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УПРАВЛЕНИЕ НАПРЯЖЕННО-ДЕФОРМАЦИОННЫМ СОСТОЯНИЕМ МАССИВА ГОРНЫХ ПОРОД ПУТЕМ ФОРМИРОВАНИЯ РАЗНОПРОЧНОСТНОЙ ЗАКЛАДКИ

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Аннотация: Переход горных работ на более глубокие горизонты, истощение запасов месторождений и усложнение горно-геологических условий приводит к возникновению геотехногенных катастроф. Для исключения негативных последствий разработки полезных ископаемых необходимо решение задач, позволяющих более существенно управлять горным давлением, что улучшит безопасность ведения горных работ, внедрение новых технологических решений, дающих возможность одновременной отработки месторождений открытым и подземным способами, а также снизить негативные последствия геотехнологии на биологический оптимум региона. Анализ опыта применения закладочных работ позволяет сделать вывод о необходимости более широкого применения данной технологии, необходимости ее совершенствования ввиду того, что позволяет нивелировать недостатки других систем, обеспечить более безопасное ведение горных работ и гарантировать более высокую полноту выемки полезного ископаемого. Оценка напряженно-деформационного состояния горного массива в зависимости от варианта формирования искусственного массива, произведенная при использовании метода конечных элементов, позволяет установить границы изменений значений напряжения. Сравнительный анализ параметров плоскости обнажений закладки позволяет сделать вывод, что при извлечении запасов в сложных горнотехнических условиях для заполнения выработанного пространства возможно применение разнопрочностной закладки разной. На основе разнопрочностной закладки предложен ряд технологических решений, позволяющих снизить себестоимость закладочных работ, сохранив при этом безопасность и полноту выемки при отработке маломощных и средней мощности как крутопадающих, так и пологих рудных тел.

Ключевые слова: геотехноогия, геомеханика, добыча полезного ископаемого, закладка, закладочные работы, разнопрочный закладочный массив, твердеющая смесь, горный массив, камерная система разработки, ленточный целик, математическое моделирование, прочность, прочностные характеристики, методика.

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Stress–strain behavior control in rock mass using different-strength backfill

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Abstract: Transition of mining to deeper horizons, depletion of mineral reserves and complication of geological conditions can induce manmade disasters. To avoid the negative consequences of mineral mining, it is necessary to improve the ground control procedures for enhancement of mining safety, to introduce new engineering solutions that enable hybrid open pit/underground mining and to abate adverse impact of geotechnology on the local biological optimum. The analysis of the backfilling experience allows for the conclusion on the necessity of improvement and wider application of this technology as it makes it possible to level the disadvantages of other systems, promotes safety of mining operations and ensures more complete mineral extraction. The finite element-based stress–strain analysis of rock mass depending on the backfilling variant defines the variation range of stresses. The comparative studies into the parameters of the exposed backfill surfaces allow concluding on applicability of different-strength backfill in mineral mining in difficult geological conditions. Based on using different-strength backfill, the authors propose some engineering solutions capable to reduce the cost of backfilling operations at the maintained safety and completeness of mineral extraction in mining thin and moderately thick steeply dipping and flat ore bodies.

Key words: Geotechnology, geomechanics, mineral mining, backfill, backfilling operations, different-strength fill mass, cemented paste backfill, rock mass, room-and-pillar mining system, rib pillar, mathematical modeling, strength, strength characteristics, procedure.

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Introduction

Constantly growing human needs call for increasing extraction of minerals from the subsoil, which implies continuous expansion of the mining industry. The increase in the volume of mineral extraction and the growing demand for constant buildup of production predetermine the use of high mining technologies to ensure maximum productivity at minimum costs. When choosing the method and systems of mining, only technical and economic indicators of production are taken into account while the environmental impact is neglected [1]. It is preferred to combine the open-pit mining method with the prevailing underground mining method of stoping with caving. The use of these technologies is connected with ground surface disturbance and lacks environmental safety [2].

