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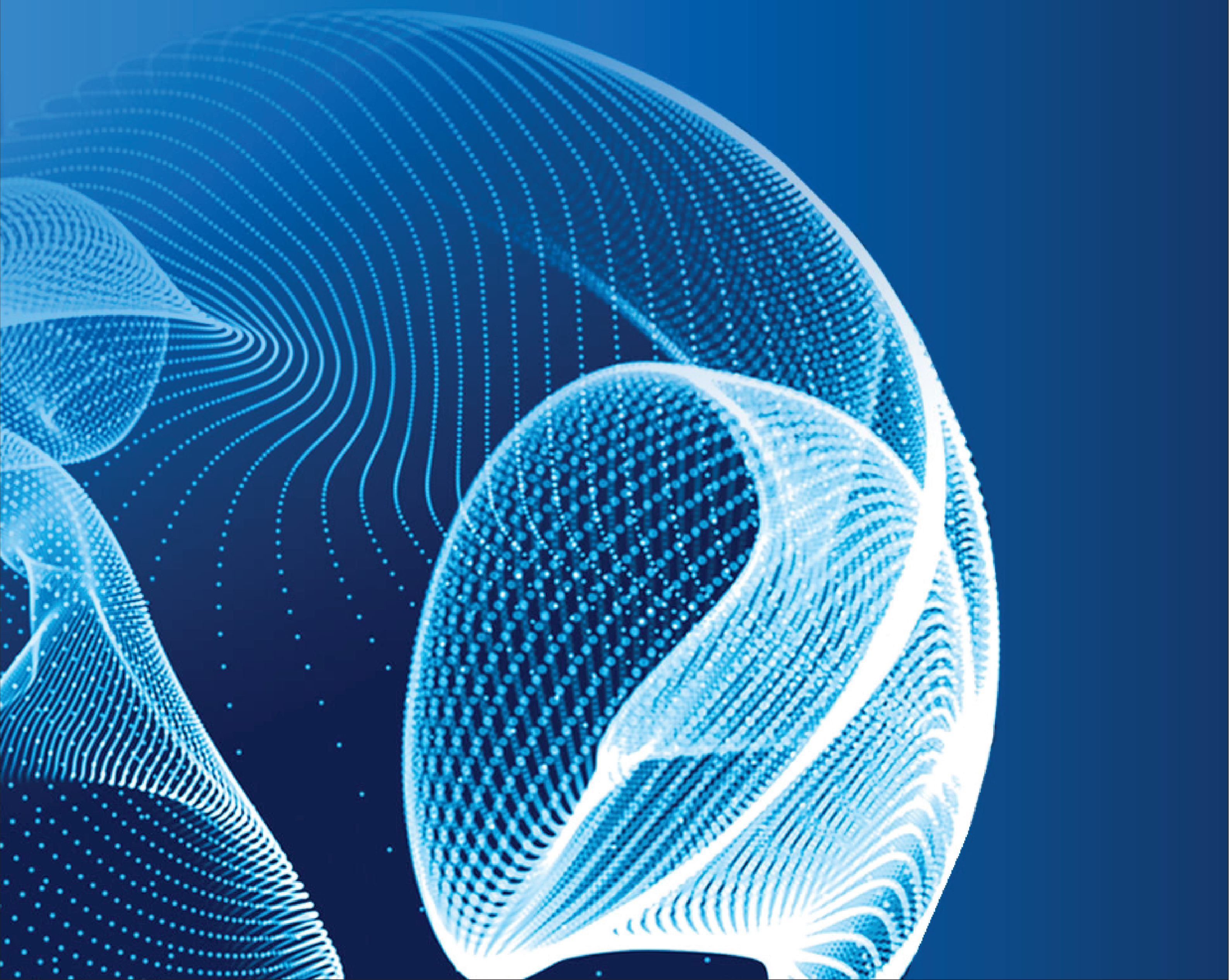

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On the issue of processing of accumulated solid waste of enterprises of the mining and metallurgical industry of Kazakhstan

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Abstract. Based on a detailed analysis of the current state of the accumulated solid waste of mining and metallurgical enterprises, new approaches to the classification of industrial waste are proposed. Outdated methods based on the industry principle do not allow to fully assess the danger of waste and effectively plan its disposal. The new solutions presented in the work for the creation of a technological and economic cadastre with the development of state standards for classified groups of waste will optimize the processes of their processing and disposal, ensure the environmental safety of production and environmental management. The introduction of the technological and economic cadastre of industrial waste involves the formation of a unified database containing information on the composition, properties, volumes of generation and possible methods of processing the accumulated solid waste. This will allow enterprises and processing organizations, as well as interested investors, to gain access to up-to-date information necessary to make informed decisions in the field of waste management. In addition, the developed inventory will become a key tool for monitoring and controlling the generation and movement of waste, which will increase the transparency and efficiency of the waste management system. In general, the introduction of a modern industrial waste classification system is a prerequisite for the transition to sustainable development and conservation of natural resources, including reducing the negative impact of waste on the environment, and creating new opportunities for economic growth.

Keywords: *waste, processing, classification, ecology, metal recovery, resource conservation, additional source of raw materials.*

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1. Introduction

Kazakhstan, with its large reserves of polymetallic ores, is a site for numerous processing enterprises specializing in lead and zinc. Although the key goal of beneficiation is to increase the concentration of valuable elements, this process is inevitably accompanied by the generation of a significant amount of waste. These wastes, however, retain residual concentrations of important metals, including non-ferrous metals and gold. Decades of active mining of precious metals have led to the accumulation of huge volumes of mining waste, forming dumps and tailings dumps. Man-made deposits have emerged, characterized by industrial reserves and a content of useful components comparable to low-grade ores, which are now actively involved in processing. Often, in mining waste, useful components, in particular, precious and non-ferrous metals, are presented mainly in a finely dispersed state and hard-to-extract forms [1-6]. Efficient recovery of hard-to-recover gold bound to sulphides, coated with films and finely interspersed in acid-soluble minerals is an important technological aspect that facilitates more complete metal recovery and waste recycling using modern methods.

In the current situation, the processing of man-made deposits, namely waste from processing plants, is a promising area that combines economic feasibility and environmental responsibility. Recycling not only recovers valuable metals, reducing dependence on primary mining, but also significantly reduces the amount of waste that has a negative impact on the environment.

The development of effective technologies for the extraction of valuable components from mining waste is an urgent scientific and technical task. Traditional ore processing methods are often inefficient enough to recover fine gold and other valuable metals from waste. In this regard, new methods such as bioleaching, sorption technologies, extraction and electrochemical methods are being actively researched and implemented.

An important aspect of waste recycling is an integrated approach that takes into account the mineralogical composition of waste, the content of valuable components and environmental limitations. The development of optimal technological schemes of processing requires detailed studies, including the analysis of the mineral composition, the determination of the optimal parameters of the leaching, ion exchange and extraction processes, as well as the assessment of the environmental safety of the technologies used.

Wastes from processing plants are characterized by a complex mineralogical composition, fine inclusions of valuable components and the presence of harmful impurities. This complicates the application of traditional metal recovery methods such as flotation and cyanidation. In modern conditions, the processing of minerals using traditional deep beneficiation technologies is becoming economically inexpedient, since their capabilities are limited and inefficient for ores with a submicrogranular structure, the mineral aggregates of which are difficult to selectively open into individual phases with a useful component [2, 3, 6, 7].

The reduction of reserves and the decrease in the quality of ores stimulates the use of more complex grinding and beneficiation schemes, equipment and reagents, which leads to an increase in the cost of processing, ahead of market prices for final products, a decrease in the competitiveness and investment attractiveness of the mineral resource complex of Kazakhstan. A radical solution to the problem is to change the ore processing scheme [8].

For the economy of Kazakhstan, the transition of the mining and metallurgical complex of the republic to a circular economy within the framework of the «zero waste» concept using resource-saving and energy-efficient technologies is of paramount importance [9]. The development and design of new technologies aimed at the integrated processing of multicomponent raw materials - accumulated waste from lead-zinc processing plants, seems to be very relevant.

The economic and environmental importance of involving tailings from processing plants will not only make it possible to obtain additional profits, but also significantly reduce the volume of stored waste, prevent pollution of soil and water resources, and, ultimately, improve the environmental situation in the regions where the enterprises are located.

In this regard, the development of innovative and environmentally friendly technologies for the extraction of valuable components from man-made deposits is a key factor for the sustainable development of the mining and metallurgical industry of Kazakhstan. Such technologies must ensure a high degree of metal recovery, minimize waste generation and resource consumption, and meet stringent environmental standards.

One of the promising areas is the use of bioleaching methods based on the use of microorganisms to dissolve sulfide minerals and release the valuable components contained in them [10]. Bioleaching offers a number of advantages, including low energy consumption, the ability to process low-grade ores and waste, and environmental friendliness. However, for the successful application of bioleaching, it is necessary to take into account the mineralogical composition of the waste, select the optimal strains of microorganisms and control the process parameters.

Another promising area is the application of methods for selective metal extraction using organic reagents, such as extractants and chelating agents. These methods allow to extract valuable components from solutions with high selectivity, minimizing loss and contamination. However, the selection of the optimal reagent and extraction conditions requires a thorough study of the chemical properties of metals and minerals, as well as laboratory and pilot tests.

This paper provides a substantiation of an integrated, innovative and environmentally friendly approach to the processing of waste from lead-zinc processing plants in Kazakhstan, aimed at increasing the efficiency of using the resource potential of man-made raw materials and reducing the environmental consequences.

The introduction of innovative technologies for processing waste from lead-zinc processing plants will allow Kazakhstan not only to strengthen its resource base and increase the competitiveness of the mining and metallurgical industry, but also to make a significant contribution to environmental protection and sustainable development of the regions. This requires active cooperation between scientific organizations, enterprises and government agencies, as well as attracting investment in the development and implementation of new technologies.

2. Analytical basis for assessing accumulated solid waste

Kazakhstan's geopolitical and economic interests in the long term will depend on the state of the country's mineral resource base. At the same time, taking into account the fact that primary sulphide ores are not unlimited, it has great interest to involve in the processing of accumulated solid intermediate products, sludges, slags and tailings of processing plants in order to comprehensively extract valuable metals from them.

According to of the Ministry of Industry and New Technologies of the Republic of Kazakhstan in dumps, tailings dumps and storage tanks of mining enterprises of Kazakhstan, about 34.2 *billion tonnes* man-made mineral formations (TMO): 72% are dump rocks, 20% are dump tailings of ore beneficiation, 8% are other TMOs. As of 2017, there are 775 objects of man-made mineral formations registered by the State Cadastre, of which 109 are free from subsoil use, 666 are located at operating enterprises and mines.

The annual growth in the volume of TMO accumulated due to the increase in mining and processing of minerals in Kazakhstan is 350-400 *million tonnes*. At the same time, the total annual level of TMO consumption is about 11% of the total output. In the developed industrial countries of the world, the level of industrial waste use reaches 70-80%.

Recently, the terms «technical mineral formations» or «technogenic raw materials» are increasingly found in various fields, including the mining and metallurgical industry and other sectors of the economy. It is important to emphasize the lack of a generally accepted and clear scientific definition for these categories. According to the study [11], «technogenic raw materials» are industrial wastes and dumps, which indicate the imperfection and low efficiency of the technologies, processes and equipment used.

The widespread use of this term, to a certain extent, hinders the disposal of waste from the mining and metallurgical complex, the integrated use of non-renewable natural mineral resources and the full involvement of secondary raw materials in the production cycle. Thus, the use of the concept of «technogenic raw materials» does not seem to be entirely justified.

During ore beneficiation, 75-85% of the base metals accounted for in the supplied ores are extracted into concentrates, the remaining part is stored in dumps. During metallurgical processing, the extraction of basic metals into rough products is 80-95%, the remaining part also goes to dumps. The ores of most non-ferrous metal deposits are complex. Their industrial value is determined by the presence of the content of the main components in them. In addition to the main components, ores contain precious metals (gold, silver, platinum).

The ores contain dispersed and rare metals (bismuth, selenium, tellurium, rhenium, cadmium, titanium, vanadium, etc.). The specificity and peculiarity of the beneficiation of such ores is characterized by the fact that the bulk of valuable metals is lost with dumps, substandard ores and tailings.

As the analysis shows, insufficient attention is paid to the problems of assessing the impact of industrial waste, including toxic, on human life arising from the disposal of industrial waste. At present, due to the lack of a proper system of accounting and control of industrial waste, specialized places for their storage and processing, it is not possible to determine the total volume of waste generation, both by type and by roll. The data available in official sources give a certain general picture of the current situation with industrial waste in the post-Soviet countries and reinforce the need to solve the problem of their disposal.

For example, in Russia, the volume of unprocessed and non-neutralized waste has increased by 16% over the past ten years. 4.5 billion tons of production and consumption waste are stored annually on the surface of the earth. The total amount of accumulated waste is 50 billion tons, and more than 250 thousand hectares of land are occupied for storage. In 2019 alone, about 130 million tons of toxic waste were generated at industrial enterprises, which is 9.2% more than in 2000. The main volume of toxic waste falls on ferrous and non-ferrous metallurgy enterprises.

According to the State Statistics Committee of Ukraine, during 2010, Ukrainian enterprises accumulated about 80 million tons of toxic waste against 77.6 million tons in the previous year. Moreover, of the total amount of accumulated waste, 48.8 million tons (62%) are placed in places of organized storage, of which 19% are in storage facilities that are operated in violation of environmental safety requirements, or do not meet current standards. At the same time, the country's industrial enterprises continue to send waste to landfills. As of January 1, 2004, 2745.1 million tons of toxic waste had accumulated in the storage facilities and on the territory of the country's enterprises. On average in the country *1 sq. km* at the beginning of 2004, 4.5 thousand tons of toxic industrial waste were stored in storage facilities and on the territory of enterprises.

Comparative data for Kazakhstan is not encouraging either. According to the official data of the Ministry of Industrial Development of the republic, to date, more than 20 billion tons of solid waste have already been accumulated, 75% of which falls on the share of mining enterprises, 20% on processing plants, and the remaining share on non-ferrous metallurgy enterprises.

For Kazakhstan, as well as for Russia and Ukraine, toxic waste, which is part of the structure of accumulated industrial waste, is particular concern in terms of the degree of impact on the environment and human life. On the territory of the republic, this category of waste is represented by a complex conglomerate of a mixture consisting of toxic, hazardous and mixed waste. The annual increase in their volumes, mainly stored in the open state, is the main reason for the observed serious violation of the ecological balance in the biosphere. As a result, the degree of impact of harmful substances on human life contained in toxic waste has significantly increased.

According to the Ministry of Emergency Situations, about 86 million tons of maintenance are generated annually in the republic, 63% of which falls on the share of non-ferrous metallurgy waste. The dynamics of the formation and use of toxic waste on our territory is shown in Figure 1.

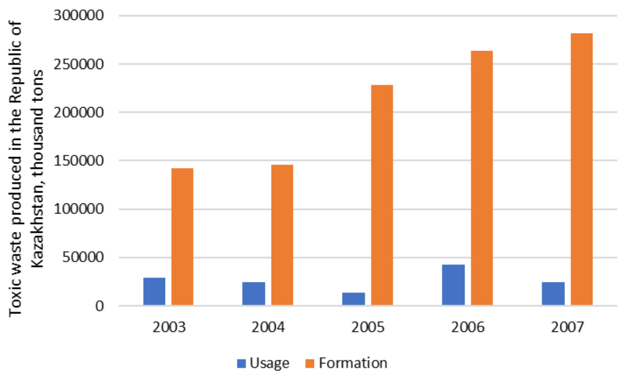

Figure1. Formation and use of toxic production waste in the period of 2003-2007

In most cases, technogenic raw wastes are located in places unsuitable for storage and are concentrated mainly in depressed regions of the republic. Thus, according to the state statistical reporting for 2007, as a result of the activities of industrial enterprises of the East Kazakhstan region (EKR), about 1401150 thousand tons of industrial waste were accumulated. The general structure of accumulated waste is presented in Figure 2.

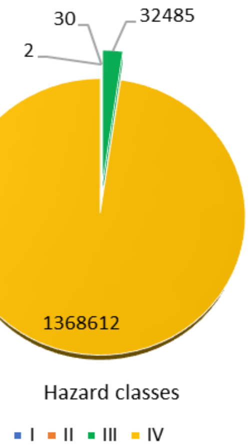

Figure 2. Structure of industrial waste accumulated in East Kazakhstan region (2007)

The situation in the region is aggravated by the fact that enterprises neutralize only an insignificant part of waste, and the main part of it, consisting of waste from the mining and processing complex and metallurgical production, is sent to places of organized storage.

