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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

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Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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GEOMECHANICAL JUSTIFICATION OF UNDERGROUND MINING TECHNOLOGIES FOR ORE DEPOSITS IN COMPLEX ROCK MASSIFS FROM THE STANDPOINT OF NATURE AND RESOURCE CONSERVATION

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Abstract. *Relevance.* Underground mining of ore deposits in complex rock masses generates stress-strain states that can reduce the stability of mine workings, the completeness of ore extraction, and the environmental safety of the areas. Insufficient consideration of the structural and petrographic heterogeneity of the rock masses limits the effectiveness of traditional design solutions. *Objective.* To summarize and systematize the patterns of rock behavior during underground mining of ore deposits and to substantiate technological approaches to managing the stress state of the rock mass from the standpoint of nature and resource conservation. *Methods.* The methods used are analysis and generalization of theoretical and experimental research in the field of geomechanics and geomanagement, modeling of the stress-strain state of rock masses, assessment of working stability, and a comparative analysis of mined-out space reclamation technologies (isolation, caving, backfilling, combined schemes). The article examines the application options for hardening backfill mixtures and in-situ leaching tailings. *Results and conclusions.* It is established that rock mass destruction proceeds with the formation of structural blocks interacting as rigid bodies with elastic contact, while geomechanical balance of the rock mass is achieved by dividing it into sections with subcritical stresses. It is demonstrated that combined void filling technologies enable targeted stress management, reducing ore contamination with rock, and improving working stability. Transitioning the backfill mass to triaxial compression increases its bearing capacity by 2–3.7 times and reduces mining costs. A conclusion is drawn regarding the feasibility of integrated management of natural and man-made stresses as a key factor in improving the efficiency and environmental safety of underground ore deposit mining.

Keywords: rock massifs, underground mining, geomechanics, stress-strain state, backfill, stability of workings, geouse

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ТАБИҒАТ ЖӘНЕ РЕСУРСТАРДЫ ҮНЕМДЕУ ТҰРҒЫСЫНАН КҮРДЕЛІ ТАУ-КЕН МАССИВТЕРІНДЕГІ КЕН ОРЫНДАРЫ ҮШІН ЖЕРАСТЫ ТАУ-КЕН ТЕХНОЛОГИЯЛАРЫН ГЕОМЕХАНИКАЛЫҚ НЕГІЗДЕУ

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Аннотация. *Өзектілігі.* Күрделі құрылымды тау жыныстарындағы кен кен орындарын жерасты игеру тау-кен қазбаларының тұрақтылығын, кен қазбаларының толықтығын және аумақтардың экологиялық қауіпсіздігін төмендетуге қабілетті кернеулі-деформацияланған күйлердің қалыптасуымен қатар жүреді. Массивтердің құрылымдық және петрографиялық гетерогенділігінің жеткіліксіз есебі дәстүрлі жобалық шешімдердің тиімділігін шектейді. *Мақсат.* Кенді кен орындарын жер асты қазу кезінде тау жыныстарының мінез - құлық заңдылықтарын жалпылау және жүйелеу және табиғи және ресурстарды үнемдеу тұрғысынан массивтің шиеленісті жағдайын басқарудың технологиялық тәсілдерін негіздеу. *Әдістері.* Геомеханика және геополяция саласындағы теориялық және эксперименттік зерттеулерді талдау және жалпылау әдістері, тау жыныстарының кернеулі-деформацияланған күйін модельдеу, қазбалардың тұрақтылығын бағалау және өндірілген кеңістікті өтеу технологияларын салыстырмалы талдау (оқшаулау, құлау, бетбелгі, аралас схемалар) қолданылды. Қатайтатын толтырғыш қоспалар мен жер асты шаймалау қалдықтарын қолдану нұсқалары қарастырылған. *Нәтижелер мен қорытындылар.* Тау жыныстарының жойылуы қатты денелер сияқты серпімді жанасумен өзара әрекеттесетін құрылымдық блоктардың пайда болуымен жүретіні анықталды, ал массивтің геомеханикалық тепе-теңдігі оны критикалық кернеулері бар аймақтарға бөлу арқылы жүзеге асырылады. Бос орындарды өтеудің біріктірілген технологиялары кернеу жағдайын мақсатты түрде реттеуге, тау жыныстарының бітелуін азайтуға және өндірістің тұрақтылығын арттыруға мүмкіндік беретіні көрсетілген. Бетбелгі массивінің үш осьті қысуға ауысуы оның жүк көтергіштігін 2-3,7 есе арттырады және өндіріс шығындарын азайтады. Кен кен орындарын жерасты игерудің тиімділігі мен экологиялық қауіпсіздігін арттырудың негізгі факторы ретінде табиғи және техногендік кернеулерді кешенді басқарудың орындылығы туралы қорытынды жасалды.

