	04	03
Extraction ratio	(%)	89	93.75
Factor of safety	F_s	2.54	1.38

Analysis performed by finite element method (FEM). We used the Plaxis 3D calculation software; it is based on the finite element method. The adopted model is shown in Fig. 3. To implement it, we applied the following approach:

1. We chose the geometry of the model that is closest to the real geometry of the mine with the proposed technique.

2. We followed the same approach that was applied in the mine, that is to say, phase excavation (Fig. 4). Phased excavation involves creating voids based on the operating history.

In the current operation, according to the survey inside the mine and the results obtained by TAM, it is concluded that the mine is very stable.

After the finite element analysis, we understood the following elements.

In the proposed technique, the total displacement is 0.259 mm (Fig. 5), indicating the advantage of the proposed method. The displacement is very low, which implies that the mine remains stable.

Fig. 6 shows the mean stresses according to the 4 phases of excavation for the proposed technique above the room's roof and the pillar layout located at a depth of 110 m.

The mean stress in the surrounding stope area is 38 MPa, decreasing gradually with the distance. In the inferior and superior zones of the pillars, the vertical stresses are similar in the peripheral area of room and pillar, and the failure in this area is not critical.

Fig. 7 illustrates the traces of the main stresses according to the 4 phases of excavation for the proposed technique. At 110m depth and with a large reach of the rooms, the total stresses (39.93 MPa) decrease gradually with distance and spread from the roof to the surface.

In the pillars, however, we note (phases 1, 3) a low shear, which, as we may generalize, will increase with the increase in the recovery height. This situation is not to cause instabilities.

Conclusions.

1. The results of the chamber and pillar stability analysis indicate a safety factor of 1.38 for the proposed technique. In addition, the total displacements are 0.259 mm. Thus, the proposed operating technique of the mine will not cause stability problems.

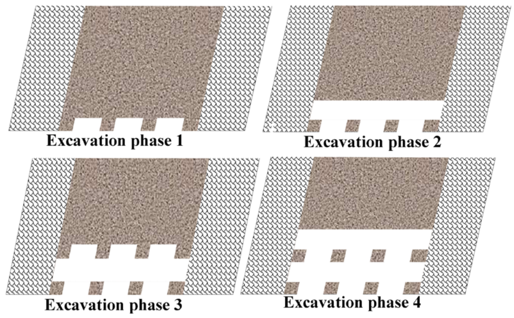


Fig. 4. Sequence excavation phase

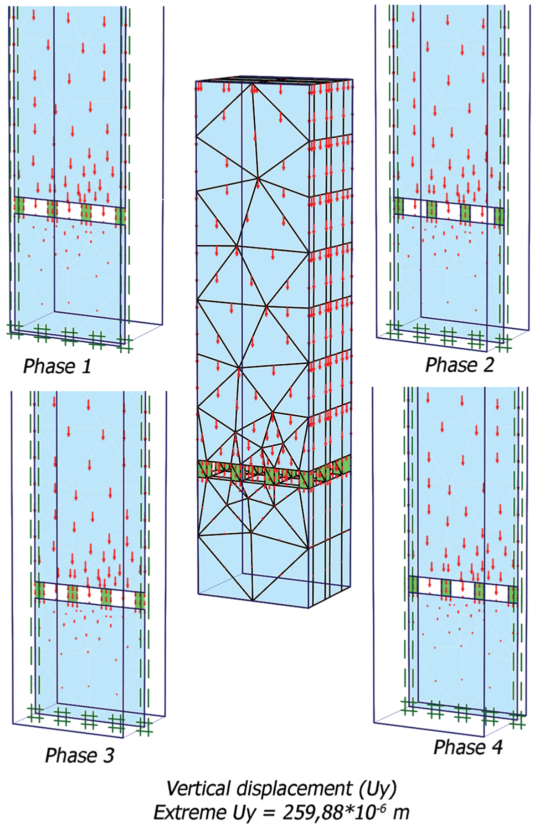


Fig. 5. Vertical displacement according to the 4 phases of excavation for the proposed technique