The annual generation of waste from the mining and processing complex from overburden, tailings of processing plants belonging to hazard classes 3-4, with the widest range of ingredients, is about 20 *million tons.*

Metallurgical production waste is placed in dumps, waste heaps, sludge reservoirs and occupies an area of 436 hectares. Some of the dumps are stored in water protection zones. Such waste disposal leads to environmental pollution due to dust dispersion and erosion by rain and melt water, as well as pollutes surface and groundwater.

With the waste accumulated in the region, formed in the production chain "mining - processing - metallurgy", more than a third of the non-ferrous and precious metals mined with ores is lost, huge reserves of various construction raw materials are frozen. Through losses of metals are: lead – 33%, zinc – 28%, copper – 21%, gold – 41%, silver – 35%.

The total through losses, 15-20% of non-ferrous metals and 8-12% of precious metals are lost during mining, 43-48% and 74-75%, respectively, during metallurgy, 35-42% of non-ferrous metals and 14-17% of precious metals. The excess of losses of valuable components during beneficiation by 2-3 times compared to losses in mining and metallurgical processing led to the emergence of numerous technogenic deposits. According to the Territorial Department of Environmental Protection of East Kazakhstan region, it is currently not possible to accurately determine the volume of industrial wastes and, moreover, to manage them.

Waste management on a regional scale is carried out through the Ministry of Ecology and Natural Resources and their structural divisions, which limits the control, regulatory and management capabilities of local territorial departments. The Territorial Administrations are granted independence only in terms of issuing permits for the storage (burial) of waste.

From the above, it follows that if the issues of waste processing for enterprises are interest from a technological point of view, then in general, for the region, the solution of the issue is relevant, first of all, from the point of view of ensuring the environmental safety of the region.

The sustainability of the accumulated process, and the continuing growth in the volume of new waste received, significantly exacerbated the negative consequences, which began to seriously affect the life of people and the technological side. Thus, the comparative data given in Figure 3 show that the negative environmental consequences affecting human health in the republic are quite high.

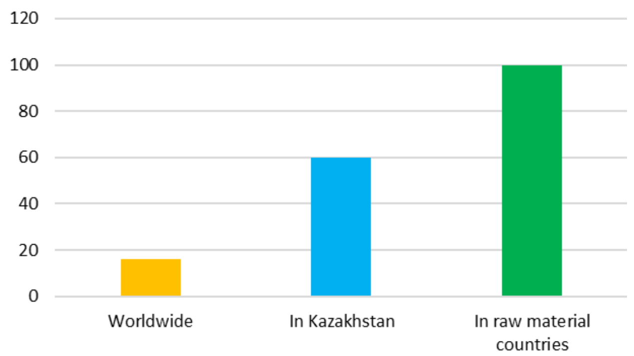

Figure 3. Solid waste yields, t/person per year

The negative consequences of accumulated industrial waste are associated with the fact that more than a third of non-ferrous, rare, rare-earth, strategic and precious metals mined with ores are lost with waste. The content of valuable components in waste often exceeds their content in developed deposits. If we take into account that the problem of increasing the use of production waste lies not only in its negative impact on the environment, but also in its potential value as a possible secondary raw material resource, then it is quite possible to assert that they are used as a strategic raw material for additional extraction of a complex of valuable metals. The data given in Figure 4 confirm the opinion expressed.

As the analysis shows, the main reason for the negative impact on the environment, and human life, consists not so much in the growth of production, as in the absence of integrated processing of minerals, as well as the disposal of large volumes of accumulated and current waste on the territories of enterprises.

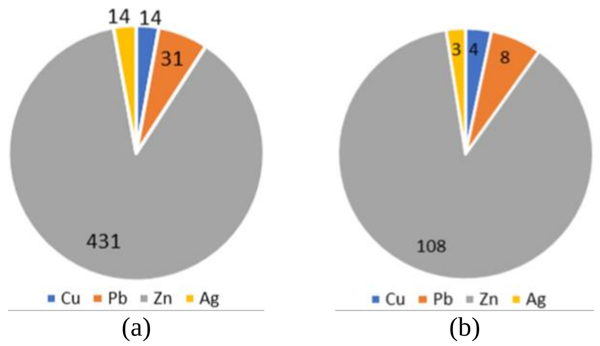

Figure 4. Volumes of non-ferrous metals accumulated in solid waste in Kazakhstan (million tons): (a) mineral processing; (b) metallurgy

Existing methods of processing industrial substandard waste, «tied» to the main technological schemes, have already become difficult and ineffective. The complexity of the use of raw materials has decreased, there has been a decline in the end-to-end extraction of even base metals. In addition, the disruption of horizontal ties between enterprises, associated primarily with changes in forms of ownership, led to a significant accumulation of solid waste and tailings directly on the territories of mining and metallurgy industries, causing significant damage to the environment and human life. This picture is especially characteristic of those regions where lead enterprises are located.

The organization of solid waste processing would make it possible to additionally extract not only base metals, but also valuable associated metals, the cost of which is commensurate, and sometimes even exceeds the cost of the main products of the enterprise. After the extraction of valuable metals, the demetallized silicate part can be used for the production of building materials. In favor of solid waste processing, we can also cite the absence of special costs for extraction and transportation, which make up the largest part in the cost structure.

As a result of the lack of effective technologies for processing solid tailings and waste, there is an incomplete, not comprehensive development of the mineral resources of the republic, technologically returned valuable components - rare and trace metals - are irretrievably lost. To solve the problems of environmental protection and the use of natural resources, the Government of the Republic invests considerable amounts of financial resources every year. Moreover, as the dynamics of investments shown in Figure 5 shows, their volumes increase every year.

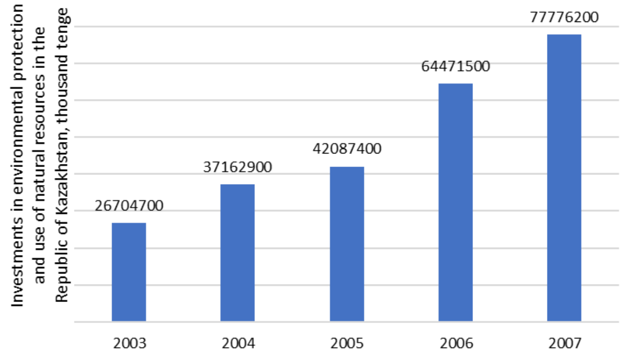

Figure 5. Growth of investments aimed at environmental protection and use of natural resources of the Republic of Kazakhstan

However, in spite of the cardinal measures taken, in almost all regions of the republic there is an inappropriate, and most importantly, irrational use of the allocated financial investments. An increase in the efficiency of the use of allocated funds can be achieved and, in the case, where and when the indicated problem has a fundamental justification for its solution, taking into account the specifics of the object under study and the region as a whole. In some cases, the absence of such approaches cannot provide a concrete solution to the problem on the part of responsible executors in full. For example, in the Register of Environmental Problems of the Republic of Kazakhstan, in the column «problem» (in relation to the East Kazakhstan region), it is indicated: *the presence of ownerless waste from the mining industry*. Further, in the column «Ways to solve the problem», the general solution is indicated - *the disposal of ownerless waste from the mining industry.* The following column deserves special attention – «Measures taken», which states literally the following: *«The issues of reclamation of dumps and tailings of the mining industry are not being resolved due to lack of financial resources. At existing enterprises, the issues of neutralization and reclamation of dumps are not included in investment obligations»*. There are many such examples in the Register. We think that there is no need to comment here.

In our opinion, a significant obstacle to the effective disposal or treatment of solid waste is the use of outdated approaches to assessing its quality. Methods, regulations, standards and technical conditions developed back in the Soviet period do not correspond to modern realities.

It is important to note that many existing standards, specifications, certificates and passports created for certain types of industrial products and waste are currently either not applied or have lost their relevance. For example, all technical specifications regulating substandard industrial products (such as lead-copper mattes) and oxide-sulfide melts of lead production are no longer in force, although the volume of accumulated waste reaches tens of thousands of tons.

The lack of up-to-date regulations governing the handling of these products makes it difficult to process them rationally. These wastes continue to be disposed of in open areas, occupying significant areas. The presence in them, along with base metals, of a high content of toxic impurities, increases their negative impact on the ecological situation, environmental protection and public health. Similar examples can be found in various regions of the country.

The negative consequences of waste become especially serious when it contains toxic substances, which, as previously demonstrated, is relevant for accumulated waste in the East Kazakhstan region.

3. Results and discussion

3.1. Classification of accumulated industrial waste

Good classification of solid waste is essential for effective waste management, including planning for recycling and the necessary investments. An analysis of scientific publications shows that existing approaches to the classification of industrial waste are often based on their origin by industry.

Production waste is the remains of raw materials, materials and semi-finished products that have lost their original properties in the production process. However, the re-involvement of this waste in recycling can give it new, valuable properties. It is necessary to study, analyze and classify them, preparing them for processing in order to extract useful components, and send the remaining slag materials to the construction industry. Despite the existing classification based on industries, each industry has its own system, which makes comprehensive waste management difficult. New approaches to classification are needed, taking into account common characteristics, which will make it possible to group industrial waste into separate categories.

Optimization of environmental safety of production in non-ferrous metallurgy is achievable with an integrated approach to each object under study - semi-product, industrial waste or slag. Separate processing of industrial products and waste from processing plants and metallurgical enterprises will have a positive effect on the environment. The involvement of secondary raw materials from dumps will clean the territories of enterprises, prevent pollution of water basins and reduce dust emissions into the atmosphere.

First stage research should include the implementation of measures to Classification of each type of industrial waste, with the establishment of their quantitative and qualitative completeness, with further identification of various wastes according to common features and grouping into common groups of interest for the extraction of a particular valuable component from them. This is the basic and necessary condition. It should be noted that in this case the concepts of «inventory» and «classification» should not be identified.

As the analysis [12, 13] shows, the old classifications of wastes by industry and morphological composition that have been developed and are still in force can no longer be a criterion for judging their hazard and choosing a method of disposal. This is due to the fact that each type of waste generated contains a set of chemicals characterized by their different toxicity, which can have a different polluting effect on the soil, groundwater, water of open water bodies and cause a negative impact on human health along ecological chains.

The implementation of the first stage of work will allow to most accurately determine the hazard class of a particular waste, and optimize the choice of the method of disposal, neutralization and disposal of waste. Identification of waste by properties and its classification will create an opportunity for further development of a state standard for each specific group of waste.

3.2. Development of a technological and economic cadastre

The purpose of the research should be to create a technological and economic cadastre of solid waste from mining and metallurgical enterprises. This will make it possible to streamline the received and accumulated materials and waste, determine their hazard class and impact on the environment, assess the economic feasibility of recycling and develop effective technologies.

Outdated methods based on the industry principle do not allow to fully assess the danger of waste and effectively plan its disposal. The proposed integrated approach, including the creation of a technological and economic cadastre and the development of state standards for classified groups of waste, will not only optimize the processes of processing and disposal, but also ensure the environmental safety of production and environmental management.

The introduction of a technological and economic cadastre of industrial waste involves the creation of a single database containing information on the composition, properties, volumes of generation and possible methods of processing each type of waste. This will allow enterprises and processing organizations to gain access to up-to-date information necessary to make informed decisions in the field of waste management. In addition, the cadastre will become a tool for monitoring and controlling the generation and movement of waste, which will increase the transparency and efficiency of the waste management system as a whole.

3.3. Standardization of waste groups and processing priorities

Second stage – development of state standards for newly classified wastes in a single group. Such a solution will make it possible to carry out certification, certification of waste and products of its processing, as well as to provide information about waste as hazardous substances or secondary material resources. At the same time, it will be possible to perform any actions related to the storage, placement, processing and transportation of waste, including marketing, storage, disposal, burial or destruction.

The implementation of the complex of these works should be carried out under the strict control of state bodies of republican, regional and local significance with the involvement of a wide range of scientific specialists in a particular field. These works should be aimed at solving key areas, such as:

– classification of accumulated and current waste in the territory of the republic with the identification of the volumes of valuable components contained in them;

– substantiation and development of proposals for additional production of metals from classified waste by replacing primary sources of raw materials;

– providing up-to-date complete information on waste for potential investors wishing to purchase a particular group of waste or take part in their processing;

– preparation and adoption of competent decisions by experts authorized by local authorities when considering issues of storage, transportation, processing or disposal of waste;

– selection of the most effective technologies for the processing of specific metal-containing waste.

The development of national standards for classified waste groups is an important step to ensure the uniformity and comparability of waste data, as well as to establish requirements for their treatment and disposal. Standards must take into account both environmental and economic aspects, as well as comply with international norms and requirements. This will create clear rules of the game for all participants in the waste management market and stimulate the introduction of the best available technologies.

4. Conclusions

The analysis highlights the need to move to new approaches to the classification of industrial waste. The need for a transition to new approaches to the classification of industrial wastes is shown.

The implementation of the proposed measures will require the active participation of government agencies, scientific organizations and the business community. State bodies should ensure the development and implementation of a regulatory framework, as well as monitor compliance with requirements in the field of waste management. Scientific organizations should conduct research on the development of new technologies for waste processing and disposal, as well as participate in the development of standards and inventories. The business community should invest in the creation of infrastructure for waste processing and disposal, as well as introduce modern technologies at their enterprises.

In general, the introduction of a modern industrial waste classification system is a prerequisite for the transition to sustainable development and conservation of natural resources. This will not only reduce the negative impact on the environment, but also create new opportunities for economic growth and development.

Author contributions

Conceptualization: ND, YZ; Data curation: ND, YZ; Formal analysis: AA, ND, VK; Funding acquisition: AA; Investigation: ND, YB; Methodology: ND, VK; Project administration: YZ, YB; Resources: AA, VK; Software: AA, VK; Supervision: ND, AA; Validation: YZ, VK; Visualization: AA, YZ; Writing – original draft: AA, ND; Writing – review & editing: ND, VK. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Қазақстанның тау-кен металлургия кешені кәсіпорындарының қатты жинақталған қалдықтарын қайта өңдеу мәселесіне

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Аңдатпа. Тау-кен-металлургия кешені кәсіпорындарының жинақталған қатты қалдықтарының ағымдағы жай-күйін егжей-тегжейлі талдау негізінде өнеркәсіптік қалдықтарды жіктеуде жаңа тәсілдер ұсынылды. Салалық принципке негізделген ескірген әдістер қалдықтардың қауіптілігін толық бағалауға және оларды жоюды тиімді жоспарлауға мүмкіндік бермейді. Қалдықтардың жіктелген топтары үшін мемлекеттік стандарттарды әзірлей отырып, технологиялық-экономикалық кадастр құру жөніндегі жұмыста келтірілген жаңа шешімдер оларды қайта өңдеу және кәдеге жарату процестерін оңтайландыруға мүмкіндік береді, өндіріс пен табиғат пайдаланудың экологиялық қауіпсіздігін қамтамасыз етеді. Өнеркәсіптік қалдықтардың технологиялық-экономикалық кадастрын енгізу жинақталған қатты қалдықтардың құрамы, қасиеттері, түзілу көлемі және оларды қайта өңдеудің ықтимал тәсілдері туралы ақпаратты қамтитын бірыңғай деректер базасын қалыптастыруды көздейді. Бұл кәсіпорындар мен қайта өңдеу ұйымдарына, сондай-ақ мүдделі инвесторларға қалдықтарды басқару және басқару саласында негізделген шешімдер қабылдау үшін қажетті өзекті ақпаратқа қол жеткізуге мүмкіндік береді. Сонымен қатар, әзірленген кадастр қалдықтардың пайда болуы мен қозғалысын бақылау және бақылаудың негізгі құралы болады, бұл қалдықтарды басқару жүйесінің ашықтығы мен тиімділігін арттырады. Тұтастай алғанда, өнеркәсіптік қалдықтарды жіктеудің заманауи жүйесін енгізу қалдықтардың қоршаған ортаға теріс әсерін азайтуды және экономикалық өсу үшін жаңа мүмкіндіктер жасауды қоса алғанда, табиғи ресурстарды орнықты дамытуға және сақтауға көшу үшін қажетті шарт болып табылады.

Негізгі сөздер: *қалдықтар, қайта өңдеу, жіктеу, экология, металдарды алу, ресурстарды үнемдеу, қосымша шикізат көзі.*

К вопросу переработки твердых накопленных отходов предприятий горно-металлургического комплекса Казахстана

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Аннотация. На основании детального анализа текущего состояния накопленных твердых отходов предприятий горно-металлургического комплекса предложены новые подходы в классификации промышленных отходов. Устаревшие методы, основанные на отраслевом принципе, не позволяют в полной мере оценить опасность отходов и эффективно планировать их утилизацию. Приведенные в работе новые решения по созданию технолого-экономического кадастра с разработкой государственных стандартов для классифицированных групп отходов позволит оптимизировать процессы их переработки и утилизации, обеспечит экологическую безопасность производства и природопользования. Внедрение технолого-экономического кадастра промышленных отходов предполагает формирование единой базы данных, содержащей информацию о составе, свойствах, объемах образования и возможных способах переработки накопленных твердых отходов. Это позволит предприятиям и перерабатывающим организациям, а также заинтересованным инвесторам получить доступ к актуальной информации, необходимой для принятия обоснованных решений в области обращения и управления с отходами. Кроме того, разработанный кадастр станет ключевым инструментом для мониторинга и контроля за образованием и движением отходов, что повысит прозрачность и эффективность системы управления отходами. В целом, внедрение современной системы классификации промышленных отходов является необходимым условием для перехода к устойчивому развитию и сохранению природных ресурсов, включая снижение негативного воздействия отходов на окружающую среду, и создания новых возможностей для экономического роста.