Түйін сөздер: тау жыныстары, жерасты қазбалары, геомеханика, кернеулі деформацияланған күй, бетбелгі, қазбалардың тұрақтылығы, геополяция

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ГЕОМЕХАНИЧЕСКОЕ ОБОСНОВАНИЕ ТЕХНОЛОГИЙ ПОДЗЕМНОЙ РАЗРАБОТКИ РУДНЫХ МЕСТОРОЖДЕНИЙ В СЛОЖНОСТРУКТУРНЫХ СКАЛЬНЫХ МАССИВАХ С ПОЗИЦИЙ ПРИРОДО- И РЕСУРСОСБЕРЕЖЕНИЯ

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Аннотация. *Актуальность.* Подземная разработка рудных месторождений в сложноструктурных скальных массивах сопровождается формированием напряжённо-деформированного состояния, способного снижать устойчивость горных выработок, полноту выемки руд и экологическую безопасность территорий. Недостаточный учёт структурной и петрографической неоднородности массивов ограничивает эффективность традиционных проектных решений. *Цель.* Обобщить и систематизировать закономерности поведения скальных пород при подземной разработке рудных месторождений и обосновать технологические подходы к управлению напряжённым состоянием массива с позиций природо- и ресурсосбережения. *Методы.* Использованы методы анализа и обобщения теоретических и экспериментальных исследований в области геомеханики и геопользования, моделирование напряжённо-деформированного состояния скальных массивов, оценка устойчивости выработок и сравнительный анализ технологий погашения выработанного пространства (изоляция, обрушение, закладка, комбинированные схемы). Рассмотрены варианты применения твердеющих закладочных смесей и хвостов подземного выщелачивания. *Результаты и выводы.* Установлено, что разрушение скальных пород протекает с формированием структурных блоков, взаимодействующих как жёсткие тела при упругом контактировании, а геомеханическая сбалансированность массива достигается его разделением на участки с докритическими напряжениями. Показано, что комбинированные технологии погашения пустот позволяют целенаправленно регулировать напряжённое состояние, снижать засорение руд породой и повышать устойчивость выработок. Переход закладочного массива к трёхосному сжатию увеличивает его несущую способность в 2–3,7 раза и снижает затраты на добычу. Сделан вывод о целесообразности комплексного управления природными и техногенными напряжениями как ключевого фактора повышения эффективности и экологической безопасности подземной разработки рудных месторождений.

Ключевые слова: скальные массивы, подземная разработка, геомеханика, напряжённо-деформированное состояние, закладка, устойчивость выработок, геопользование

Introduction. Underground mining of ore deposits in rock masses is a key pillar of modern mining production and plays a significant role in providing the global economy with mineral resources. Globally, deposits confined to complex, tectonically faulted, and energy-rich rock masses are becoming increasingly important. Their development is accompanied by intense stress redistribution, the development of deformation processes, and increased risks to the stability of mine workings and the earth's surface. Increasingly complex mining and geological conditions, increasing mining depths, and stricter environmental requirements are driving a steady demand for scientifically proven technologies for managing the stress-strain state of rock masses, ensuring safety, complete reserve recovery, and minimizing the anthropogenic impact on the environment (Abbas et.al., 2025; Al Smadi et.al., 2025; Tynchenko et.al., 2024).