In case of using mining systems with natural support of stoping space to ensure ground surface preservation, the problems connected with waste rock dumps and tailings ponds remain unsolved [2–4]. The environmental impact and additional costs of waste management are widely discussed in [5–9], and the ecological and economic costs of storage and haulage of waste are analyzed in [10, 11]. Mining systems with natural support of stoping space are characterized by high losses of mineral

reserves — up to 70–75%. Sometimes, as a result of mistakes made during mine operation, or as a result of secondary mining (completion) of abandoned mineral reserves, induced disasters take place in the form of roof falls or flooding in mines (Silvinit and Uralkali mines, Perm Region), water breakthrough from open pit to underground mine (Mir mine, Republic of Sakha, Yakutia) and rock bursts which invoke earthquakes (Umbozero mine, Murmansk Region, etc.) [2, 4] or strong high dynamic phenomena [12, 13].

Progress of systems with backfill of mined-out void

Over the past 40 years, systems with artificial support of mining area, namely, systems with backfill, have been widely developed and used. The systems with backfill in such a short period have significantly evolved from dry fill to hydraulic fill on the basis of complex composite materials. Such a wide application of the technology with backfill was due to the fact that it allowed avoiding the above-listed disadvantages of other systems to a greater extent and ensured more complete extraction of minerals [1, 3]. However, due to the relatively high cost, this technology has a dominant application only in high-value ore production, or in mining in very complex geological conditions [14]. In coal mines, backfill was used in thick and very thick deposits and in the fields with a high risk of gas emissions [15]. Extraction was carried out by means of dead-end chambers with their subsequent expansion and with filling of mined-out void [16]. Due to the high cost of backfilling operations, the use of backfill in extraction of low-value minerals was abandoned since it increased the cost of production.

Creating a solid artificial fill mass makes it possible to fully use the advantages of cemented paste backfill. This is due to the fact that during the construction of an artificial fill mass, the conditions related to the parameters of extraction blocks, seismic impact of blasting, height of exposed rock surfaces and normative strength are observed. These factors are quite rigid and reflect the load-bearing capacity of the created backfill mass, which disables the cost reduction [17, 18].

Cemented paste backfill is a composite material capable of hardening in underground conditions; it includes the following components: binder, aggregate, chemical additives (if necessary) and water. As an aggregate, it is possible to use not only traditional mining products or building materials (sand, crushed stone, etc.), but also intermediate products (waste: slag, tailings of concentrators, ash, etc.) [3, 17, 19]. The use of intermediate mining products in backfilling is available in two options: placement of a limited amount of waste not included in backfill; use of waste in preparation of backfill mixture. At the same time, it is necessary to consider that creation of a fill mass with the set standard characteristics is the paramount task of safe mining [20, 21].

Despite the main drawback of using the technology with backfill, namely, its high cost, this technology remains the only one that most completely eliminates the negative consequences arising from the use of other systems, and allows reducing the environmental impact of mining [2–4, 17, 21]. In coal deposits, waste from lignite dumps was used as backfill; the spatial variability of properties of such backfill was studied in [22].

For wider application of the mining technology with backfill, it is necessary to reduce the cost of backfilling operations by means of depreciation of backfill components, elimination or limited use of expensive binders and by use of industrial waste as an aggregate; modification of continuous backfilling through the use of new engineering solutions. Pursuing these

objectives can ensure high safety of mining operations and reduce the impact of mining on local ecology.

One of the ways to solve this problem is to create a different-strength backfill such that its parameters can be adjusted in a given range with a wide use of waste materials. It is necessary to find and study the laws of formation and change of the geomechanical situation during mineral mining with regard to the sequence of mining operations in order to determine the normative characteristics of artificial fill masses and their parameters depending on composition and properties of backfill material. The use of new engineering solutions in mining with different-strength backfill based on by-products of mining solves a number of economic and environmental problems at the same time, which is quite relevant at this time and has a great macroeconomic importance. The use of local natural materials and intermediate products (mining and processing waste) can significantly cut down the cost of backfilling operations, improve stability of dumps and tailings ponds and reduce the land withdrawal area for mining purposes [23].