Ключевые слова: *отходы, переработка, классификация, экология, извлечение металлов, ресурсосбережение, дополнительный источник сырья.*

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Modeling the effect of porosity and pore morphology on the mechanical properties of titanium structures for osteosynthesis

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Abstract. In this study, numerical modeling of porous titanium structures intended for use in osteosynthesis systems was performed using the finite element method. The main objective of the work was to evaluate the mechanical behavior of porous structures with different pore geometrical parameters and levels of porosity. For this purpose, representative volume elements (RVE) were constructed, representing fragments of the porous structure. These elements were analyzed under uniaxial loading in order to determine the distribution of stresses and strains within the material. During the simulations, several structural variants with different porosity levels and pore sizes were examined. The obtained results demonstrated that porosity is a key parameter that significantly influences the mechanical behavior of the material. With increasing porosity, a rise in stress concentration in the struts between pores was observed, along with increased heterogeneity of stress and strain fields. This effect is associated with the reduction of the effective load-bearing cross-sectional area of the material and the redistribution of loads within the structure. Analysis of the stress–strain curves for models with pore sizes of 200, 400, and 600 μm showed that, at a fixed level of porosity, variation in pore size has a relatively minor effect on the effective elastic modulus of the material. At the same time, it was established that the geometrical shape of the pores has a more significant impact on the mechanical properties of the structure, including stiffness and stress distribution. The obtained results confirm that optimization of pore geometry is an important factor in the design of porous titanium implants aimed at improving their biomechanical compatibility with bone tissue.

Keywords: *porous titanium structures, osteosynthesis, porosity, finite element method, mechanical properties.*

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1. Introduction

In modern orthopedics, metallic and biodegradable materials are primarily used for the internal fixation of limb fractures. However, the elastic modulus of metallic materials (such as stainless steel, titanium, and its alloys) differs significantly from that of human bone tissue [1-3]. The elastic modulus of cast titanium is approximately 100 GPa, while that of the widely used titanium alloy Ti6Al4V is about 110 GPa [4-6].

In contrast, the elastic modulus of human bone ranges from 15 to 30 GPa and depends on factors such as sex, age, and overall health condition [7-9]. The difference in elastic modulus between human bone and titanium implants leads to the so-called stress shielding effect, which may necessitate revision surgery [10, 11]. The mismatch between the high elastic modulus of implants and the biomechanical properties of bone negatively affects callus formation and fracture healing, potentially requiring additional surgical intervention [4, 5].

Therefore, the development of internal fixation systems that do not require secondary surgery for removal has remained an important research topic in the orthopedic community for many years [7, 8]. To reduce the elastic modulus of metallic materials, researchers have investigated porous materials for use in medical metallic implants [9].

The porous architecture of implants plays a key role in determining their mechanical and biological properties. It has been established that increasing porosity promotes improved osseointegration and bone tissue ingrowth; however, it simultaneously leads to a reduction in the strength and stiffness of the material. Therefore, optimization of the parameters of porous structures, including the level of porosity, pore size, and pore morphology, represents an important task in the design of implants for osteosynthesis [12].

Porous materials used for implants in the treatment of bone injuries and defects typically require a porosity ranging from approximately 30% to 85%. In such materials, the pores should preferably be interconnected and uniformly distributed; alternatively, depending on specific requirements, a portion of the pores may be interconnected while still maintaining a uniform distribution. This structural configuration facilitates effective integration of the material with human bone tissue [9, 11].

Currently, a number of technologies have been developed that enable the fabrication of porous titanium structures with different morphologies, pore sizes, and levels of mechanical strengths. Figure 1 illustrates porous titanium structures used in orthopedic applications.

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Figure 1. Orthopedic devices made of porous titanium

Porous titanium can be produced using additive manufacturing technologies such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), powder metallurgy methods, space-holder techniques, Binder Jetting, as well as technologies for producing metallic foams and combined gradient structures [13-15]. In addition, porous structures can be fabricated using Spark Plasma Sintering and open-cell architectures. However, the aforementioned porous materials often exhibit characteristics such as small pore sizes, non-uniform pore distribution, poor permeability, or the presence of numerous micropores within the pore wall structure, which may hinder their application as biomaterials [16-18].

When developing modern implant materials, particular attention is given to their elastic modulus, compressive strength, and biocompatibility [19-20].

In recent years, the development of porous metallic structures has become one of the most promising directions in biomedical engineering and orthopedics. In this context, numerical modeling of porous structures using the Finite Element Method has gained particular importance. Nevertheless, many porous materials produced by the aforementioned methods still possess limitations, including small pore sizes, non-uniform pore distribution, low permeability, or the presence of numerous micropores in the pore wall structure [21-23].

Such structural features can significantly limit their application as biomaterials. Moreover, they may negatively affect both the mechanical properties of the material and the processes of osseointegration, since insufficient pore interconnectivity and improper pore geometry hinder bone tissue ingrowth and reduce the transport of nutrients and cells within the implant [24].

In this context, optimization of the porous architecture becomes particularly important, including the control of pore size, shape, distribution, and the overall level of porosity. Experimental investigation of all possible pore geometry variations is a complex, time-consuming, and costly process. Therefore, in recent years numerical modeling of porous structures using computer simulation and the Finite Element Method has become increasingly widespread (Design, Modeling, Additive Manufacturing, and Polishing of Stiffness-Modulated Porous Nitinol Bone Fixation Plates Followed by Thermomechanical and Composition Analysis).

Modeling makes it possible to analyze in detail the influence of porous architecture parameters on the stress–strain state of the material, evaluate the distribution of stresses and strains within the structure, and predict the effective mechanical properties of porous constructions. The application of such approaches significantly accelerates the design process of biomedical implants and allows the determination of optimal parameters of porous structures that provide the required combination of strength, stiffness, and biological compatibility (Novel Clinical Applications of 3D-Printed Highly Porous Titanium for Off-the-Shelf Cementless Joint Replacement Prostheses).

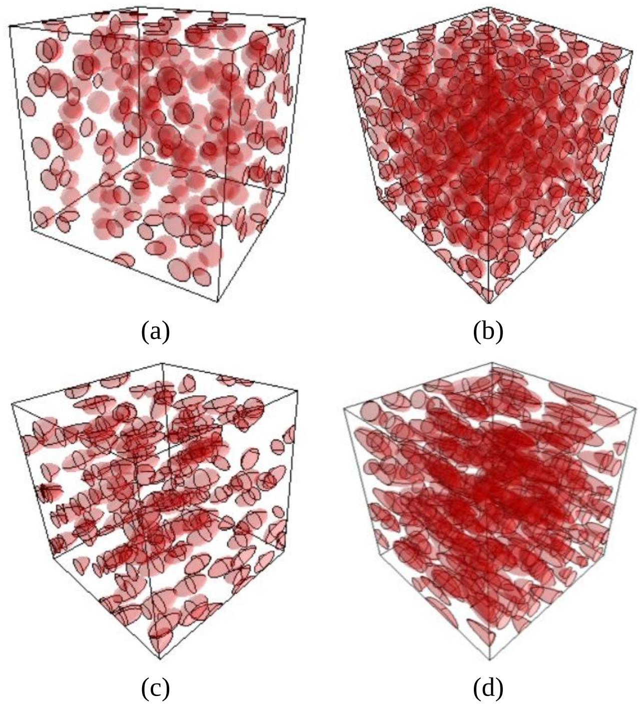
Based on the relevance of the studies mentioned above, this work conducts computational experiments using the DIGIMAT software in order to identify the relationships between porosity, pore size, and pore shape and their influence on the elastic modulus of titanium.

2. Materials and methods

The numerical investigation of the effects of porosity, pore size, and pore morphology on the mechanical properties of titanium material was performed using the DIGIMAT MF/FE software, designed for multiscale modeling of heterogeneous media. In the study, a micromechanical model of a Representative Volume Element (RVE) was employed, enabling consideration of the influence of the material's internal structure on its effective mechanical properties.

The matrix material was the titanium alloy Ti-6Al-4V, whose mechanical properties were defined using a linear-elastic isotropic model. The parameters used in the simulations were: elastic modulus $E = 110$ GPa, Poisson's ratio $\nu = 0.33$, and density $\rho = 4430$ kg/m^3. Pores were modeled as inclusions with zero stiffness and zero density, corresponding to the idealized case of a completely void volume.

Porosity was varied within a specified range to assess its effect on the material's effective elastic properties. Pore size was defined using a characteristic linear parameter of the inclusions at a fixed volume fraction, while pore shape was modeled as spherical, ellipsoidal, and cellular (architected) structures. Figure 2 illustrates the pore parameters and their orientations.



(a) (b)

(c) (d)

Figure 2. Representative volume element of a titanium matrix filled with pores: (a) spherical pores with 30% porosity; (b) spherical pores with 50% porosity; (c) ellipsoidal pores with 30% porosity; (d) ellipsoidal pores with 50% porosity

During modeling, three main structural parameters were varied: the volume fraction of pores (porosity), pore size, and pore shape. Table 1 presents the parameter variations used in the computational experiments.

Table 1. Parameters of the computational experiment

№	Porosity, %	Pore size	Pore shape
1	30	200/300/400	Sphere / Ellipsoid
2	40	200/300/400	Sphere / Ellipsoid
3	50	200/300/400	Sphere / Ellipsoid
4	60	200/300/400	Sphere / Ellipsoid

The calculations were performed using the finite element method in combination with a homogenization procedure [25, 26]. Boundary conditions were applied as uniform deformation of the representative volume element, ensuring the accurate determination of averaged stresses and strains. The simulations yielded the effective elastic modulus, Poisson's ratio, and stress distribution within the porous structure, and the influence of pore morphology on the material's mechanical behavior was analyzed. The obtained results were further used to assess the effect of pore morphology on the mechanical performance of porous titanium and to compare them with theoretical models such as the Gibson-Ashby model.

3. Results and discussion

First, the numerical experiment was conducted using the DIGIMAT MF module, modeling structures with different pore sizes while maintaining a constant solid-phase volume fraction. The calculations were performed under uniaxial tensile loading with a prescribed deformation, enabling assessment of the effect of pore morphology on the stress-strain response and the effective elastic modulus of the material. The results are presented in Figure 3.

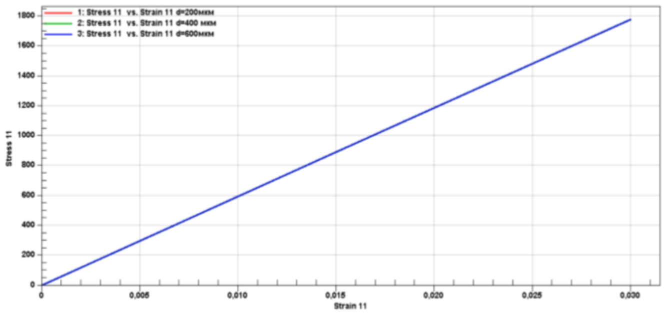
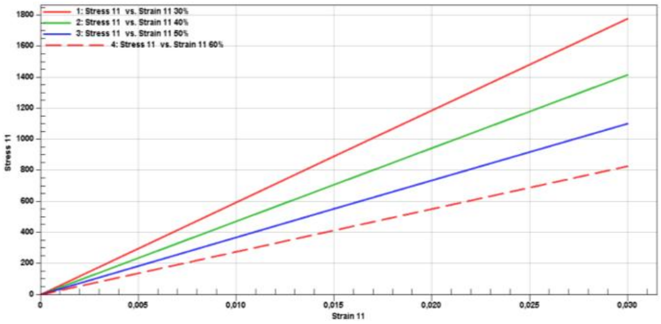


Figure 3. Stress-strain diagram for pore sizes of 200 μm, 400 μm, and 600 μm

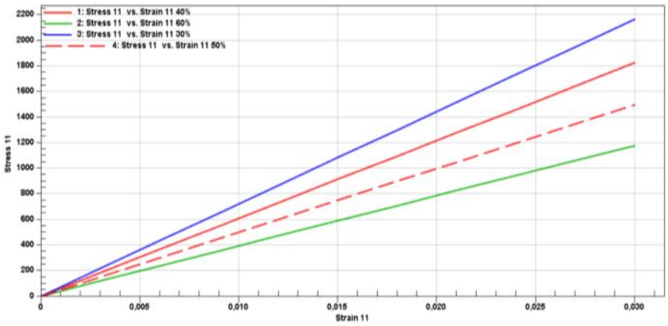
All stress-strain curves exhibit nearly identical slopes, indicating that the elastic modulus is similar regardless of pore diameter. Next, calculations were performed in the DIGIMAT MF module for different pore shapes, ellipsoidal and spherical, at varying porosity levels as specified in Table 2. The results are presented in Figure 4

Table 2. Stress values (u = 0.01) and elastic modulus for different porosity levels and pore shapes

Porosity, %	Ellipsoidal aspect ratio 6		Spherical aspect ratio 1	
	σ, MPa	*E*, GPa	σ, MPa	*E*, GPa
30	700	58.5	600	59
40	600	47	450	47.1
50	500	36.8	380	36.6
60	400	27.94	280	27.5



(a)



(b)

Figure 4. Tensile stress-strain diagram (u = 0.01) with pore diameter 200 μm; (a) spherical pores, (b) ellipsoidal pores

Apparent differences in the slopes of the stress-strain curves are observed for the two pore shapes.

Despite differences in pore geometry, the effective elastic modulus of porous titanium with ellipsoidal and spherical pores at the same porosity is similar. This can be explained by the fact that the elastic modulus is an integral material property, primarily determined by the volume fraction of the solid phase rather than the local pore shape. According to the Gibson-Ashby model, the effective elastic modulus of porous and cellular materials is described by the following expression [27]:

$$E = E_S\left(1-\varphi\right)^n, \tag{1}$$

where E_s is the elastic modulus of the dense material; φ is the porosity; n is the exponent determined by the type of cellular structure and the deformation mechanism.

At a fixed porosity, the influence of pore shape on the global stiffness of the material is secondary. However, pore geometry has a significant effect on the local stress distribution: ellipsoidal pores exhibit higher stress concentrations due to their smaller radius of curvature and pronounced anisotropy, leading to higher equivalent stresses than spherical pores. Thus, for the same effective elastic modulus, differences in the stress state are primarily attributed to stress concentration effects rather than changes in the bulk elastic properties of the material [28, 29].

Third, finite element modeling was performed using the DIGIMAT FE module. Figure 5 shows the distribution of equivalent stresses obtained from the finite element analysis of a porous titanium structure in DIGIMAT FE. The calculations were carried out for a representative volume element with specified porosity and pore size under uniaxial loading. The visualization enables analysis of stress distribution within the material volume and identification of stress concentration zones resulting from the porous structure's geometry.

(a)

(b)

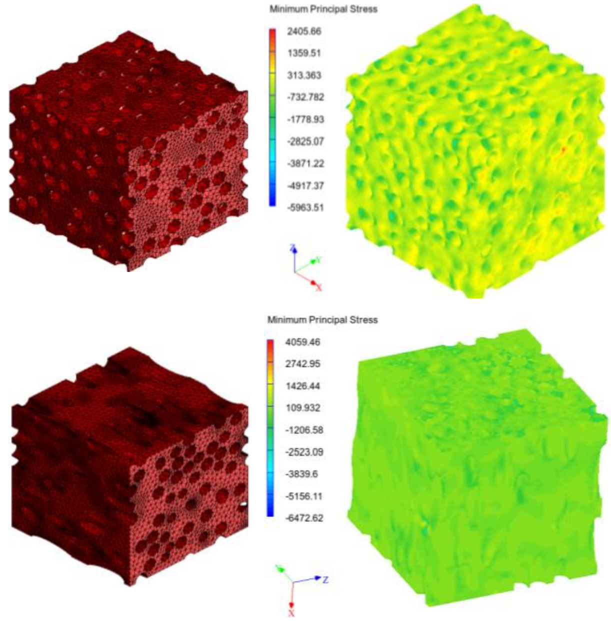


Figure 5. Distribution of equivalent stresses in a porous titanium structure under uniaxial loading (porosity 30%, pore size 200 µm): (a) with a spherical pore, (b) with an ellipsoidal pore

The numerical modeling of stress distribution in the representative volume of porous titanium revealed that the local components of the stress tensor reach 2405 MPa for spherical pores and 4059 MPa for ellipsoidal pores, due to stress concentration in the ligaments between pores. At the same time, the volume-averaged stresses remain significantly lower than the local maxima, confirming the validity of the homogenization approach.