One widely used approach to solving the problem of mine stability and rock pressure control is geomechanical modeling of rock masses using simplified assumptions of quasi-isotropy. In a number of published studies, this approach has allowed for the determination of the distribution of principal stresses around stopes and development workings, the identification of stress concentration zones, and the validation of pillar and chamber parameters. For example, studies analyzing roof stability in fractured rock formations have shown that, given certain ratios between the working span and the rock strength, a natural load-bearing arch is formed, ensuring the roof's integrity without additional support (Bosikov et.al., 2023; Malozyomov et.al., 2024; Tynchenko et.al., 2024). Numerical calculations have made it possible to predict permissible working sizes and reduce accident rates. However, a significant drawback of this approach is its poor consideration of the structural heterogeneity of the rock mass, its block structure, and the anisotropy of its strength properties, which reduces the reliability of predictions when developing complex deposits.

Another common approach is stress management through the use of forced or controlled rockfall mining systems. Several studies have shown that caving host rock allows for stress redistribution, reduces rock pressure concentrations on pillars and support elements, and increases ore recovery. Experimental and industrial data indicate a reduction in maximum stresses in the near-margin zone by tens of percent and a decrease in the volume of hazardous deformations. However, such technologies are associated with significant contamination of the mined ore with rock, difficulties in monitoring the condition of the caving mass, and increased environmental risks associated with possible ground deformations and land alienation (Kulikova et.al., 2023; Smee et.al., 2010).

Technologies for backfilling mined spaces with hardening mixtures have seen significant development, being considered an effective tool for managing rock pressure and ensuring rock mass stability. Several studies have found that backfilling significantly reduces rock mass deformations, reduces ground subsidence, and ensures a more uniform stress distribution. Numerical and experimental results show that when a backfill mass transitions from uniaxial to triaxial compression, its bearing capacity increases severalfold, while mine maintenance costs decrease. The main challenges of this approach remain the high cost of backfill materials, the need to transport them to depth, and the shortage of binders, which limits the widespread use of the technology in large-scale mining environments (Nayak et.al., 2024; Zaalishvili et.al., 2024).

A separate area of research concerns the use of natural and man-made materials as gob fillers. Published studies have examined the potential of using tailings and ISL products, which, upon natural hardening, form artificial masses with strengths up to several megapascals. The obtained numerical data demonstrate the ability of such masses to withstand significant loads and participate in stress redistribution. The advantage of this approach is the reduction of waste volumes and increased resource efficiency in mining operations. However, the long-term strength characteristics of such artificial masses, their degradation processes, and their impact on filtration and geo-ecological conditions remain insufficiently studied.

Considerable attention in scientific publications is given to combined technologies based on the combined use of mine sealing, backfilling, and rock caving. Research results demonstrate that combining various void filling methods enables flexible management of rock mass stress, adapting the technology to specific mining and geological conditions. Numerical estimates demonstrate a reduction in stress concentrations in critical zones and an increase in the stability of stopes. However, the complexity of designing such schemes, the need for detailed geomechanical justification, and the increased requirements for rock mass monitoring remain constraints to their implementation (Filina et.al., 2024; Shabanov et.al., 2023; Myrzakulov et.al., 2024).