In mining in difficult geological conditions, the most promising trend in ground control is the use of technologies with backfill made of combined materials and composites. The studies have determined the manmade fill safety that changes over time [24]. Cemented paste backfill creating an artificial fill of different strengths is the basis of the combination. Such fill mass is created from different-strength structural components combining natural and artificial pillars and loose material placed in secondary chambers or internal parts of an extraction block. In this regard, further studies of the geomechanical behavior of different-strength backfill are necessary and the technology of its creation requires further improvement.

Stress–strain analysis of backfill depending on the variant of its formation

It is possible to use the Barton method of rock mass quality assessment [25], or the Roslow and Heintze scheme of the finite element-based stress–strain analysis of different strength materials [26]. Potential fracturing and the effect of various mining systems on the integrity of water-resistant strata were analyzed in plane strain conditions in [27]. Displacement monitoring and sensitivity analysis in the observational method are described in [28].

We believe that the scheme by Roslow and Heintze in the program FLAC3D 5.01 is the most appropriate for these studies; the scheme uses the finite element method and provides a complete understanding of the existing different systems than the real model but as close to the algorithmic description.

When modeling, three series of models were created with different conditions of mined-out voids. In the first series, the void was not filled; in the second series, the voids were filled with different mixtures; in the third series, the combined scheme was used: optional advanced fill material and durable enough fill mass.

It can be derived from the analysis of the results (Table 1) that the stress state of rock mass varies significantly depending on the condition of the voids, and the ranges of changes in the stress values are quite wide: from 1.2 to 7.2 MPa. When mined-out stopes are filled with low-strength materials or mixtures (σ_x up to 1 MPa), tension of the surrounding rock mass lowers 1.4–1.6 times compared to the initial version without backfill. The effect of partial extraction of the protective layer on safety indicators was identified and rather comprehensively described in [29]. The reduction in stresses in adjacent rock mass by two or more times as against the reference version is observed when

Table 1

Stress state of model systems
Характеристика напряженности в моделируемых сериях

Model	Mined-out void	Geomechanical parameters	
		Maximum stress, MPa	Hazard factor
I, 2	Not filled	7.2	1
II, 2	Filled with low strength material	4.5	0.63
II, 4	Filled with durable material	3.24	0.45
II, 6	Compound backfill	3.6	0.5
III, 2	Advanced backfill with low-strength material	4.4	0.61
III, 4	Advanced backfill with durable material	4.0	0.56

the voids are filled with different-strength mixtures.

An intermediate value with regard to the first models of backfill belongs to the composite fill of voids; here, the average third of a void is filled with dry rocks or with a low-strength mix, and side zones are filled with a strong backfill. In this model of fill mass formation, the normal stresses are the same as in the variant with a strong fill but differ significantly from the model with a low-strength backfill.

From the comparative analysis of the backfill alternatives in Table 1, it can be concluded that the safest option is the model with cemented paste backfill. The presence of unfilled voids increases the hazard factor to 1. The maximum values of stresses in rock mass surrounding voids with a strong backfill material and composite backfill differ slightly, which allows us to consider the different-strength backfill as a possible way to control the stress–strain behavior of rock mass and to reduce significantly the cost of backfilling operations as a result.

The research has found that the ground surface–rock mass–void system is a discrete medium, and its rigidity undergoes changes as a result of deformation due to redistribution of stresses subject to various tectonic and structural factors. The structural elements form an elastic «pillow» which increases the strength of adjacent rock mass, with the loss of the load-bearing capacity of fill mass. The geomechanical balance of the rock mass–backfill system is preserved due to the jamming of structural blocks in the zone of loosening, and the stress–strain behavior recovers due to the «reset» of stresses in the roof and owing to the lateral pressure of structural blocks.

$$\sigma_x^0 \le \sigma_x^0 + \sigma_r = \\ = \int_0^{z_{0\max}} fx\left(dx_1, dx_2, \dots dx_n\right) \to \sigma_{cl} = \\ = \int_0^{z_{0\max}} fx\left(dH_s\right) \quad (1)$$

where σ^0_x are the stresses in the upper softened perimeter layer of rock mass, MPa; σ_r is the tension of the structural blocks in the lower layer, MPa; σ^{res}_x is the residual strength of softened rocks, MPa; Z_0 is the length of flat exposed rock span, m; $x_1 \dots x_n$ are the characteristics of the material of the structural blocks; σ_{cl} is the backfill strength, MPa; H_s is the height of void to be filled, m.