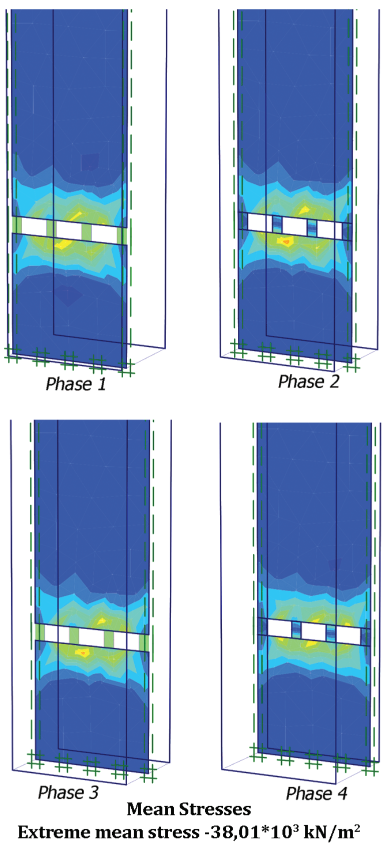


Fig. 6. Mean stresses according to the 4 phases of excavation for the proposed technique

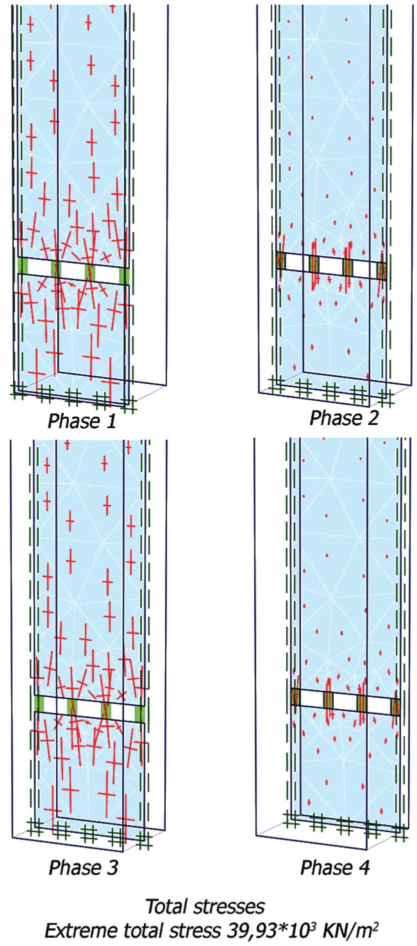


Fig. 7. Traces of the main stresses according to the 4 phases of excavation for the proposed technique

2. The production ratios show that the extraction rate of the current technique is 89 % and for the proposed technique it is 93.75 %. Thus, these results show that the proposed technique proved to be advantageous and more practical.

3. The stability studies confirm the fact that geotechnical research with computer applications (numerical methods) in underground mining can make a significant contribution to developing safer and more economical stopping methods.

Recommendations. Using more than one method in underground mining for stability analysis is the best solutions for achieving reliable results.

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Аналіз стійкості стовпів підземної шахти Шаабі Ель-Хамра (Алжир) аналітичними та чисельними методами

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Мета. Аналіз стійкості камерно-стовпових систем розробки як тієї, що використовується в даний час, так і пропонованої для використання на цинковій шахті (Шаабі Ель-Хамра). Використовуються два різних підходи: аналітичний метод для площини вхідних отворів фільтра свердловини (ПВОМ) і чисельний метод (метод кінцевих елементів – МКЕ) із застосуванням програми PLAXIS 3D.

Методика. У даній роботі виконується аналіз стійкості камерно-стовпових систем розробки шахти Шаабі Ель-Хамра. По-перше, за допомогою ПВОМ був визначений коефіцієнт міцності для двох умов: 1) використовувана в даний час система в камерах шириною 8,0 м із секційними стійками 4,0 × 4,0 м; 2) пропонована технологія в камерах шириною 9,0 м із секційними стійками 3,0 × 3,0 м. По-друге, був застосований чисельний метод для аналізу стійкості опор і величини відстані переміщення з використанням програми PLAXIS 3D.