A number of studies examine stress management methods by varying drilling and blasting parameters and regulating seismic impact on the rock mass. Experimental data show that varying blasting patterns, charge mass, and fracture boundary conditions enables control of seismic wave parameters and stress redistribution. This helps reduce dynamic loads and minimize rock mass damage. However, this approach requires high design accuracy and does not ensure long-term stress stabilization without combination with other technologies. An analysis of published studies shows that despite the significant number of papers devoted to rock mass management, many treat the masses as relatively homogeneous and do not fully account for their structural and petrographic heterogeneity. In the context of complex ore deposits, this leads to limited applicability of the resulting recommendations and the need for further development of integrated approaches combining geomechanical analysis, technological solutions, and geomanagement principles.

In this context, the approach taken in this study is relevant and important, as it aims to systematize the behavior patterns of stress-strain rock masses specifically in the context of underground mining of complex deposits. Of particular importance is the substantiation of combined technologies for mined-out space reclamation using hardening mixtures and in-situ leaching products, which allow for simultaneous stress management, increased ore recovery, and reduced environmental impact. This approach meets modern requirements for environmental and resource conservation and allows us to consider the ore-bearing massif as a natural-technogenic system, the stability of which can and should be purposefully regulated during mining operations.

The aim of this study is to substantiate the patterns of behavior of stress–strain rock massifs during underground mining of structurally complex ore deposits, as well as to assess the effectiveness and feasibility of technologies for managing the stress state of the rock mass through controlled void repayment and backfilling in order to improve mining efficiency, stability of workings, and environmental safety under real operating conditions.

Methods and Materials. In this paper, the research methods and materials focus on analyzing and substantiating the behavior of ore-bearing rock masses during underground mining operations under complex geological conditions and intense stress redistribution. The methodological framework for the study addresses the need for a comprehensive assessment of the natural and man-made "ore-bearing rock mass–mine workings–mined-out space" system, the stability of which is compromised during the stope extraction stage.

The source materials include the results of theoretical and experimental studies in geomechanics, design and operational documentation for underground mines, and generalized information on the physical and mechanical properties of rock masses typical of ore deposits with complex structures. The analysis included massifs composed of fractured and blocky rock formations with a uniaxial compressive strength of 80–180 MPa, an elastic modulus of 20–60 GPa, a Poisson's ratio of 0.18–0.28, and an average density of 2.6–2.9 g/cm^3. The geometric parameters of the stopes and chambers were assumed to be within the range typical for underground ore mining: spans of 6–18 m, chamber heights of 10–30 m, and working depths of 300 to 900 m.

The research methods included an analytical assessment of the stress-strain state of the rock mass, based on classical concepts of rock mechanics and rock pressure theory, as well as modeling of the rock mass's behavior during the formation of workings and their subsequent collapse. Particular attention was paid to analyzing the processes of rock failure, resulting in the formation of structural blocks interacting with each other as rigid bodies with elastic contacts. For this purpose, computational models were used to evaluate stress redistribution and the formation of zones with subcritical and critical stress values around stopes.

The stability of the roof and sides of the workings was assessed differentially for different development systems, taking into account the possibility of a natural collapse vault. Calculations were performed assuming a flat roof within the load-bearing element of the rock structure, which minimized contamination of the ore with rock. Rock mass stability was analyzed based on fracturing, block size, and the configuration of the mined space.

The study examined and compared mined-out space reclamation technologies, including void isolation with barriers, controlled and forced rock caving, and backfilling with various materials. The backfilling materials analyzed included hardening mixtures based on mineral binders with a design strength of 0.5–3.0 MPa, bulk materials, and ISL tailings, which can naturally harden to form artificial masses with a strength of up to 1 MPa. To assess backfilling effectiveness, filler volumetric compression parameters were used, with the transition from uniaxial to triaxial compression providing a 2–3.7-fold increase in bearing capacity.

The study included data on the ratio of the volumes of formed voids to the filled space, allowing for an assessment of the degree of compensation for overburden pressure. Combination technologies were analyzed, in which some voids were isolated and others were filled with hardening mixtures and leach tailings. For these schemes, fill volumes, the proportion of active backfill, and its impact on stress redistribution in the ore-bearing rock mass were calculated.