The strength of the backfill and the lateral pressure increase when the artificial fill mass enters the volumetric compression mode. In this case, the increase in the load-bearing capacity of the geomechanical system can be considered by introducing the parameter k_z in equation (1):

$$\sigma_x^0 \le \sigma_x^0 + m\sigma_r =$$

$$= \int_0^{z_{0max}} fx\left(dx_1, dx_2, \dots dx_n\right) \to \sigma_{cl} = \quad (2)$$

$$= k_z \int_0^{z_{0max}} fx\left(dH_s\right)$$

where m is the coefficient of lateral expansion; k_z is the strengthening factor of fill mass.

The strengthening factor characterizes the degree of compensation of a void in a geomechanical system. The compensation is maximum when backfill is equally strong as the material being mined, and the minimum compensation is when backfill is composed of dry rocks with high compression properties (Table 2).

As a result of the perimeter zone support by backfill, the stress is created by the integral influence of all elements of the system:

$$\sigma_M = n_1\sigma_{n3} + n_2\sigma_{c3} + n_3\sigma_{m3} +$$
$$+ n_4\sigma_{H3} + n_S\sigma_x^{res} = \sum_1^l n_l\sigma_m^Y \quad (3)$$

where σ_{n3}; σ_{c3}; σ_{m3}; σ_{H3} are the stress values for strong, medium-strength and low-strength composition of cemented paste and dry rock backfill; l is the number of reinforcing elements; $n_1 \dots n_S$ are the mass numbers of the material in the total amount of the mixture; σ^Y_m is the strength of the reinforcing materials.

Comparing the actual and the estimated plane parameters of exposed backfill, it is possible to conclude that mineral mining in complicated mining conditions can use backfill composed of different materials with different strength.

Engineering solutions for different-strength backfill

Based on the calculations and implemented research, with regard to the data in Tables 1 and 2, it is possible to offer a number of engineering solutions to reduce the cost of backfilling operations at the maintained safety and completeness of mineral extraction from thin and medium-thick steep and shallow ore bodies.

Basic design principles:

- complete filling of mined-out stopes with backfill;
- no open stoping in insufficiently stable areas;
- differentiation of engineering solutions with respect to the cost of backfilling operations.

Option 1. Sublevel stoping and different-strength backfill.

A stoping level is extracted by stopes arranged across of the ore body strike. Preparation: drivage of ventilation and haulage horizons. Face-entry drivage: vertical drilling every 15–25 m along sublevel cross drifts; sublevel drifts are driven from the center of the ore body. Stoping (Fig. 1) begins with top cutting to a height of 8–10 m with subsequent backfill of the mined-out space with cemented paste backfill of increased durability. After the backfill reaches the design strength, stoping is continued on the sublevels under the artificial crown. Stoping is carried out so

Table 2

Strengthening factor as function of strength of material
Зависимость коэффициента упрочнения от прочности материала

Backfill	Strength	Strengthening factor
Strong cemented paste backfill	3–15	0.97–1
Weak cemented paste backfill	1.0–3.0	0.9–0.95
Low-strength cemented paste backfill	0.5–1.0	0.82–0.9
Dry rock fill	>0.4	0.7–0.8