Physically, stresses in the material concentrate in regions with abrupt changes in geometry or small radii of curvature. For spherical pores, the radius of curvature is uniform in all directions, resulting in a more even stress distribution. In contrast, ellipsoidal pores have sharp regions (small radius of curvature at the ends of the ellipse), leading to substantial stress concentrations.

4. Conclusions

In finite element modeling, titanium models with varying porosity and pore diameter were used. According to our calculations, the most significant variable affecting stress concentration and the heterogeneity of the stress-strain field is matrix porosity. Analysis of the stress-strain response for different pore sizes (200, 400, and 600 µm) showed that, at a fixed porosity, changes in pore size have a negligible effect on the effective elastic modulus of the material. Further analysis of the modeling results indicated that, while pore size has little influence on mechanical properties at a fixed porosity, pore shape, as reflected in the aspect ratio, is the key factor. It was found that as the deviation from spherical pore shape increases (i.e., higher aspect ratio), the effective mechanical properties, particularly the elastic modulus, decrease.

To achieve optimal properties for titanium implants, a new design of porous titanium with gradient porosity is proposed. Future work will focus on the development and testing of advanced materials intended for biomedical applications.

Author contributions

Conceptualization: MI, EI; Data curation: GS, AD; Formal analysis: MI, EI, AD; Funding acquisition: MI, AT; Investigation: GS, AT; Methodology: AD, EI; Project administration: MI, AT; Resources: GS, MI; Software: EI, AD; Supervision: MI, GS; Validation: EI, AT; Visualization: EI, MI; Writing – original draft: MI, AT; Writing – review & editing: MI, AT. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Остеосинтезге арналған титан құрылымдарының механикалық қасиеттеріне кеуектілік пен кеуектер морфологиясының әсерін модельдеу

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Аңдатпа. Осы зерттеуде остеосинтез жүйелерінде қолдануға арналған кеуекті титан конструкцияларын сандық модельдеу Finite Element Method (соңғы элементтер әдісі) негізінде жүргізілді. Жұмыстың негізгі мақсаты – кеуектердің әртүрлі геометриялық параметрлері мен кеуектілік деңгейлері жағдайында кеуекті құрылымдардың механикалық мінез-құлқын бағалау болды. Осы мақсатта кеуекті құрылымның фрагменттерін сипаттайтын өкілдік көлемдік элементтер – Representative Volume Element (RVE) қалыптастырылып, материал ішіндегі кернеулер мен деформациялардың таралуын анықтау үшін олар біросьтік жүктеме жағдайында талданды. Модельдеу барысында кеуектіліктің әртүрлі деңгейлері мен кеуек өлшемдері бар құрылымдардың бірнеше нұсқасы қарастырылды. Алынған нәтижелер кеуектілік материалдың механикалық мінез-құлқына шешуші әсер ететін негізгі параметр екендігін көрсетті. Кеуектілік артқан сайын кеуектер арасындағы байланыс аймақтарында кернеулердің шоғырлануы өсетіні, сондай-ақ кернеу мен деформация өрістерінің біркелкі еместігі күшейетіні байқалды. Бұл құбылыс материалдың тиімді жүк көтеретін қимасының азаюымен және құрылым ішіндегі жүктемелердің қайта бөлінуімен түсіндіріледі. Кеуек өлшемдері 200, 400 және 600 мкм болатын модельдер үшін кернеу–деформация тәуелділігі қисықтарын талдау нәтижесінде кеуектілік деңгейі тұрақты болған жағдайда кеуек өлшемінің өзгеруі материалдың тиімді серпімділік модуліне салыстырмалы түрде аз әсер ететіні анықталды. Сонымен қатар кеуектердің геометриялық пішіні құрылымның механикалық қасиеттеріне, соның ішінде қаттылығына және кернеулердің таралуына едәуір ықпал ететіні анықталды. Алынған нәтижелер кеуекті титан имплантаттарын жобалау кезінде олардың сүйек тінімен биомеханикалық үйлесімділігін арттыру мақсатында кеуек пішінін оңтайландыру маңызды фактор болып табылатынын растайды.

Негізгі сөздер: *кеуекті титан құрылымдары, остеосинтез, кеуектілік, соңғы элементтер әдісі, механикалық қасиеттер.*

Моделирование влияние пористости и морфологии пор на механические свойства титановых структур для остеосинтеза

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Аннотация. В данном исследовании было проведено численное моделирование пористых титановых конструкций, предназначенных для применения в системах остеосинтеза, с использованием метода конечных элементов. Основной целью работы являлась оценка механического поведения пористых структур при различных геометрических параметрах пор и уровнях пористости. Для этого были сформированы характерные объемные элементы (Representative Volume Element, RVE), представляющие собой фрагменты пористой структуры, которые анализировались при одноосной нагрузке с целью определения распределения напряжений и деформаций в материале. В ходе моделирования были рассмотрены несколько вариантов структуры с различными уровнями пористости и размерами пор. Полученные результаты показали, что пористость является ключевым параметром, оказывающим определяющее влияние на механическое поведение материала. При увеличении пористости наблюдается рост концентрации напряжений в перемычках между порами, а также повышается неоднородность полей напряжений и деформаций. Это связано с уменьшением эффективной площади несущего сечения материала и перераспределением нагрузок внутри структуры. Анализ кривых зависимости напряжения от деформации для моделей с размерами пор 200, 400 и 600 мкм показал, что при фиксированном уровне пористости изменение размера пор оказывает сравнительно незначительное влияние на эффективный модуль упругости материала. В то же время установлено, что геометрическая форма пор оказывает более существенное влияние на механические свойства структуры, включая жесткость и распределение напряжений. Полученные результаты подтверждают, что оптимизация формы пор является важным фактором при проектировании пористых титановых имплантатов для улучшения их биомеханической совместимости с костной тканью.

Ключевые слова: *пористые титановые конструкции, остеосинтез, пористость, метод конечных элементов, механические свойства.*

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Electromagnetic inter-well scanning (EIWS): scientific foundations, geological context, and applications in uranium in-situ leaching

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Abstract. Electromagnetic inter-well scanning (EIWS) is an advanced geophysical method that enables volumetric, time-resolved imaging of electrical conductivity within the inter-well domain of uranium in-situ leaching (ISL) systems. This article presents a comprehensive theoretical, geological, and methodological analysis of EIWS and evaluates its significance for monitoring reactive fluid transport in heterogeneous sandstone aquifers. The study highlights the method's sensitivity to salinity, porosity, permeability evolution, geochemical reactions, and acid front migration – key factors that govern ISL efficiency, breakthrough timing, and environmental containment. Through expanded discussion of electromagnetic physics, tomographic inversion, dynamic subsurface monitoring and operational optimization, EIWS is shown to be a transformative tool for characterizing subsurface processes that were previously inaccessible. The article concludes that EIWS fundamentally enhances recovery efficiency, improves sweep uniformity, strengthens environmental oversight, and establishes a new standard for scientific control of ISL operations.

Keywords: *electromagnetic inter-well scanning, uranium ISL, conductivity tomography, reactive transport, permeability heterogeneity, in-situ recovery monitoring.*

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1. Introduction

Uranium in-situ leaching (ISL), also known as in-situ recovery (ISR), has become the principal extraction technology for sandstone-hosted uranium deposits throughout the world. This transition has been driven not only by economic considerations but also by major environmental and operational benefits. Unlike traditional surface or underground mining, ISL does not require large excavations, waste rock removal, or tailings storage, and therefore minimizes ecological footprint, land disturbance, and long-term reclamation costs [1]. What makes the method especially attractive is the way it exploits the natural porosity and permeability of sedimentary aquifers, using them as dynamic reactors where uranium dissolution occurs directly within the geological formation. This allows the exploitation of deep, low-grade orebodies that would otherwise remain uneconomic under conventional mining technologies.

Despite these advantages, ISL has always faced a fundamental scientific challenge: the reactive transport processes that control uranium recovery occur in subsurface regions that operators cannot directly observe. The dissolution of uranium-bearing minerals, the movement of chemically reactive lixiviant solutions, the redistribution of groundwater, the formation of preferential flow channels, and the evolution of porosity and permeability take place in a three-dimensional space between injection and production wells. This inter-well region is the central arena of ISL, yet most traditional measurements and monitoring tools provide only indirect or incomplete information about it.

Borehole geophysical logging, although technologically advanced, is inherently limited to the immediate neighborhood of the wellbore. Resistivity, natural gamma, neutron porosity, density, induction, and spectral gamma logs provide valuable insights, but their depth of investigation typically does not exceed several tens of centimeters around the casing [2]. This small measurement volume represents only a tiny fraction of the overall region affected by leaching. Hydrodynamic tests such as pumping or slug tests provide transmissivity and storage parameters, but these are spatially averaged quantities that cannot resolve heterogeneity, channeling, or compartmentalization at the scale relevant to operational control [3]. Flow modeling, even in its most sophisticated forms, depends heavily on conceptual geological models that cannot be validated volumetrically. Tracer tests may confirm general hydraulic connectivity, yet they tend to overlook detailed internal structuring of the flow field, and their interpretation is complicated by retardation, adsorption, and dispersion [4].

Because of these limitations, ISL operations often remain partly empirical, relying on indirect indicators of sweep efficiency, breakthrough timing, and acid distribution. The lack of volumetric visibility in the inter-well space means that operators may not fully understand whether injected fluids are accessing targeted ore zones, bypassing stagnant volumes, or leaking vertically toward confining layers. This lack of insight translates into uncertainties in uranium recovery, acid losses, environmental risk, and the reliability of predictive reservoir models.

Electromagnetic inter-well scanning (EIWS) directly addresses this long-standing observational gap. The method is based on transmitting controlled electromagnetic waves from one borehole and recording their response in a second borehole. Because electromagnetic wave propagation is highly sensitive to the electrical conductivity of the medium, the amplitude and phase of arriving signals contain information about the conductivity distribution within the entire inter-well region [5]. Conductivity in porous media is strongly affected by pore-water salinity, acidity, ion mobility, and porosity – all of which evolve dynamically during ISL as chemical reactions proceed and permeability structures change. This makes EIWS not only a geophysical measurement but effectively a reactive transport monitoring tool, capable of revealing the geometry and evolution of fluid migration and geochemical alteration zones.

The result is a fundamentally new mode of reservoir observation. Instead of being limited to the borehole wall or relying solely on indirect tests, the operator gains access to volumetric, time-evolving images of the subsurface. EIWS can reveal preferential flow paths, stagnant pockets, erosion windows, bypassed ore zones, and geochemical fronts. It provides operational intelligence for adjusting wellfield hydraulics, optimizing injection strategies, and ensuring environmental containment. Finally, by offering time-lapse imaging, EIWS moves the ISL industry closer to the concept of a continuously monitored, dynamically optimized subsurface system.

2. Theoretical and methodological foundations of EIWS for uranium ISL

2.1 Geological heterogeneity and its role in reactive fluid transport

Understanding the geological framework of sandstone-hosted uranium deposits is essential for interpreting EIWS data and predicting how injected solutions will migrate through the reservoir. These deposits were formed in a variety of depositional environments: fluvial, deltaic, aeolian, and lacustrine and they exhibit heterogeneity at multiple scales. This heterogeneity is the defining characteristic controlling fluid transport, acid propagation, and overall leaching performance [6].

At the broader geological scale, uranium-bearing aquifers typically consist of stacked sandstone bodies interlayered with siltstones, clays, and paleosols. Their geometry reflects the dynamics of ancient river channels, floodplains, and deltaic distributary systems, resulting in a complex architecture of permeable and semi-permeable units. In fluvial systems, channel belts may contain coarse, well-sorted sands with high permeability, whereas overbank deposits may include fine-grained, low-permeability sediments. These architectural elements produce natural compartments that differ significantly in their hydraulic conductivity and transmissivity.

At the intermediate scale, variations in bedding, lamination, cementation, and diagenetic alteration impose additional controls on flow. For instance, thin clay drapes or ripple laminations may act as barriers to vertical fluid movement, causing acidized fluids to migrate laterally rather than vertically. Cross-bedded or inclined heterolithic strata may enhance anisotropy, promoting channelized flow along preferential lines while limiting access to adjacent volumes. The interplay between these sedimentary structures forms a hierarchical network of flow paths and baffles that is highly sensitive to chemical alteration.

At the micro-scale, pore-throat size distributions, grain contacts, diagenetic cements, and mineralogical variations determine pore connectivity and local reactivity. Carbonate dissolution plays a major role during acid leaching, increasing porosity and altering flow pathways [6]. Conversely, precipitation of secondary minerals, such as gypsum or silica, may locally reduce permeability. Since these reactions are spatially variable, the effective hydraulic structure of the reservoir continually evolves during ISL.

Reactive transport processes further complicate this geological setting. When sulfuric acid is injected, the first stage of reaction typically involves dissolution of carbonates and ferric minerals, releasing ions into the fluid phase and increasing conductivity. As the acid front moves, it may encounter zones rich in reactive minerals, which rapidly consume acid and buffer pH. In other areas, particularly those with limited permeability or restricted fluid access, the acid front may stall or bypass, leaving behind stagnant zones that retain uranium but do not meaningfully contribute to recovery [1].

Geological heterogeneity therefore produces highly uneven sweep patterns. Fluvial channel sands may become heavily acidized, showing increased conductivity detectable by EIWS, while adjacent siltstone lenses remain unperturbed. Erosion windows may permit uncontrolled fluid communication between stratigraphic levels, introducing environmental and operational risks. In contrast, subtle clay-rich barriers may protect deeper or adjacent zones from acid invasion, preserving their natural state.

Because conductivity responds strongly to both lithological and geochemical differences, EIWS provides a means of capturing these complex interactions within the inter-well space. Conductive anomalies often correlate with acid-invaded zones, high-salinity pockets, or dissolution-enhanced pathways. Resistive anomalies typically indicate unreacted ore, clay-rich barriers, or isolated regions that fail to participate in flow. Over time, as the acid front migrates and the reservoir evolves, EIWS can track these changes, revealing dynamic patterns that reflect the combined influence of geology, hydrodynamics, and geochemistry.

In summary, the geological heterogeneity of ISL deposits is not merely a static background but an active participant in the leaching process. It shapes the geometry of flow, controls the distribution of reactive phases, and ultimately governs the efficiency of uranium extraction. EIWS, by imaging conductivity changes arising from these processes, offers a window into the inner workings of the reservoir, allowing operators to move beyond empirical approaches and toward scientifically grounded optimization of ISL operations.

2.2 Physical principles of electromagnetic inter-well scanning

Electromagnetic inter-well scanning (EIWS) is grounded in the classical physics of electromagnetic wave propagation in conductive, porous, fluid-saturated geological media. The fundamental basis of the method rests on Maxwell's equations, which together describe how time-varying electric and magnetic fields interact with materials that possess conductivity, permittivity, and permeability. Although the theory is well established, its application within chemically reactive environments such as uranium ISL presents a complex interplay between physics, geology, fluid chemistry, and evolving rock properties. The subsurface conditions shaped by in-situ leaching provide a highly dynamic electromagnetic medium, whose properties change over time as dissolution and precipitation processes modify pore networks, fluid composition, and ion mobility.

In a conductive geological medium, electromagnetic field propagate in a diffusive rather than wave-like manner. This means that instead of traveling as well-defined waves, the electromagnetic energy penetrates the formation with exponential attenuation governed primarily by the electrical conductivity of the medium. The relevant expression controlling penetration depth is the skin depth, which is inversely proportional to the square root of conductivity and frequency. High conductivity, as commonly found in acidized or highly saline zones, leads to rapid attenuation. This sensitivity is precisely what makes EIWS valuable in ISL settings acidized zones are strongly conductive and therefore produce measurable changes in amplitude and phase between transmitter and receiver.

The relationship between electrical conductivity and subsurface conditions is complex but highly advantageous for monitoring ISL. Conductivity increases significantly when sulfuric acid dissolves carbonates and sulfates [7], releasing ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-}, and H^+ into the pore fluid. These ions enhance the fluid's ability to carry electric current, producing sharp contrasts relative to less impacted regions. As the leaching front advances, these chemical transformations modify not only fluid conductivity but also the mineral structure, pore geometry, and microfracture network. Zones experiencing active dissolution tend to become more conductive due to increased ionic strength and improved pore connectivity. In contrast, areas undergoing secondary mineral precipitation, such as gypsum formation, may exhibit reduced conductivity or complex mixed responses. EIWS is sensitive to all of these processes.