Результати. Використання більше одного методу в підземних виїмках для аналізу існуючої та пропонованої технологій є найкращим рішенням у досягненні надійних результатів.

Наукова новизна. Новизна даної роботи полягає у використанні двох різних методів ПВОМ і чисельного методу (МКЕ) для аналізу стійкості камерно-стовпових систем розробки на шахті та підтвердження точності цього методу у сфері гірничої промисловості.

Практична значимість. Результати аналізу стійкості камерно-стовпових систем розробки визначають коефіцієнт міцності 1,38 для запропонованої технології. Більш того, максимальне зміщення становить 0,259 мм. Таким чином, запропонована технологія роботи із пластом не викличе проблем зі стійкістю. Коефіцієнт продуктивності показує, що норма вилучення технології, що вже використовується, становить 89 %, тоді як для пропонованої – 93,75 %. Таким чином, результати показують, що запропонована технологія продуктивна й більш практична. Дослідження стабільності підтверджують той факт, що геотехнічні дослідження із застосуванням комп'ютерних технологій (чисельні методи) у підземних виїмках роблять значний внесок у розвиток більш безпечних і економних систем розробки з посиленими заходами щодо захисту здоров'я, безпеки та навколишнього середовища.

Ключові слова: *шахти та гірнича справа, продуктивність, стійкість, камерно-стовповий, коефіцієнт міцності, МКЕ, шахта Шаабі Ель-Хамра*

Анализ устойчивости столбов подземной шахты Шааби Эль-Хамра (Алжир) аналитическими и численными методами

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Цель. Анализ устойчивости камерно-столбовых систем разработки как используемой в настоящее время, так и предлагаемой для использования на цинковой шахте (Шааби Эль-Хамра). Используются два разных подхода: аналитический метод для расчета площади входных отверстий фильтра скважины (МРПВО) и численный метод (метод конечных элементов – МКЭ) с применением программы PLAXIS 3D.

Методика. В данной работе выполняется анализ устойчивости камерно-столбовых систем разра-

ботки шахты Шааби Эль-Хамра. Во-первых, с помощью МРПВО был определен коэффициент прочности для двух условий: 1) используемая в настоящее время система в камерах шириной 8,0 м с секционными стойками 4,0 × 4,0 м; 2) предлагаемая технология в камерах шириной 9,0 м с секционными стойками 3,0 × 3,0 м. Во-вторых, был применен численный метод для анализа устойчивости опор и величины расстояния перемещения с использованием программы PLAXIS 3D.

Результаты. Использование более одного метода в подземных выемках для анализа существующей и предлагаемой технологий является лучшим решением в достижении надежных результатов.

Научная новизна. Новизна данной работы состоит в использовании двух разных методов МРПВО и численного метода (МКЭ) для анализа устойчивости камерно-столбовых систем разработки на шахте и подтверждения точности этого метода в сфере горной промышленности.

Практическая значимость. Результаты анализа устойчивости камерно-столбовых систем разработки определяют коэффициент прочности 1,38 для предлагаемой технологии. Более того, максимальное смещение составляет 0,259 мм. Таким образом, предлагаемая технология работы с пластом не вызовет проблем с устойчивостью. Коэффициент продуктивности показывает, что норма извлечения уже используемой технологии составляет 89 %, тогда как для предлагаемой – 93,75 %. Таким образом, результаты показывают, что предлагаемая технология продуктивна и более практична. Исследования стабильности подтверждают тот факт, что геотехнические исследования с применением компьютерных технологий (численные методы) в подземных выемках делают значительный вклад в развитие более безопасных и экономных систем разработки с усиленными мерами по защите здоровья, безопасности и окружающей среды.

Ключевые слова: *шахты и горное дело, производительность, устойчивость, камерно-столбовой, коэффициент прочности, МКЭ, шахта Шааби Эль-Хамра*

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