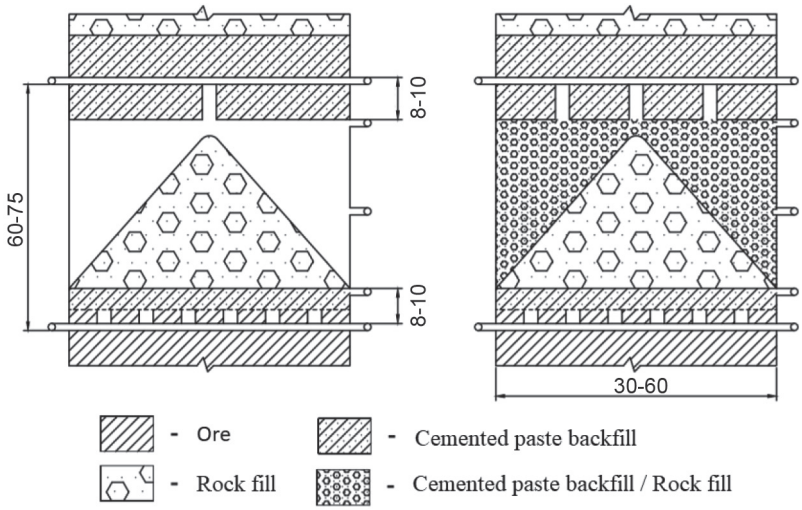

Fig. 1. Room-and-pillar mining with different-strength backfill at the boundaries of extraction blocks

Рис. 1. Вариант системы разработки с разнопрочностной закладкой путем создания высокопрочного массива на границах блоков

that operations on the upper sublevel are ahead of the lower sublevel operations by 4–5 m. After breaking and discharge of ore from the floor layer, the void is filled with different-strength backfill. At the initial stage, the artificial pillar 8–10 m high is formed by filling a room with cemented paste mixture via filling wells. Then the stope is partially filled with a low-strength composition of crushed gangue, which provides the required strength properties. After filling the mined-out void with dry rocks, the remaining area of the stope is filled with dry rock-and-cemented paste mixture. The granulometric composition of dry rock is selected with regard to the

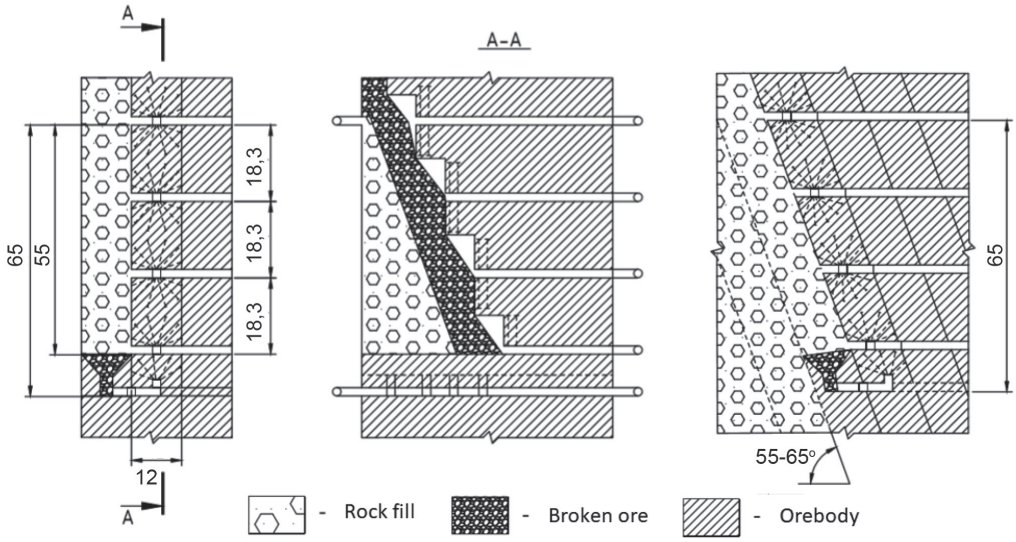

Fig. 2. System of mining with sublevel cross drifts on inclined layers with backfill

Рис. 2. Система разработки подэтажными ортами наклонными слоями с закладкой

highest void ratio for deeper and more effective penetration of cement grouting.

The area of the ore body is not divided into rooms and pillars, and the extraction of ore from a stope is carried out in one stage.

Option 2. Stoping with sublevel cross drifts in inclined layers with backfill.

First, long hole blasting is carried out to make a slot raise. After broken ore from the raise slotting is discharged, stoping begins. The overlying sublevel stoping goes a little ahead of the underlying sublevel. First, ore is broken in vertical cuts on the lower level; then, ore is broken simultaneously on two sublevels displaced relative to each other; after that, mining is carried out on three sublevels, at the same offset. Finally, a solid pillar is blasted, which is connected with the haulage ramp at the bottom. Broken ore is discharged by stages using the ramp. Then the mined-out space is filled with rock (dry) fill. The backfill is distributed in the stopes at an angle of natural inclination with respect to the entire parts of the sub-levels. Further extraction of ore reserves is carried out by ore breaking in cuts of the same width on the inclined layers of the rock (dry) fill.