The operational configuration of EIWS involves deploying a controlled electromagnetic transmitter in one well and a sensitive receiver in another well spaced typically between 20 and 80 meters away. The transmitter emits electromagnetic waves over a range of frequencies [8,9]. Lower frequencies penetrate more deeply into the formation and sample the entire inter-well region, while higher frequencies provide finer discrimination of shallow or localized features. The receiver measures both amplitude and phase shift, which encode information about the medium through which the waves have passed. Unlike borehole logs that measure properties immediately adjacent to the borehole wall, EIWS captures volumetric information, integrating responses across the entire inter-well trajectory.

The interpretation of EIWS measurements depends heavily on solving a nonlinear inverse problem. Electromagnetic wave propagation in a conductive medium is governed by partial differential equations that must be numerically approximated. Forward modeling predicts the electromagnetic response for a hypothetical conductivity distribution. The inverse problem seeks to find the conductivity distribution that best explains the observed data. However, this inversion is inherently ill-posed: many possible conductivity models can produce similar electromagnetic responses, especially when data are noisy or incomplete. Therefore, robust regularization techniques are required to stabilize the inversion. Modern EM inversion approaches incorporate constraints such as smoothness, spatial coherence, and prior geological knowledge to produce geologically plausible models [10-12].

Regularization strategies, such as Tikhonov regularization or model-weighted smoothing, are essential in preventing nonphysical oscillations. Recent developments also include the use of geostatistical priors, Bayesian inversion frameworks, and machine-learning-enhanced inversion methods. Numerical modeling studies of electromagnetic wave propagation in heterogeneous aquifers have shown that sensitivity is highest along direct transmitter–receiver paths but remains significant in off-path regions, meaning that EIWS can effectively map zones not directly aligned with the inter-well axis. This makes EIWS particularly suitable for complex geological formations where flow pathways may diverge significantly from the direct line connecting two wells.

In an ISL environment, the physical interpretation of EIWS can be enhanced by integrating chemical and hydrological understanding. For example, at the early stages of acid injection, conductivity increases sharply at the leading edge of the acidic plume. This creates a fast-moving, conductive front often detectable as a pronounced anomaly in EIWS. As leaching continues, conductivity may evolve due to mineral dissolution, partial neutralization of acid, and changes in salinity. Toward the end of the leaching cycle, when the formation is rinsed, conductivity anomalies may diminish or change shape, providing a diagnostic indicator of the effectiveness of rinsing or the extent of residual acidic zones.

The dynamic nature of electromagnetic properties under ISL conditions implies that EIWS can serve not merely as a static imaging tool but also as a temporal monitoring system. Time-lapse measurements allow operators to observe the evolution of subsurface conductivity fields, track acid front movement, and detect changes in permeability or flow patterns. When EIWS data are collected at regular intervals, they form a temporal sequence that can be used to reconstruct the four-dimensional behavior of the reservoir. This makes EIWS one of the few technologies capable of delivering real-time, volumetric assessment of subsurface reactive transport.

Another factor influencing EIWS responses is the presence of anisotropy in geological formations. Many sedimentary aquifers exhibit anisotropic conductivity due to bedding planes, lamination, or preferential orientations of clay minerals. Anisotropy affects electromagnetic wave propagation differently depending on field orientation, thus making inversion more complex. Advanced EIWS implementations can incorporate tri-axial transmitter and receiver systems to better resolve anisotropy and improve tomographic accuracy.

Finally, while metallic casings commonly found in ISL wells can distort electromagnetic fields, modern EIWS systems incorporate sophisticated calibration procedures and casing compensation algorithms. These developments allow the method to be used effectively even in fully cased production wells, which is a major advantage over some forms of geophysical logging that require open holes or special well completions.

Overall, the physical principles of EIWS reflect a rich interplay between electromagnetic theory, subsurface geology, fluid chemistry, and reactive transport processes. It is this combination of sensitivity to chemical changes, compatibility with cased wells and volumetric coverage that makes EIWS uniquely suited for ISL monitoring. The method moves beyond traditional geophysical tools by providing actionable, physically grounded insights into the evolving conditions within the inter-well region, where the critical processes of uranium leaching are most actively occurring.

3. Results and discussion

3.1 Dynamic monitoring of ISL processes and practical significance

One of the most powerful aspects of electromagnetic inter-well scanning is its ability to monitor reactive fluid movement and geochemical transformations dynamically throughout the operational life of an in-situ leaching (ISL) wellfield. While traditional geophysical logs and hydrogeological measurements capture only static snapshots or indirect indicators of the subsurface, EIWS offers a fundamentally different perspective - one that evolves over time and reflects the continuous progression of the leaching system as it moves through distinct operational stages. In this sense, EIWS is not merely a diagnostic tool but a framework for adaptive management, enabling timely decisions driven by real-time information about how injected fluids are distributed, how the ore is being accessed, and where inefficiencies or risks may be emerging.

From the very beginning of ISL operations, EIWS provides actionable insights. During the initial acid push phase, the foremost priority is to understand whether the injected lixiviant is penetrating the intended ore-bearing intervals and whether it is doing so evenly across the inter-well region. Early EIWS surveys typically reveal the initial geometry of acid invasion. Highly conductive anomalies tend to form rapidly where permeability is greatest, often highlighting pre-existing geological features such as paleo-channels, permeable layering, or localized microfracture networks. These early observations serve as a «first look» into the functional connectivity of the reservoir, identifying channels that will dominate flow as operations progress.

As injection continues, time-lapse EIWS begins to reveal the dynamics of the acid front. In an idealized scenario, the front advances smoothly and symmetrically through the inter-well region, ensuring a large contacted volume and high sweep efficiency. However, actual field conditions rarely conform to this ideal. Geological heterogeneity, variable permeability, anisotropy, and subtle structural controls frequently distort the shape of the reaction front. EIWS can detect these distortions with sufficient clarity to allow meaningful operational adjustments. If the acid front is advancing too rapidly along a high-permeability corridor, the increasing conductivity will highlight this «fast path», enabling operators to reduce injection in certain wells, reallocate flow, or temporarily shut in areas that are advancing too quickly.

At the same time, EIWS can identify zones of poor fluid access. These appear as persistently resistive regions between wells, often indicating stagnant pockets that remain uncontacted by the acid front. Such stagnant zones are operationally significant because they frequently contain uranium that remains unrecovered even after extensive leaching. They also represent areas where the chemical environment may remain reducing, buffering the advance of acid and slowing the kinetics of dissolution. Once identified, these stagnant volumes can be targeted with specific engineering measures, such as modifying injection depths, stimulating flow pathways, or implementing alternating injection–extraction regimes to redistribute pressure gradients.

As the leaching cycle progresses into the mid-stage, the relationship between conductivity and reactive transport becomes more complex. Conductivity may continue increasing in areas where continued dissolution mobilizes ions, but other zones may transition toward mixed or even decreasing conductivity if secondary mineral precipitation occurs or if acid is consumed faster than it is replenished. These subtle patterns are invaluable for understanding the underlying reaction mechanisms. For example, a localized decline in conductivity during the mid-stage may indicate gypsum precipitation or partial clogging of pore throats, reducing permeability and altering flow patterns. Such emergent behaviors are nearly impossible to detect without volumetric monitoring such as EIWS.

The dynamic capability of EIWS becomes even more valuable as operators move toward later stages of leaching, where production volumes begin to decline and breakthrough events start to dominate. Breakthrough, when injected acid preferentially reaches production wells through highly permeable channels, can drastically reduce sweep efficiency and increase chemical losses. EIWS provides a means to detect early signs of breakthrough by imaging increasingly conductive zones that begin to form near production wells. When these anomalies appear, operators can redistribute injection away from problematic wells or introduce balancing injections in other parts of the wellfield to mitigate the effects of channeling.

The ability to detect vertical or lateral migration beyond the intended extraction zone is another critical function of EIWS monitoring. While ISL relies on the presence of confining layers to restrict vertical fluid movement, weak points such as erosion windows, poorly cemented intervals, or subtle fractures may permit cross-formational communication. Conductive anomalies appearing above or below the ore zone in EIWS data can indicate such breaches [13,14]. Early detection is essential, as excursion events represent both environmental risks and regulatory compliance issues. EIWS provides operators with the sensitivity needed to identify these migration patterns long before conventional groundwater sampling or hydraulic monitoring would detect them.

In the final stages of ISL operations, as the wellfield transitions to rinse and restoration, EIWS plays a unique role in evaluating the effectiveness of flushing operations. Residual acid, elevated salinity, and persistent conductive anomalies may indicate zones where restoring groundwater quality will be challenging [15-18]. These anomalies help identify areas that require targeted hydraulic isolation or extended rinsing. Because restoration is often the most time- and cost-intensive part of ISL operations, the ability to map residual conductive zones helps operators optimize restoration strategies and avoid unnecessary effort in areas already stabilized.

From an economic perspective, the operational significance of EIWS cannot be overstated. By improving sweep efficiency, reducing acid losses, mitigating breakthrough risks, enhancing uranium recovery, and ensuring more efficient rinsing, EIWS enables substantial cost savings.

Operational improvement is only one dimension of EIWS's importance; environmental protection is another. Because EIWS can detect the migration of conductive fluids beyond the wellfield boundaries or outside the intended stratigraphic interval, it helps prevent and control environmental excursions. By providing early detection of leakage, EIWS enables operators to respond before excursions become serious or regulatory thresholds are exceeded. This capability aligns with modern environmental governance frameworks, which increasingly require real-time or near-real-time monitoring of subsurface processes to ensure safe operation.

On a broader conceptual level, EIWS contributes to a shift in the philosophy of subsurface resource management. Historically, ISL operations have relied heavily on indirect inference; now, with EIWS, operators gain a capacity for direct observation of subsurface reactive transport processes. This transition mirrors other advances in earth science, such as the adoption of time-lapse seismic monitoring in hydrocarbon reservoirs. In many ways, EIWS represents a similar leap forward for the uranium industry, creating the basis for a more predictive, more controllable, and more scientifically grounded operational paradigm.

In summary, the dynamic monitoring capabilities of EIWS make it an essential tool for modern ISL operations. Its ability to visualize the evolution of the reservoir, detect operational issues before they become problematic, guide real-time decision-making, and improve both economic and environmental performance establishes EIWS as a cornerstone technology for the future of uranium in-situ leaching.

3.2 Limitations, uncertainties, and methodological challenges

Despite the clear advantages and transformative potential of Electromagnetic inter-well scanning, the method is subject to a variety of limitations and uncertainties that must be carefully understood when applying it to the complex subsurface environments encountered in uranium ISL operations. These limitations arise from both fundamental physical constraints and practical operational considerations. Recognizing them allows practitioners to correctly interpret tomographic images, integrate EIWS data with other datasets, and ultimately improve the reliability of reservoir evaluations.

One of the primary challenges arises from the diffusive nature of electromagnetic propagation in conductive geological media. When conductivity is high, as it often is in acidized, saline, or clay-rich formations, electromagnetic waves experience rapid attenuation. This reduces depth of investigation, creates blind zones in high-conductivity strata, and limits the ability to resolve fine-scale features. In certain ISL environments, particularly those with thick layers of conductive clays or shales, the penetration depth of higher-frequency signals may be severely constrained. Lower frequencies can mitigate this issue, but at the cost of reduced spatial resolution. Thus, EIWS must balance frequency selection with geological characteristics to maximize effectiveness.

Another significant limitation concerns anisotropy in sedimentary formations. Many uranium-bearing sandstone aquifers exhibit pronounced anisotropy resulting from bedding planes, lamination, preferential alignment of clay minerals, or depositional features such as cross-bedding. Anisotropy affects how electromagnetic waves propagate, sometimes allowing preferential propagation along certain directions while attenuating waves in others. If anisotropy is not incorporated into the inversion algorithm, tomographic images may misrepresent the geometry or magnitude of conductivity features. Although advanced inversion techniques allow anisotropy to be modeled, such approaches require additional data and computational complexity.

Equally important are the effects of well casing, particularly metallic casing, which is standard in most ISL wells. Metal casing produces eddy currents [19] that distort the electromagnetic field, alter amplitude and phase measurements, and reduce signal sensitivity to the surrounding formation. These distortions must be corrected through calibration procedures, casing compensation algorithms, and careful tool design. While modern EIWS systems are capable of operating effectively in cased wells, the presence of casing still reduces sensitivity relative to open-hole environments and imposes practical constraints on tool orientation and frequency usage.

A further methodological challenge arises from the inherent non-uniqueness of the electromagnetic inverse problem. Since many conductivity distributions can produce similar electromagnetic responses, the inversion process relies heavily on regularization to select a stable and geologically plausible model. However, strong regularization inevitably smooths the resulting tomograms and may obscure fine-scale heterogeneities. Conversely, insufficient regularization may allow noise or numerical artifacts to dominate the solution. Achieving the correct balance is nontrivial and requires substantial expertise in inversion theory, numerical modeling, and reservoir geology.

Additionally, EIWS inversion is sensitive to measurement noise, which can originate from electronics, external electromagnetic interference, variable borehole conditions, and environmental factors. Noisy data can lead to instabilities in inversion, particularly in low-sensitivity regions or where wave attenuation is high. Data preprocessing, filtering, and careful acquisition protocols are therefore essential components of reliable EIWS practice.

Beyond these physical and computational challenges, there are broader uncertainties connected with reservoir complexity and incomplete geological knowledge. In many ISL fields, detailed core data may be sparse, spatially uneven, or unavailable, forcing reliance on log-based geological interpretations that may not fully capture the true heterogeneity of the system. When prior geological information is inaccurate or oversimplified, inversion algorithms may impose biases, leading to misinterpretation of conductive and resistive anomalies. Integrating EIWS with lithological, hydrodynamic, and tracer data helps reduce such risks by anchoring inversion results in multiple lines of evidence.

Another difficulty concerns multi-physics coupling. The electrical conductivity measured by EIWS reflects the combined effects of lithology, salinity, porosity, acidity, and temperature. These factors may evolve simultaneously but not linearly. For example, conductivity may increase during acidization due to increased salinity but decrease later if permeability is lost due to secondary mineral precipitation. Distinguishing between chemical and hydrological drivers of conductivity anomalies requires careful interpretation and cross-disciplinary knowledge. In some cases, calibration with laboratory measurement of conductivity–porosity–salinity relationships may be required.

Finally, EIWS faces practical limitations in spatial coverage. Although the method provides volumetric imaging between pairs of wells, full coverage of an ISL wellfield requires multiple scanning configurations. In large wellfields with dozens or hundreds of wells, achieving complete coverage may be time-consuming or logistically challenging. Prioritization strategies, where EIWS surveys focus on areas of greatest operational uncertainty, can ease this burden while still providing valuable insights.

In spite of these limitations, EIWS remains one of the most informative and adaptable monitoring techniques available for ISL operations. Many of the challenges can be mitigated through improved acquisition design, integration with other datasets, advanced inversion methods, and ongoing refinement of geological models. Indeed, as EIWS technology continues to evolve, the scope and reliability of its applications are expected to expand significantly.

4. Conclusions

Electromagnetic inter-well scanning represents a fundamental advancement in the monitoring, interpretation, and control of uranium in-situ leaching systems. In contrast to traditional geophysical and hydrological techniques, which offer only partial, indirect, or near-borehole insights, EIWS enables volumetric imaging of the inter-well region the very domain where leaching reactions occur, where permeability architecture governs flow, and where operational performance is ultimately determined. The method provides unprecedented visibility into the subsurface, revealing how injected solutions move through heterogenous sandstone aquifers, how geochemical fronts evolve, and how permeability structures transform as reactive processes unfold.

The expanded analysis presented in this manuscript demonstrates that EIWS is more than an incremental improvement in subsurface monitoring; it is a paradigm shift. By leveraging the sensitivity of electromagnetic fields to fluid chemistry, porosity, and geochemical alterations, EIWS offers a means of directly observing the dynamic behavior of the reservoir. Conductive anomalies highlight preferential flow channels, breakthrough pathways, and acidized zones, while resistive anomalies illuminate stagnant pockets, lithological barriers, and regions of limited hydraulic connectivity. These insights empower operators to identify inefficiencies early, adjust wellfield hydraulics in real time, and ensure that the leaching system performs as intended.

The geological heterogeneity characteristic of sandstone-hosted roll-front uranium deposits further increases the importance of such imaging. These reservoirs exhibit a complex hierarchical structure, ranging from grain-scale porosity variations to large-scale channel systems, all of which influence the transport of reactive solutions. EIWS enables practitioners to capture the cumulative effects of this heterogeneity. It makes possible a more nuanced understanding of why some regions of the reservoir leach efficiently while others remain under-reacted, why breakthrough occurs prematurely in certain wells, and how hydraulic connectivity evolves in response to chemical transformations.