Additionally, comparative analysis and practical experience summarizing from underground mining were used to identify the advantages and limitations of various technological solutions. An environmental and economic assessment was conducted taking into account the cost of backfill materials, the volume of land to be acquired, and the degree of preservation of the earth's surface. The combination of methods and materials used allowed for the formulation of substantiated conclusions regarding the feasibility of integrated stress-strain management of rock masses during underground mining of complex ore deposits.

Results. The conducted research revealed characteristic patterns in the behavior of ore-bearing rock masses during underground mining of complex-structure deposits, related to stress redistribution, deformation development, and the formation of load-bearing rock structures. Analysis of geomechanical data revealed that when the massif is opened by stopes and development workings, rock fracture occurs primarily along existing fracture systems, forming structural blocks ranging in size from 0.3 to 2.0 m, which interact with each other as rigid bodies with elastic contact. Contact stresses between blocks in the marginal zone of workings reached 0.6–0.8 times the ultimate strength of the rock under uniaxial compression, confirming the possibility of forming stable roofs and load-bearing elements with a favorable goaf configuration. A calculated assessment of the stress-strain state of the rock mass at working depths of 300–900 m revealed that vertical stresses due to overburden pressure range from 8–25 MPa, while horizontal stresses can exceed vertical stresses by 10–40%, depending on tectonic conditions. Without rock mass management measures, stress concentration zones of up to 1.5–2.2 times the average stress level develop in the marginal zones of stopes, leading to increased deformation of the roof and sides of the workings and a higher risk of collapse.

A roof stability analysis revealed that in fractured rock formations with stope spans of up to 12–15 m and a working height of up to 25 m, a natural collapse vault can form, ensuring the preservation of a flat roof within the load-bearing element of the rock structure. At the same time, relative vertical roof displacements did not exceed 3–6 mm, which corresponds to a stable rock mass and minimal contamination of the mined ore with rock. Increasing the working span beyond 18 m without additional measures resulted in increased deformations of 12–18 mm and the loss of stability of individual blocks.

A comparative analysis of mined-out space suppression technologies showed that void isolation with barriers reduces rock mass deformations by 10–15% compared to uncontrolled caving, but does not eliminate the formation of localized zones of elevated stress. Controlled and forced caving redistributes stresses and reduces peak stresses in near-margin zones by 20–30%, but is accompanied by an increase in ore contamination by 12–18% and complicates rock mass monitoring.

The most pronounced stress management effect was achieved using mined-out space backfilling technologies. Calculations and a summary of experimental data showed that the use of hardening backfill mixtures with a design strength of 0.5–3.0 MPa reduces maximum stresses in the ore-bearing rock mass by 25–40% and decreases vertical roof deformations by 1.8–2.3 times. Moreover, the transition of the backfill mass from uniaxial to triaxial compression with a volumetric compression ratio of 2–3 resulted in an increase in its bearing capacity by 2.0–3.7 times, confirming the high effectiveness of backfill as a means of regulating overburden pressure.

Additional results were obtained by analyzing the use of ISL tailings as gob fill. It was established that, during natural hardening, such materials form artificial masses with a strength of up to 1 MPa, capable of supporting a portion of the load from the overlying rock. Combined backfill options, including hardening mixtures and leach tailings, ensured a more uniform stress distribution and made it possible to optimize the volume of expensive backfill materials without compromising the stability of the mass.

The obtained results showed that the effectiveness of stress-strain management of rock masses is largely determined by the state of the gob and the properties of the fill materials. This served as the basis for classifying the methods of filling voids according to the principle of their condition and technological features, presented below in Table 1.