Option 3. Room-and-pillar mining with different-strength backfill.

A thick and steeply dipping ore body is divided into extraction blocks. An extraction block is split into rooms within a level so that the rooms are arranged across the strike of the ore body (the location along the strike is possible depending on the ore body thickness). The preparatory work is similar to Option 1, which is drivage of entries on ventilation and haulage levels. Breakage of blocks is carried out vertically from sublevel cross drifts. After extraction of ore reserves from the rooms, the rooms are backfilled (Fig. 3). At the initial stage, high-strength mixtures are laid on the bottom of a room, which creates a sufficiently strong artificial crown for stoping on underlying horizons. The fill mass in the area of isolating partitions is carried out by technology that excludes their destruction under excessively high pressure from the backfill.

Measures to prevent excessive pressure on the partitions include:

- Suspension of feed of backfill mixture into a room after partial overlap of the partitions (possible overlap to the whole height) until complete loss of backfill flowabil-

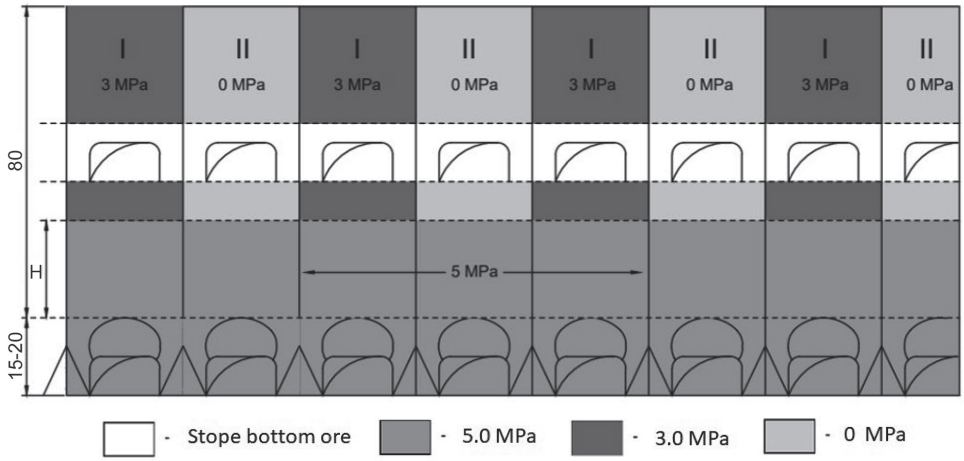

Fig. 3. Room-and-pillar mining with high-strength crown

Рис. 3. Камерная система разработки с возможностью формирования в отрабатываемых блоках искусственного массива различной прочности и созданием высокопрочной потолочины

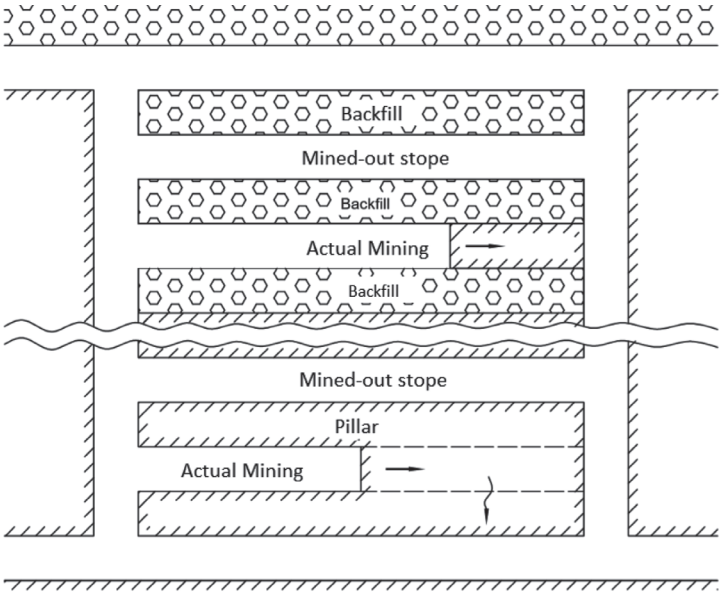

Fig. 4. Two-stage stoping with rib pillar and backfilling

Рис. 4. Камерная система разработки с оставлением ленточного целика при двухстадийной выемке с последующей закладкой

ity (specific consumption of cement is inversely proportional to suspension time);