In addition to its operational benefits, EIWS enhances environmental assurance. Uranium ISL requires strict containment of reactive solutions within designated aquifer boundaries, and EIWS provides the sensitivity and spatial resolution necessary to detect vertical or lateral migration before it becomes significant. By identifying unanticipated conductive anomalies outside the production horizon, EIWS enables early intervention and reduces the risk of excursions into surrounding groundwater systems. This capability will only grow in importance as the regulatory landscape tightens and environmental standards become more stringent.

Author contributions

Conceptualization: BVT; Data curation: BVT; Formal analysis: BVT; Funding acquisition: BVT; Investigation: BVT; Methodology: AAB; Project administration: AAB; Resources: BVT; Software: BT; Supervision: AAB; Validation: BVT; Visualization: BVT; Writing – original draft: BVT; Writing – review & editing: AAB. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Электромагниттік ұңғымааралық сканерлеу (ЭҰС): ғылыми негіздері, геологиялық контексті және уран жер асты шаймалау кезіндегі қолданылуы

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Аңдатпа. Электромагниттік ұңғымааралық сканерлеу (ЭҰС) ұңғымааралық кеңістіктің электр өткізгіштігінің көлемдік картасын қамтамасыз етеді және уранды жер асты ұңғымалы шаймалау (ЖҰШ) тиімділігін анықтайтын геологиялық факторларды тікелей бағалауға мүмкіндік береді. Құмтас коллекторларының литологиялық және құрылымдық гетерогенділігі-гранулометрияның өзгергіштігі, қабаттылық, саз қабаттары, өткізгіштік анизотропиясы, диагенетикалық түрлендірулер және жергілікті тектоникалық бұзылулар кәріз ағындарының, сүзу қиын аймақтардың және сілтілеу процесіне кенді интервалдардың қатысу деңгейінің қалыптасуын бақылайды. ЭҰС осы контрасттарға жоғары сезімталдыққа ие және реагенттердің кеңістіктік таралуын бекітеді, бұл тосқауыл горизонттарын, тоқырау аймақтарын және қышқыл майданының жеделдетілген ілгерілеу учаскелерін анықтауға мүмкіндік береді. Уақытша томограммалар геохимиялық өзгерістердің динамикасын көрсетеді және геологиялық құрылым, гидродинамикалық процестер мен уранның алынуы арасындағы байланысты ашады. ЭҰС деректерін геологиялық модельдеумен және стратиграфиялық құрылымдармен интеграциялау қабаттың жай-күйін бағалаудың дәлірек тәсілін қалыптастырады, ұңғымалар торын оңтайландыруға, қамтудың біркелкілігін арттыруға және экологиялық қауіпсіз пайдалануды қамтамасыз етуге мүмкіндік береді.

Негізгі сөздер: *электромагниттік ұңғымааралық сканерлеу, геологиялық әртектілік, стратификацияланған құмтастар, өткізгіштік анизотропиясы, уран ЖҰШ.*

Электромагнитное межскважинное сканирование (ЭМС): научные основы, геологический контекст и применение при подземном выщелачивании урана

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Аннотация. Электромагнитное межскважинное сканирование (ЭМС) обеспечивает объёмное отображение электрической проводимости межскважинного пространства и позволяет напрямую оценить геологические факторы, определяющие эффективность подземного скважинного выщелачивания урана (ПСВ). Литологическая и структурная неоднородность песчаниковых коллекторов — изменчивость гранулометрии, слоистость, глинистые прослои, анизотропия проницаемости, диагенетические преобразования и локальные тектонические нарушения контролируют формирование канализированных потоков, зон затруднённой фильтрации и уровня вовлечённости рудных интервалов в процесс выщелачивания. ЭМС обладает высокой чувствительностью к этим контрастам и фиксирует пространственное распределение реагентов, что позволяет выявлять барьерные горизонты, застойные зоны и участки ускоренного продвижения кислотного фронта. Временные томограммы отображают динамику геохимических изменений и раскрывают взаимосвязь между геологическим строением, гидродинамическими процессами и извлекаемостью урана. Интеграция данных ЭМС с геологическим моделированием и стратиграфическими построениями формирует более точный подход к оценке состояния пласта, позволяет оптимизировать сетку скважин, повысить равномерность охвата и обеспечить экологически безопасную эксплуатацию.

Ключевые слова: *электромагнитное межскважинное сканирование, геологическая неоднородность, стратифицированные песчаники, анизотропия проницаемости, ПСВ урана.*

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Mitigation of air leakage in underground coal mines: A case study of the Quang Ninh coalfield, Vietnam

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Abstract. The stability and efficiency of ventilation systems in underground coal mines are crucial for ensuring production safety and protecting workers' health. Air leakage not only reduces the efficiency of fresh air supply to working places, including longwall faces, dead-end roadways, and large underground openings, but also contributes to hazards such as spontaneous coal combustion and methane accumulation, which may lead to explosions. In addition, air leakage significantly increases the energy consumption of main fan operation. Therefore, it is necessary to investigate and propose solutions to reduce air leakage in underground coal mines. Based on the mining and ventilation layout, as well as the existing ventilation works, the authors carried out field surveys, measurements, analyses, and evaluations in order to propose measures for reducing air leakage through mine ventilation works. In addition, several design solutions for ventilation gates, ventilation doors, and retaining walls were proposed for application in underground coal mines of the Quang Ninh coalfield, Vietnam. The research methods used in this study included data collection, field surveys, in-situ measurements, field analysis, and evaluation of the obtained results. The proposed solutions have been applied in mine production and have shown positive results, including reduced air leakage, improved ventilation efficiency, better operating performance of the main fans, and lower ventilation costs for the entire mine. The results of this study can also serve as a basis for underground coal mines to develop ventilation plans and to select and install appropriate ventilation works for reducing air leakage throughout the mine.

Keywords: *air leakage, air leakage reduction, ventilation works, main fan stations, underground coal mines, Quang Ninh coalfield.*

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1. Introduction

Underground coal mines operated by Vietnam National Coal-Mineral Industries Holding Corporation Limited are currently facing a number of ventilation-related challenges. Mining activities are being conducted at increasing depths, many mines are classified as grade III or supergrade in terms of gas emission, and ventilation systems are becoming more complex, especially in mines where several levels are mined simultaneously. Under such conditions, significant air leakage through ventilation structures often occurs, resulting in an insufficient air supply to working places [1].

Air leakage refers to the transfer of air from intake airways to return airways without passing through the required working places, such as mining faces, development headings, or large underground openings. It can be classified into internal and external leakage. Internal leakage occurs within mining districts and ventilation structures inside the mine, whereas external leakage mainly occurs through fan drifts and main fan installations. In practice, leakage through ventilation structures may account for 70-90% of the total internal air leakage in a mine. Excessive leakage reduces the amount of air delivered to active workings, worsens underground microclimatic conditions, and negatively affects both labour productivity and workers' health. In mines with high methane emissions, insufficient air quantity may also prevent methane dilution to permissible limits, thereby increasing the risk of fires and explosions [2].

Many studies have addressed the issue of air leakage in underground mines. Previous research has focused on gas control, mine climate, and ventilation processes [3-5]; the characteristics, mechanisms, and intensity of air leakage [6-8]; airflow simulation and the influence of leakage on mine ventilation networks [9-15]; and the regularities of air leakage in underground coal mines [16-18]. Other studies have considered optimization of ventilation networks to reduce leakage losses [19-23], the influence of leakage on spontaneous combustion hazards and fire prevention measures [24-27], as well as air leakage in complex coal mines, mine microclimate assessment, and energy-saving solutions for ventilation systems [28-30]. In the Quang Ninh coalfield of Vietnam, a number of studies have also investigated leakage resistance and leakage assessment in mines [31, 32], ventilation network evaluation and ventilation door systems at Khe Cham Coal Mine [33-35], and the operating conditions of main fan stations at several mines, including Nam Mau Coal Mine [36-39].

Although these studies have made an important contribution to understanding and controlling air leakage in underground coal mines, they have generally focused on individual mines, specific ventilation installations, or individual aspects of ventilation performance. A systematic and large-scale survey of ventilation structures in underground coal mines of the Quang Ninh coalfield has not yet been carried out. In practice, many mines attempt to compensate for leakage by increasing the total air quantity supplied underground. However, this approach increases electricity consumption, accelerates ventilation equipment wear, and may destabilize the ventilation network without eliminating the root causes of leakage. Therefore, a comprehensive study aimed at identifying and proposing effective measures to mitigate air leakage through ventilation structures in underground coal mines of the Quang Ninh coalfield is both necessary and timely. The results of this study can serve as a practical basis for improving ventilation efficiency and enhancing mine ventilation safety in the region.

2. Materials and methods

2.1. Ventilation works in underground coal mines

Ventilation doors are among the most important ventilation works used for regulating and directing airflow in underground coal mines. Due to the dense network of tunnels, underground coal mines often use hundreds of ventilation doors installed at different locations. These doors are concentrated in crosscuts, transport tunnels, and areas adjacent to ventilation shafts. Their main role is to separate airflow, prevent bypassing between fresh and dirty air flows, regulate and distribute airflow to longwall faces and preparatory faces according to the ventilation design, and facilitate transportation by allowing people, equipment, and electric trains to pass through while ensuring the isolation of the ventilation system.

Ventilation doors include automatic ventilation doors, reversing ventilation doors, and manual ventilation doors. Automatic ventilation doors are widely deployed in modern mines such as Ha Lam, Khe Cham, and Vang Danh. These doors use hydraulic or pneumatic piston systems, allowing electric trains to pass through without stopping for manual opening. Reversing ventilation doors are designed with two-way hinges to ensure stable operation when the main fan system reverses the airflow in the event of a malfunction. Manual ventilation doors are still used in preparatory furnace areas and in medium- and small-scale mines.

The materials commonly used for manufacturing ventilation doors are steel or wood covered with corrugated iron. Some modern mines are gradually switching to composite plastic or high-strength steel doors in order to prevent corrosion in humid environments.

A ventilation gate is a ventilation work constructed in mine tunnels to separate fresh air from dirty air. It is installed in mine workings that must remain airtight but are also frequently used by personnel and transport vehicles. To effectively isolate air flows and minimize air leakage, at least two ventilation gates should be installed simultaneously in order to create an air chamber.

Retaining walls are used in areas where mining has been completed and in tunnels that are temporarily shut down for more than six months. Before constructing a retaining wall, all materials, equipment, and electrical cables in the tunnels must be removed.

Retaining walls include fixed retaining walls and temporary retaining walls. Fixed retaining walls are built to isolate tunnels and areas where mining has been completed, as well as tunnels that are temporarily shut down or not used for a period longer than six months. In the case of fire-resistant retaining walls, the wall is built of stone or solid brick, with a thickness of at least 0.55 m. In other tunnels, the retaining wall is constructed of solid brick, with a thickness of 0.45 m. Temporary retaining walls are built to isolate tunnels and mining areas where production is temporarily suspended for a period of up to six months. These walls are usually constructed of sandbags or soil, with a thickness of at least 0.6 m. The wall is built at a distance of no more than 4 m from the fresh airflow.

2.2. Classification, types and consequences of air leakage

2.2.1. Classification of air leakage

Air leakage in underground coal mines can be classified into underground air leakage, surface air leakage, and mine-wide air leakage. Underground air leakage, or in-mine air leakage, occurs within mine ventilation works such as ventilation doors, ventilation gates, retaining walls, air bridges, and previously mined-out areas. Surface air leakage, or external air leakage, occurs at the main fan station or between the ground surface and the ventilation shaft. This may involve air leaking from the surface into the ventilation shaft when exhaust fans are used, or air leaking from inside the mine to the outside when forced fans are used in the ventilation shaft. Mine-wide air leakage includes both in-mine and surface air leakage.

2.2.2. Types of air leakage

According to its distribution characteristics, air leakage may be classified as localized, continuously distributed, or mixed. Localized air leakage refers to leakage concentrated at a specific location, such as leakage through ventilation works. Continuously distributed air leakage occurs along a certain length or area, for example through parallel tunnels or excavated zones. Mixed air leakage combines both localized and continuously distributed leakage. For example, air leakage may occur through a pair of parallel tunnels excavated in a coal seam, where localized leakage takes place through the retaining walls of the connecting tunnel, while continuously distributed leakage occurs through the coal pillar between the two tunnels.

2.2.3. Consequences of air leakage

The consequences of air leakage are serious and multifaceted. First, air leakage reduces the airflow supplied to consumption places, especially at the main mining faces, where workers operate and where methane and other harmful gases are present. Second, insufficient airflow worsens workplace conditions, making the air hotter and stuffier due to inadequate dilution of contaminants and insufficient cooling, which in turn reduces labour productivity and increases the risk of heat stress and worker fatigue. Third, in mines with high methane emissions, insufficient airflow may prevent methane concentrations from being diluted below the permissible limit of 1%, and any sudden increase in methane concentration may lead to catastrophic mine fires or explosions. In addition, air leakage increases production costs, since the mine must operate the main fans at higher power in order to compensate for airflow losses and maintain the required air quantity at mining faces. This results in higher electricity consumption and greater maintenance costs. Finally, air leakage complicates ventilation management, leading to inaccuracies in the calculation and adjustment of the overall mine ventilation regime.

2.3. The influence of air leakage on the working mode of the main fan

Figure 1 shows the general schematic diagram for determining the optimal operating point of the main fan, thereby determining the fan's working mode. The graph shows that once point A is determined as the optimal operating point of the main fan, the air pressure of h_A and the airflow of Q_A generated by the fan, as well as the impeller angle and fan power, can be determined. This forms the working mode of the main fan for ventilating the entire mine.

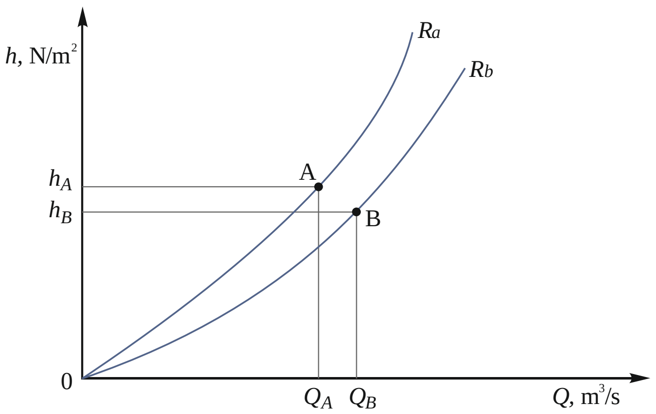


Figure 1. Influence of air leakage on the operating mode of the main fan in underground coal mines: R_a, R_b – mine resistance characteristic curves; h_A – fan pressure at operating point A; Q_A – airflow at operating point A; h_B – fan pressure at operating point B; QB – airflow at operating point B

In the case of air leakage in underground coal mines, the total resistance of the ventilation network decreases as the leakage airflow increases. This is because part of the airflow bypasses the intended working places through leakage paths, thereby changing the aerodynamic resistance of the mine ventilation network. As a result, the mine resistance characteristic curve shifts downward to curve Rb, and the fan operating point moves from A to B. Consequently, the airflow required from the fan increases from Q_A to Q_B, while the fan pressure decreases from h_A to h_B, as shown in Figure 1. This increased airflow can, in many cases, lead to motor overload or even motor burnout. In axial fans, when the operating point shifts to the right side of the characteristic curve, this risk is particularly high.

The influence of air leakage on the working mode of ventilation fans is especially negative when the main fans are connected in parallel, because the operating parameters of the fan may shift to a very low-efficiency zone.

From the practical problems mentioned above, it is clear that measures to prevent air leakage must be applied regularly to ensure ventilation safety and the stable operation of underground coal mines.

2.4. Standards for air leakage through ventilation works in underground coal mines

2.4.1. Standards in some countries around the world

In Russia, a considerable number of studies have been conducted on mine ventilation in general and on air leakage in particular. The external air leakage coefficient through ventilation shafts and air ducts is adopted according to the following values [40, 41]. For fan stations located in vertical shafts, the maximum external air leakage coefficient is $K_{rn} = 1.25$ for shafts equipped with skip hoisting, which corresponds to 25% of the airflow through the fan, and $K_{rn} = 1.20$ for shafts equipped with cage hoisting, which corresponds to 20% of the airflow through the fan. For fan stations located in a fan drift without connection to ventilation shafts, or in ventilation shafts without transport devices and sealed by ventilation gates, the maximum external air leakage coefficient is $K_{rn} = 1.10$, corresponding to 10% of the fan airflow. For fan stations located in fan drifts connected to ventilation shafts, or in ventilation shafts with transport devices, the maximum external air leakage coefficient is $K_{rn} = 1.20$, corresponding to 20% of the fan airflow. Thus, external air leakage depends on the function of the ventilation shaft connected to the fan drift where the fan station is located, particularly on whether transport devices are present, as well as on the cross-sectional area of the fan drift. According to Russian calculations, external air leakage ranges from 1.10 to 1.25, which corresponds to 10% to 25% of the fan airflow.