Table 1. Classification of void repayment methods

Classes	Groups	Options
With mine working isolation by fencing	With bulkheads	Wooden, rock Concrete
With rock caving to fill the mined-out space	Forced caving	With or without ore
	Controlled caving	With or without ore
With backfilling of the mined-out space with compensating materials	With hardening mixtures	Layer and chamber systems
	With bulk materials	From the surface and from the excavation
	With in-situ leach tailings	With natural colmatation or with reinforcement

The combination of technologies with hardening backfills and hardened tailings is illustrated in Fig. 1:

$$K_2 = \frac{V_{\text{bf}} + V_{\text{PV}}}{V_{\text{p}}},$$

where *vPv* – the volume of voids filled with Pv tailings.

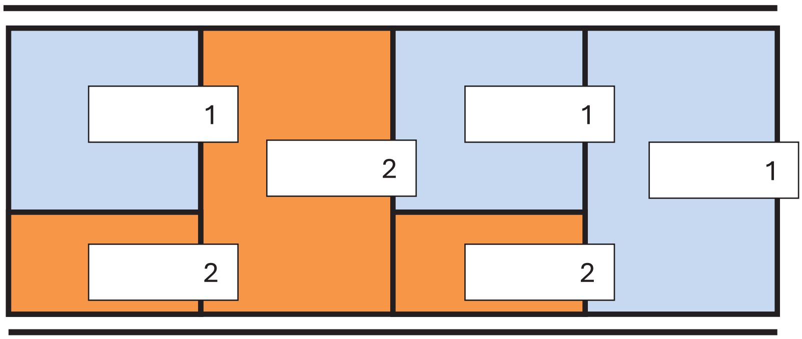

Figure 1. Combination of technologies for repayment of the developed space: 1 – leaching tails; 2 – hardening mixtures.

The scheme for combining technologies with backfilling with hardening mixtures, leaching tailings and void insulation is illustrated in Fig. 2:

$$K_b = \frac{V_{\text{bf}} + V_{\text{i}}}{V_{\text{p}}},$$

where v_{p} – the volume of isolated voids.

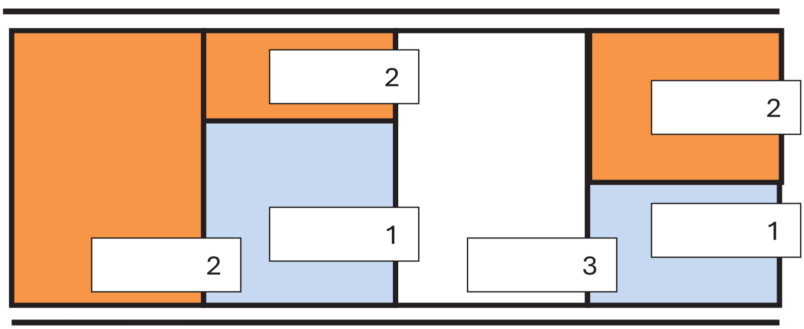

Figure 2. Combination of technologies with hardening bookmark and leaching tails: 1 – leaching tails; 2-hardening mixtures; 3 – unfilled voids

The obtained results and the presented schemes for combining mined-out space reclamation technologies demonstrate that a rational combination of hardening backfill, in-situ leaching tailings, and void isolation enables targeted regulation of the stress-strain state of the ore-bearing massif. By varying the proportions of filled and isolated space, the redistribution of rock pressure is ensured, increasing the stability of stopes and reducing the risk of roof and wall collapse. This confirms the feasibility of using combined process schemes as a tool for adapting underground mining to complex rock masses and serves as the basis for further analysis of the environmental and economic effectiveness of such solutions.

Comparative analysis of the obtained results. The results of geomechanical modeling and analysis of field data obtained during the underground mining of complex-structured ore deposits reveal a number of consistent patterns confirming the effectiveness of integrated management of the stress-strain state of the rock mass through the use of combined void repayment technologies. One of the key established regularities is the formation of structural blocks ranging in size from 0.3 to 2.0 m during the destruction of the massif, which interact as rigid bodies with elastic contact. The contact stresses between the blocks in the marginal zone of the workings reached 0.6–0.8 of the rock's ultimate strength under uniaxial compression, which confirms the possibility of forming stable roof structures and natural load-bearing arches with favorable goaf geometry.