- Application of backfill mixture with minimal lateral shrinkage.

After pouring the partitions to the whole height of 2–3 m with backfill mixture with strength of 5 MPa, the feed of the mixture to the bottom of the room is stopped for one day. Further, the room bottom is gradually filled with backfill mixture with strength of 5 MPa to a height of 15–20 m at a step of 2–3 m and at a time interval of one day. After complete overlap of the partition, the backfill mixture with strength of 5 MPa is fed to a height H (up to 20–30 m) depending on the width of the room, which completes creation of a high-strength artificial crown. Then, backfill with strength of 2–3 MPa is filled to the whole height of the room, which completes the first operation stage and creates an artificial pillar.

The second operation stage follows the same flow chart. The difference is that after formation of a high-strength crown, backfilling to the full height of the rooms is carried out with a mixture with strength of 0–0.5 MPa without binder.

Option 4. Breast stoping with rib pillar in two stages with backfill (Fig. 4).

A shallow or gently dipping ore body is divided into extraction blocks. A block is extracted by stopes d m wide and to 200 m long, with a rib pillar d m wide. The mined-out stopes are filled with material having strength of 3–4 MPa. After design strength has been achieved, the second stage of mining is started (extraction of the rib pillar). In case of guided objects on ground surface, or in the presence of overlying aquifers, the second-stage stopes are filled with backfill mixture without a binder (the backfill strength of 0–0.5 MPa) to prevent collapse of the stopes and further deformation of overlying rocks. Otherwise, it is possible to leave the mined-out voids unfilled and, subject to deformation, they will expand without reaching the ground surface, and in case of reaching the surface, this will not entail any catastrophic consequences.

Option 5. Three-stage stoping with rib pillars and backfill.

Mining of a flat or gently dipping ore body is carried out according to the same process flow chart as in Option 4. The difference is the rib pillar width of 2d m. After the first stage stoping, the stopes are filled with cemented paste mixture having strength of 1.5–2.5 MPa. Extraction of ore reserves from the rib pillar is executed in two stages: ½ part of a pillar, i.e. the width d, is extracted at the first stage with subsequent backfilling with mixture having strength of 1.5–2.5 MPa. At the second stage, the remaining part of the pillar is extracted. After that, the mined-out void is left open or filled with binder-free backfill with strength of 0–0. 5 MPa.

For Options 4 and 5, the width d is designed to ensure not only safe mining, but also more efficient use of mining equipment. In addition, before extraction of stopes of the 2nd and 3rd stages in these options, it is necessary that the area under the roof (top layer) in the filled stopes is filled with fragments detached from rock mass, loading the backfill and thus creating the geomechanical balance.

Conclusions

The proposed approach to the stress–strain analysis of rock mass in rock–backfill contact zones is recommended for the applied geotechnical assessment in the conditions of mining with manmade support of mined-out area. In difficult geological conditions, under high rock pressure, abundant water inflows and increased fracturing of rocks, the model is calibrated with regard to the geotechnical assessment of rock mass, and is refined using FLAC3D 5.01.

The proposed engineering solutions allow more durable zones to be created in the areas exposed to the greatest geomechanical impact, with the highest stresses and at the rock mass–backfill contact, while less durable zones to be formed inside artificial fill mass. The creation of a different-strength manmade fill mass ensures safer and more efficient extraction of minerals, while the cost is reduced by 30% and the backfill intensity is increased by 15–25%.

It should be noted that these engineering solutions are readily adaptable to different mining and geological conditions of deposits composed of various value minerals.

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