According to Romanian safety standards, the air leakage limits in underground coal mines are as follows [41]. Air leakage should not exceed 5% if the mine has only one airflow, that is, when air enters and leaves the mine through a single flow path. It should not exceed 10% if the mine has two airflows, that is, when air enters and leaves the mine through two different flow paths. It should not exceed 15% if the mine has more than two airflows, that is, when air enters and leaves the mine through multiple different flow paths. The air leakage standards of Romania and Russia were established during approximately the same period, namely in the 1970s and 1980s, and therefore the construction methods and the air leakage values specified in the standards are quite similar.

China currently has a highly developed mining industry. Underground coal mines in China operate under relatively favorable conditions for the application of mechanization and automation in many production stages, including mine ventilation. In China, mine ventilation is regulated on the basis of the "Safety Regulations in Coal Mining" [42] and the "Standards for Assessing the Safety Quality of Coal Mines". For underground mine ventilation in China, there are no specific standards defining the permissible level of air leakage for each individual type of ventilation structure, such as ventilation doors, air bridges, ventilation gates, or retaining walls. However, the calculation guidelines and mine safety management regulations include several relevant requirements. In particular, the ratio of required airflow, namely the airflow supplied to consumption places such as mining faces, development headings, and power stations, to the total airflow entering the mine must not be less than 85%. This means that the air leakage rate in the mine must not exceed 15%. In addition, external air leakage outside the mine, including leakage through the main fan station and fan drifts, must not exceed 5% when there is no transport equipment in the ventilation shaft and must not exceed 15% when transport equipment is installed in the ventilation shaft, as stipulated in Article 158 of the Chinese underground mining safety standard [42].

2.4.2. Standards at underground coal mines in Quang Ninh coalfield, Vietnam

In Vietnam, there are currently no national standards or industry standards specifically regulating air leakage through ventilation works. Most studies, air leakage calculation procedures, and air leakage prevention practices in Vietnam are based on inherited research results from other countries, mainly Russia and China, or on accumulated practical experience. In particular, the standards and regulations related to air leakage through ventilation works presented in specialized documents in Vietnam, as well as the standards and norms used in training materials on mine ventilation and gas management of Vietnam National Coal-Mineral Industries Holding Corporation Limited, are based on these sources. According to the mine ventilation textbook [43], the Handbook on Underground Mine Ventilation, Tunnels and Fans, and the training materials on ventilation work of Vietnam National Coal-Mineral Industries Holding Corporation Limited [44], air leakage through ventilation works may be summarized as follows.

For retaining walls, the air leakage rate ranges from 0.11 to 0.50 m^3/s. For retaining walls with ventilation doors, the air leakage rate ranges from 0.67 to 2.60 m^3/s. For air bridges, the air leakage rate ranges from 0.58 to 1.25 m^3/s. External air leakage in ventilation shafts depends on the degree of sealing of the transport shaft, whether skips or cages are used, and the external air leakage coefficient ranges approximately from 10% to 30% of the airflow entering the mine.

3. Results and discussion

3.1. Air leakage through ventilation works in underground mines of the Quang Ninh coalfield

Field surveys, measurements, and data collection on air leakage through ventilation works were conducted at 10 underground coal mines in the Quang Ninh coalfield, including Mao Khe, Nam Mau, Uong Bi, Nui Beo, Hon Gai, Quang Hanh, Duong Huy, Mong Duong, Khe Cham, and Ha Long coal mines. These are all large-scale mines belonging to Vietnam National Coal-Mineral Industries Holding Corporation Limited. Survey and measurement data were collected at the mines for ventilation doors, ventilation gates, retaining walls, and gates at the fan stations representing external air leakage.

Based on measurements taken at many different locations, the collected data covered a certain range of values, from which the corresponding average values were determined. A summary of the collected data on air leakage through ventilation works at underground coal mines in the Quang Ninh, is presented in Table 1 [45, 46]. Based on these air leakage data, the graph of air leakage through the investigated ventilation works is shown in Figure 2.

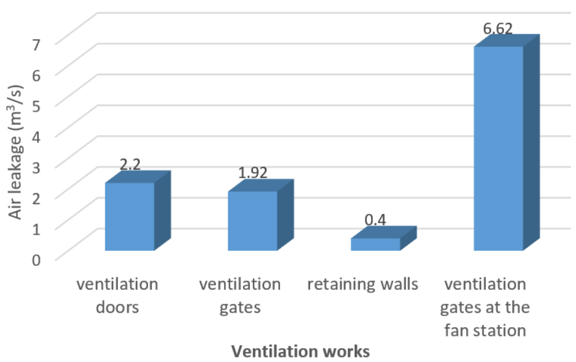


Figure 2. Graph of air leakage through ventilation works in underground coal mines in the Quang Ninh coalfield

Figure 2 shows that external air leakage through the main fan stations is the highest among the investigated ventilation works in underground coal mines of the Quang Ninh coalfield, with an average value of 6.62 m^3/s. Air leakage through ventilation doors ranks second, averaging 2.2 m^3/s, followed by ventilation gates, with an average value of 1.92 m^3/s. The lowest air leakage is observed through retaining walls, with an average value of 0.4 m^3/s.

Table 1. Summary of air leakage levels through ventilation works in underground coal mines in the Quang Ninh coalfield, Vietnam

No.	Coal mine	Air leakage through ventilation works, m^3/s				Note
		Doors	Gates	Walls	Gates at fan stations	
1	Mao Khe	1.8-2.0	1.6-2.0	0.1-0.2	3.8-14.2	Range of values
		1.9	1.8	0.15	8.25	Average
2	Nam Mau	1.8-2.2	1.6-2.0	0.0-0.5	4.6-6.5	Range of values
		2.0	1.8	0.25	5.55	Average
3	Uong Bi	1.7-2.7	1.9-2.7	0.0-0.5	1.5-7.6	Range of values
		2.2	2.3	0.25	3.3	Average
4	Nui Beo	1.8-2.3	1.7-2.5	0.0-0.25	4.5-13.9	Range of values
		2.05	2.1	0.12	7.7	Average
5	Hon Gai	1.8-2.5	1.7-2.4	0.0-0.5	1.5-12.6	Range of values
		2.15	2.05	0.25	4.7	Average
6	Quanh Hanh	1.6-2.6	1.7-2.6	0.0-0.25	2.8-7.3	Range of values
		2.1	2.15	0.12	3.6	Average
7	Duong Huy	1.8-2.8	1.7-2.6	0.25-0.5	2.0-15.5	Range of values
		2.3	2.15	0.37	7.0	Average
8	Mong Duong	2.0 -2.4	1.7-2.5	0.0-0.5	2.8-15.0	Range of values
		2.2	2.1	0.25	7.7	Average
9	Khe Cham	1.8 -2.0	1.2-2.0	0.0-0.5	3.5-18.5	Range of values
		1.9	1.6	0.25	11.0	Average
10	Ha Long	2.2-2.5	1.6-2.5	0.0-0.8	6.1-8.8	Range of values
		2.35	2.05	0.4	7.45	Average
General summary		1.6-2.8	1.2-2.7	0.0-0.8	1.5-18.5	Range of values
		2.2	1.92	0.4	6.62	Average

3.2. Assessment of air leakage through ventilation works

3.2.1. General assessment of air leakage levels through ventilation doors

According to the data presented in Table 1, the level of air leakage through ventilation doors at underground coal mines in the Quang Ninh coalfield depends on the type of door, whether temporary or permanent, the mode of transport through the door, whether for personnel only or for vehicles, the material of the door, the number of door leaves, whether the door is opened and closed manually or automatically, and whether the door is guarded.

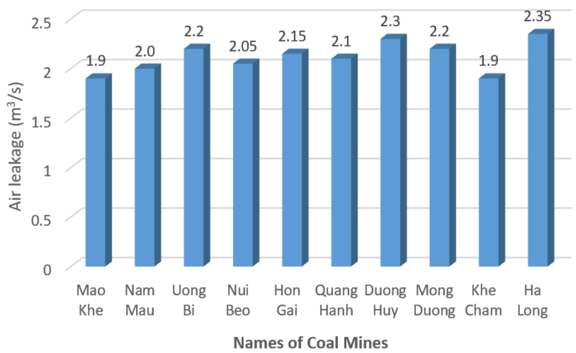
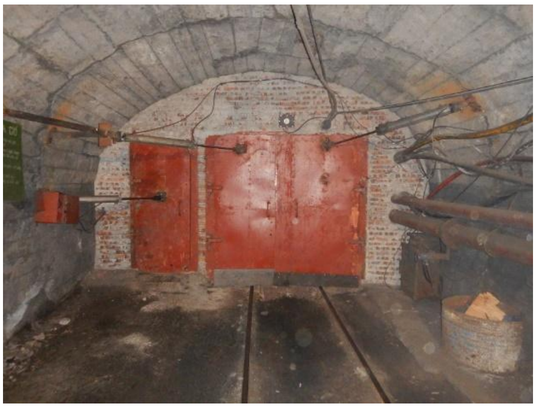


Figure 3. Graph of air leakage through ventilation doors at underground coal mines in the Quang Ninh coalfield

Thus, the survey data collected from 10 underground coal mines in the Quang Ninh coalfield, as presented in Table 1, show that air leakage through ventilation doors ranges from 1.6 to 2.8 m^3/s, with an average value of 2.2 m^3/s. The survey was conducted on doors used for air separation, with brick walls and iron doors, most of which are manually opened and closed without guards. Figure 3 shows that Ha Long Coal Mine has the highest air leakage through ventilation doors, with an average value of 2.35 m^3/s.

Mao Khe and Khe Cham coal mines have the lowest air leakage through ventilation doors, with an average value of 1.9 m^3/s. Other coal mines, including Nam Mau, Nui Beo, Hon Gai, Quang Hanh, Uong Bi, and Mong Duong, which were surveyed and measured in the field, showed similar values ranging from 2.0 to 2.2 m^3/s. Images of some ventilation doors surveyed at underground coal mines in the Quang Ninh coalfield are shown in Figure 4 [46].

(a)



(b)

Figure 4. Images of two typical ventilation doors at two underground coal mines in the Quang Ninh coalfield: (a) – Vang Danh; (b) – Mong Duong

3.2.2. General assessment of air leakage levels through ventilation gates

Ventilation gates located in the main transport tunnels, where the electric train system operates, are usually permanently constructed with two to three gates, most commonly two, and can be opened and closed either manually or automatically. Field survey results from the mines, as shown in Table 1 and Figure 2, indicate that air leakage through permanent ventilation gates ranges from 1.2 to 2.7 m^3/s, with an average value of 1.92 m^3/s. Figure 5 shows that Uong Bi Coal Mine has the highest air leakage through ventilation gates, with an average value of 2.3 m^3/s.

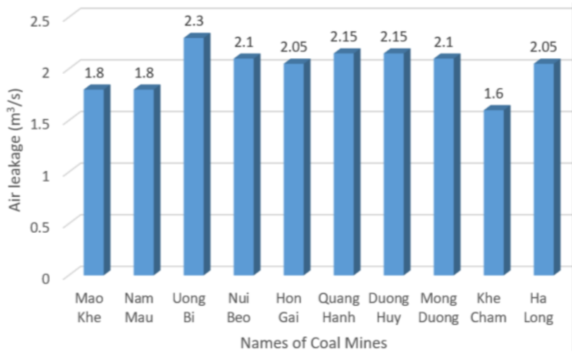


Figure 5. Graph of air leakage through ventilation gates at underground coal mines in the Quang Ninh coalfield

Khe Cham Coal Mine has the lowest air leakage through ventilation gates, with an average value of 1.6 m^3/s. Mao Khe and Nam Mau coal mines have an average air leakage of 1.8 m^3/s. Other coal mines, including Hon Gai, Ha Long, Nui Beo, Mong Duong, Quang Hanh, and Duong Huy, which were surveyed and measured in the field, showed similar values ranging from 2.05 to 2.15 m^3/s. Figure 6 shows a ventilation gate surveyed at Mong Duong Coal Mine [46].

Figure 6. Image of a manually operated ventilation gate with a brick wall and iron frame at the +30 tunnel in the Canh Dong area of Mong Duong Coal Mine

3.2.3. General assessment of air leakage levels through retaining walls

Retaining walls are usually constructed of brick, with or without plastering, or of concrete. In some coal mines with self-igniting properties, permanent walls are also constructed of fly ash. Temporary retaining walls are often built using sandbags. According to the survey data from coal mines in the Quang Ninh coalfield presented in Table 1.

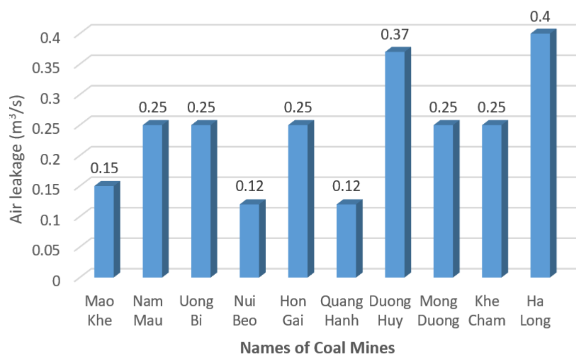


Figure 7. Graph of air leakage through retaining walls at underground coal mines in the Quang Ninh coalfield

Air leakage through retaining walls is relatively low, and at many locations no leakage was recorded. At locations where leakage does occur, it mainly appears along the sides of the tunnel or through cracks in the wall, ranging from 0.0 to 0.8 m^3/s, with an average value of 0.12 m^3/s.

Figure 7 shows that Ha Long Coal Mine has the largest air leakage through the retaining walls, averaging 0.4 m^3/s, followed by Duong Huy Coal Mine, averaging 0.37 m^3/s. Nui Beo and Quang Hanh Coal Mines have the smallest air leakage through the retaining walls, averaging 0.12 m^3/s. Nam Mau, Uong Bi, Hon Gai, Mong Duong, and Khe Cham Coal Mines all have similar air leakage, averaging 0.25 m^3/s.

3.2.4. General assessment of the level of external air leakage through main fan stations

In underground coal mines, most main fan stations have fan drifts connected to ventilation openings, including inclined shafts, horizontal roadways, or vertical shafts. At the entrances to these ventilation openings, air gates are usually installed. The level of air leakage through these gates depends on the mode of transport passing through them, whether electric trains, conveyor systems, or only personnel, as well as on whether the gates are opened and closed manually or automatically. Air leakage at these locations is usually quite significant because of the large pressure difference between the outside atmosphere and the inside of the mine openings. This is also referred to as air leakage through the air gates at the main fan stations.

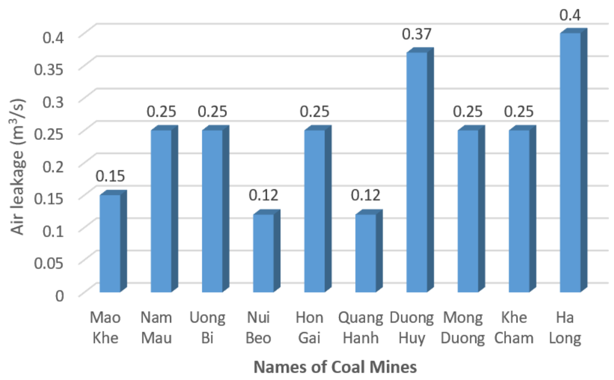


Figure 8. Graphs of external air leakage through main fan stations at underground coal mines in the Quang Ninh coalfield

According to the survey data collected at underground coal mines in the Quang Ninh coalfield, as presented in Table 1, the external air leakage at the main fan stations ranges from 1.5 to 18.5 m^3/s, with an average value of 6.62 m^3/s, corresponding to 1.5 to 22.6% of the main fan airflow, with an average of 9.16%.

Figure 8 shows that Khe Cham Coal Mine has the highest external air leakage, with an average value of 11.0 m^3/s, followed by Mao Khe Coal Mine, with an average value of 8.25 m^3/s. Uong Bi and Quang Hanh coal mines have the lowest external air leakage, with average values of 3.3 and 3.6 m^3/s, respectively. Duong Huy, Ha Long, Nui Beo, and Mong Duong coal mines all show comparable external air leakage values, ranging from 7.0 to 7.7 m^3/s. These results indicate that external air leakage at main fan stations is a major contributor to overall air loss in the ventilation systems of coal mines in the Quang Ninh coalfield and should therefore be considered a priority target for control and mitigation.

3.3. Proposed solutions to reduce air leakage through ventilation works in underground coal mines in the Quang Ninh coalfield

3.3.1. Solutions to reduce air leakage through ventilation doors

Ventilation doors must be constructed in accordance with the approved design and installed at the locations specified in the ventilation scheme. A safe clearance around the doors must be maintained in order to ensure the safe movement of personnel and transport equipment through the tunnels.