A comparative assessment of various goaf management methods showed that the use of hardening backfill mixtures with a design strength of 0.5–3.0 MPa allows reducing maximum stresses in the ore-bearing massif by 25–40% and decreasing vertical roof deformations by 1.8–2.3 times compared to uncontrolled caving. The transition of the backfill mass from uniaxial to triaxial compression with a volumetric compression ratio of 2–3 leads to an increase in its bearing capacity by 2.0–3.7 times, which significantly enhances the stabilizing effect and reduces the load on the natural rock frame.

It was also found that the use of in-situ leaching tailings as a filling material allows the formation of artificial masses with a strength of up to 1 MPa, capable of bearing part of the overlying rock pressure. The combination of hardening mixtures and leaching tailings ensures a more uniform redistribution of stresses and reduces the volume of expensive binder materials by 15–25% without compromising the stability of the workings.

The analysis of roof stability in fractured rock masses showed that with a stope span of up to 12–15 m and a height of up to 25 m, a natural load-bearing arch is formed, ensuring minimal roof displacements (3–6 mm) and reducing ore dilution. Increasing the span beyond 18 m without additional support leads to an increase in deformations to 12–18 mm and the risk of local block collapses.

Thus, the obtained results confirm that the rational combination of backfilling, void isolation, and the use of technogenic materials provides targeted regulation of the stress state of the massif, increases the stability of mine workings, and reduces the environmental impact of mining operations.

Conclusions. The conducted study allowed us to formulate the following key conclusions based on an analysis of rock mass behavior patterns and the effectiveness of goaf reclamation technologies during underground mining of complex ore deposits:

Rocks in the vicinity of mine workings are destroyed by the formation of structural blocks (0.3–2.0 m in size) interacting as rigid bodies with elastic contact. Contact stresses between blocks in the marginal zone reach 0.6–0.8 times the rock's ultimate compressive strength, creating the preconditions for the formation of a natural load-bearing arch and stable roofs with favorable stope geometry.

The most effective method for managing the stress-strain state of the rock mass is backfilling the goaf with hardening mixtures. Using backfill materials with a design strength of 0.5–3.0 MPa reduces maximum stresses in the ore mass by 25–40% and vertical roof deformations by 1.8–2.3 times compared to caving systems. A key factor in increasing the backfill's bearing capacity is its transition from uniaxial to triaxial compression, which increases the load-bearing capacity by 2.0–3.7 times.

Using ISL tailings as backfill is a resource-saving alternative. The natural hardening of such materials allows for the formation of artificial backfills with a strength of up to 1 MPa, capable of supporting some of the pressure from the overlying rock. Combining hardening mixtures and leach tailings ensures a more uniform stress distribution and allows for the optimization of binder consumption by 15–25% without compromising working stability.

Roof stability analysis confirmed that in fractured rock, with stope widths up to 12–15 m and heights up to 25 m, a natural supporting arch is formed, ensuring minimal roof displacements (3–6 mm) and reducing ore contamination by rock. Exceeding these dimensions without additional support measures leads to increased deformations of 12–18 mm and increases the risk of localized collapses.

Combined process flow diagrams, which rationally combine backfilling with hardening mixtures, the use of man-made materials (vSv tailings), and the isolation of a portion of the mined-out space, enable targeted control of rock pressure. This increases the stability of stopes and development workings, reduces the risk of roof and side collapse, and minimizes environmental impacts by reducing the volume of waste dumps and disturbed land.

Thus, the results of the work substantiate the feasibility of introducing an integrated geomechanical approach and combined technologies for the elimination of mined-out spaces as a key condition for ensuring safe, cost-effective and environmentally balanced underground development of ore deposits in complex rock massifs.

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