All ventilation doors must provide the highest possible airtightness of both the door frame and the door leaf. The joints between the door structure and the roof and sidewalls of the tunnel must be carefully sealed. At the floor contact, flexible materials such as rubber gaskets should be used in order to prevent air leakage. Permanently installed doors in main tunnels should be equipped with double-sided hinges or horizontal sliding mechanisms to facilitate airflow reversal when required.

Ventilation doors installed in main airways and ventilation tunnels must be constructed in a strong and reliable manner and should include at least two door sets forming an airlock in order to ensure continuous closure during operation. The installation of ventilation doors in inclined tunnels used for hoisting transport should be prohibited. In exceptional cases, such installation may only be allowed on the basis of a special design and an authorized hoisting schedule approved by the Director.

Before construction, the support system should be carefully inspected, and the condition of the rock mass in the roof, sidewalls, and floor of the tunnel should be checked. Coal and rock debris must be removed from the site in order to provide sufficient working space and avoid obstructing the movement of personnel and vehicles. The concentrations of CH_4, CO_2, and CO, as well as the temperature at the planned construction site, must also be checked before work begins.

For permanent doors intended for long-term service, the construction site should be selected in areas where the roof, floor, and sidewalls are geologically stable. If construction in unstable ground conditions cannot be avoided, additional reinforcement measures must be implemented to ensure sufficient compaction of the surrounding rock mass at the door site and to prevent air leakage through cracks.

Construction methods must be selected carefully, and the approved design must be strictly followed during construction. If any changes to the construction plan are required, they must be reported to the ventilation manager for review and approval.

The construction of permanent ventilation doors generally includes inspection of the selected location, construction of the wall and assembly of the door frame, and completion of the frame followed by installation of the ventilation door.

The construction of ventilation doors must be directly supervised by a responsible person who gives instructions and continuously monitors the condition of the tunnel and surrounding walls in order to respond promptly to any unsafe situations. During construction, any person passing through the work area must obtain permission from the supervisor. Before passage is allowed, the ventilation door structure must be checked to ensure safe conditions. Passage through the construction zone should be carried out carefully and without delay.

During construction, all works must comply with the approved technical measures, the national technical regulations and safety standards for underground coal mining under QCVN 01:2011/BCT issued by the Ministry of Industry and Trade on February 15, 2011, and other related procedures and regulations [47].

From the technical point of view, the ventilation door must open and close smoothly. It may be operated manually, but it should also be capable of closing automatically under its own weight due to the pressure difference. A gasket, preferably made of rubber, should be installed between the frame and the door leaf in order to reduce air leakage. The door leaf should be smooth and flat, while the door wall should be constructed of fire-resistant material and built in competent rock without cracks.

During operation, ventilation doors without a designated operator should be used only after the surrounding area has been checked for obstacles or equipment preparing to pass through. If transport equipment is approaching, priority should be given accordingly. If the passage is clear, the door may be opened for movement through the opening. For ventilation doors with a designated operator, all personnel and vehicles must obtain permission and follow the instructions of the operator before passing. If a train requests passage and an inspection shows that the route ahead is obstructed by equipment or another train, the train must be instructed to stop and wait until the route is clear before the door is opened.

The fabrication and construction of ventilation doors are usually carried out by the ventilation workshop. After installation is completed, responsibility for management and maintenance must be formally handed over to the relevant production unit or workshop within the mine management area, and this handover must be documented. If any ventilation door is damaged or if air leakage exceeds the permissible level, the ventilation workshop must be informed immediately so that repair can be carried out. During repair or replacement, temporary barriers or partitions should be installed in order to minimize air leakage and maintain production conditions. During production shifts, the ventilation section should carry out regular inspections of ventilation doors to assess their operating condition and physical state at each location. If any door is found to be damaged, deformed, or non-compliant with technical requirements, a report must be issued to the responsible unit, clearly stating the cause of the violation, identifying responsibility, and requiring immediate corrective action.

On a weekly basis, the ventilation section should compile reports on all detected violations and submit them to the Mine Ventilation and Drainage Department. These reports are then forwarded to the Director, who determines the corresponding disciplinary measures. The final penalties may be considered during monthly performance evaluations and product acceptance inspections, depending on the seriousness of each case.

3.3.2. Solutions to reduce air leakage through ventilation gates

The construction and installation of ventilation gates are generally based on the same principles as those applied to ventilation doors. However, some additional requirements should be considered during the management, construction, and operation of ventilation gates. In cases where the tunnel is used only for personnel passage, the distance between the two gates should be at least 5 m, and such gates are usually manually operated. When trains pass through the tunnel, the distance between the two gates must be greater than the maximum train length, and automatic gates should be installed.

The operating principles for ventilation gates are similar to those applied to permanent ventilation doors. However, during passage through a ventilation gate, each gate must be opened separately. After passing through the first gate, it must be closed securely before the second gate is opened. Opening both gates at the same time is prohibited because it causes air leakage. If the ventilation gate includes a side door for personnel passage, only this side door should be used, except in cases where bulky materials or equipment are being carried or transported.

Ventilation gates installed in mine roadways used for electric train transport are usually managed, maintained, and operated by the mine transport sections. Ventilation gates located in tunnels used only for personnel passage are generally managed, maintained, and operated by the ventilation sections.

3.3.3. Solutions to reduce air leakage through ventilation shafts

At main fan stations where the fan drift is connected to tunnels or ventilation shafts, ventilation gates are installed at the top of the tunnels or at the top of the ventilation shafts. To reduce air leakage through ventilation shafts, several basic solutions should be implemented.

Additional ventilation gates may be installed in the ventilation shafts, with at least two gates provided where possible. At the same time, the construction quality, installation technique, and sealing performance of these ventilation gates, as well as the sealing of covers in vertical shafts, should be improved.

Regular inspection and timely repair of any defects are also necessary, since the pressure difference on the two sides of the ventilation gates is usually very large.

The ventilation gates at the top of ventilation shafts should be designed with auxiliary doors for personnel access, and automatic opening and closing gates should be prioritized. In addition, in order to reduce air leakage through cracks in the surrounding rock into the ventilation shafts, the upper section of the shaft or connecting opening should be concreted.

Ventilation shaft entrances must be strictly controlled, and personnel and vehicles should be allowed to pass only with authorization from the responsible guard. Air leakage through ventilation shafts usually accounts for the major part of the external air leakage of a mine. In addition, significant leakage may also occur through fan station buildings, inspection doors of fan shafts, and fan blades. In shallow mines, further external leakage may occur through surface fissures or cracks extending into the mine workings.

3.3.4. Solutions to reduce air leakage through retaining walls (stoppings)

Retaining walls, or ventilation stoppings, are constructed to isolate tunnels after fire incidents or to seal off temporarily suspended roadways. The construction and opening of these isolation structures must strictly follow the approved plans and ensure compliance with safety regulations, technical standards, and operating procedures. To reduce air leakage through these structures, several fundamental measures should be implemented.

During construction, the responsible section must strictly comply with the approved technical measures, the national technical regulations and standards on safety in underground coal mining under QCVN 01:2011/BCT issued by the Ministry of Industry and Trade on February 15, 2011, and other related procedures and regulations [47].

The construction of the retaining wall, from the foundation to the full perimeter, must follow closely the sides and roof of the tunnel. The wall must be straight, flat, and airtight. It should also be equipped with pipes for monitoring or controlling the gases inside the sealed area. The construction of retaining walls must be supervised, and the condition of the tunnel and the wall must be continuously monitored in order to address any situations that may arise. Each retaining wall should also be numbered sequentially.

Fire-resistant materials that satisfy the required technical standards should be used for the construction of retaining walls, and the wall thickness should not be less than 500 mm.

The wall surface must be free of cracks, and any gaps between the wall and the sides or roof of the tunnel must be carefully sealed. If necessary, one or more layers of coating may be applied to the wall surface in order to improve its airtightness and smoothness and thereby reduce air leakage.

3.3.5. General solutions related to organization and management

Air leakage in underground mines results from a variety of factors, primarily pressure differences along leakage paths, improper construction or operation of ventilation structures, and inadequate methods of mine pressure control. Other important causes include insufficient coal pillar width between parallel roadways and surface subsidence or fracturing caused by mining activities.

Such leakage significantly reduces the supply of fresh air to working faces, leading to the accumulation of hazardous gases and coal dust, elevated temperatures, and reduced labour productivity, all of which adversely affect workers' health. In addition, air leakage forces ventilation fans to operate at higher capacities, resulting in considerable energy losses. Therefore, in addition to specific technical measures for each ventilation structure, several general organizational and management solutions should be applied.

A rational ventilation scheme and ventilation method should be selected, since air leakage in the mine is generally lower with a side ventilation scheme and higher with a central ventilation scheme. Proper planning of mining operations and the selection of appropriate technical solutions for the mine are also important, because the mining sequence and mining method have a strong influence on the level of air leakage.

Main roadways, which are intended for long-term use, should be excavated in rock whenever possible. Old and unused workings should either be demolished or isolated by retaining walls. Appropriate mine pressure control methods should also be applied in order to reduce air leakage into mined-out areas. To reduce air leakage in ventilation shafts, the number and quality of ventilation doors in inclined shafts should be increased where necessary, and the sealing quality of vertical shafts should be improved.

An important management requirement is the comprehensive improvement of the quality of mine ventilation safety personnel. Human resources are a key factor in mine ventilation safety management, and the effectiveness of ventilation safety largely depends on the competence of the responsible staff. A mine ventilation manager should have a thorough understanding of ventilation safety and of the risks associated with ventilation management. Improving the quality of mine ventilation managers requires better professional education and training in management, as well as a stronger sense of responsibility and professional ethics, with safety regarded as a primary obligation.

Mine ventilation safety measures should also be inspected and evaluated regularly. The different types of work related to mine ventilation management should be classified scientifically, with clear and logical functions, and the allocation of authority, responsibility, and benefits should be optimized according to these functions. Ineffective or inappropriate management measures should be identified and eliminated.

It is also necessary to develop and improve the relevant system of standards and to implement mine ventilation safety management in accordance with established standards. Effective ventilation management requires standardized procedures at different stages, including the installation and operation of main fan stations, local fans, and retaining walls. Standardization of work content and its implementation can improve the quality of ventilation management and ensure more accurate assessment of work quality.

Strict inspection and evaluation must also be ensured at the design stage. In order to improve the quality of the working environment and continuously comply with mine safety requirements, the design of mine ventilation facilities must strictly follow the relevant safety and design regulations.

Daily ventilation safety management is equally important. Mine ventilation equipment should be maintained regularly, and dust, dirt, and other deposits on ventilation equipment should be cleaned in a timely manner. Damaged ventilation equipment must be repaired or replaced promptly. Ventilation works such as doors, gates, and retaining walls should also be inspected regularly so that any defects or malfunctions can be detected and corrected in time.

Finally, a rational mining plan should be developed in order to ensure the stability of the mine ventilation network.

3.4. Proposed designs for ventilation works to mitigate air leakage applicable to some underground mines in the Quang Ninh coalfield

3.4.1. Ventilation gates

Ventilation gates are ventilation structures constructed to separate fresh air from return air, especially in tunnels where people and vehicles frequently pass through. To effectively isolate airflows and reduce air leakage, at least two ventilation gates should be installed together in order to create an air chamber.

Ventilation gates can be divided into two main types, namely in-mine ventilation gates and ventilation gates installed at the mine entrance in connection with fan drifts. In-mine ventilation gates are usually constructed at the main transport tunnels of the mine, where transport density is high or where human traffic is frequent. Based on the survey results and the assessment of air leakage in underground mines of the Quang Ninh coalfield, air leakage through ventilation gates mainly occurs in tunnels with a high level of electric train traffic and usually accounts for 15-20% of the airflow to the fan. Therefore, the authors propose a design of an in-mine ventilation gate system for electric train transport tunnels in order to reduce air leakage, as shown in Figure 9.

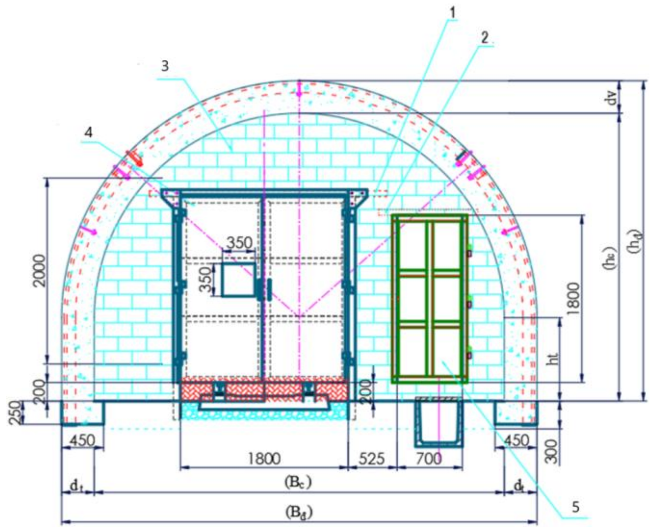


Figure 9. Schematic design of steel ventilation gates installed in a train transport ventilation shaft: 1 – steel beam U160×68×5, length 2.6 m; 2 – steel beam U160×68×5, length 1.1 m; 3 – brick wall; 4 – ventilation gate; 5 – secondary door for personnel access

3.4.2. Ventilation doors

Ventilation doors are installed in tunnels to prevent or regulate airflow while still allowing passage for people and vehicles through opening and closing.

Based on surveys and assessments of the current state of air leakage in underground mines of the Quang Ninh coalfield, air leakage is often high when ventilation doors are installed in tunnels where electric trains, conveyor belts, or scraper conveyors are in operation. Therefore, the authors propose a model design of ventilation doors for tunnels equipped with electric trains, conveyor belts, and scraper conveyors in order to reduce air leakage. This ventilation door design is shown in Figure 10.

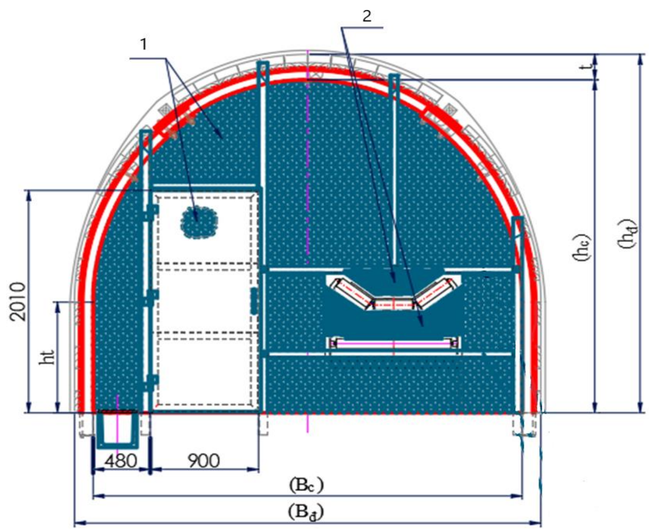


Figure 10. Schematic design of a steel ventilation door installed in a conveyor belt transport tunnel: 1 – sheet metal with a thickness of 0.5 mm; 2 – conveyor belt cover, usually made from old conveyor belts

3.4.3. Retaining walls

Retaining walls are used to isolate areas where mining has been completed, as well as tunnels that are no longer in use or are temporarily out of service (Figure 11).

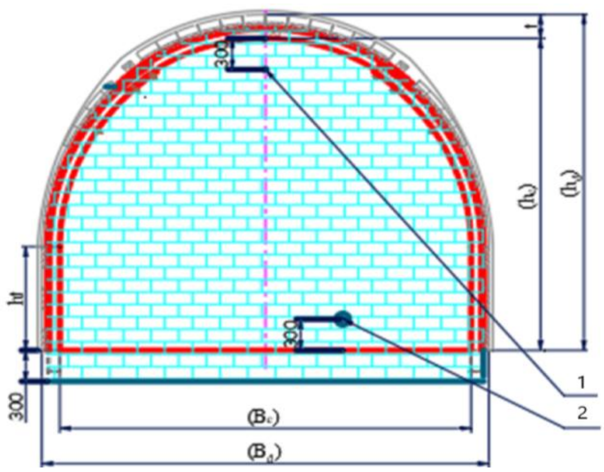


Figure 11. Schematic design of a permanent brick retaining wall: 1 – PVC pipe with a diameter of 21 mm and a shut-off valve, used for gas measurement; 2 – PVC pipe with a diameter of 100 mm, used for drainage

The authors propose a typical design of a permanent brick retaining wall to reduce air leakage, as shown in Figure 11. Permanent retaining walls are usually constructed of brick or concrete, whereas temporary retaining walls are often made of sandbags.

4. Conclusions

Ventilation networks in underground coal mines of the Quang Ninh coalfield, operated by Vietnam National Coal-Mineral Industries Holding Corporation Limited, are characterized by a high level of complexity, ranging from moderate to very complex, regardless of the production scale of the mine.

The main ventilation works used in these mines include ventilation doors, ventilation gates, and retaining walls, whereas air bridges are practically absent in this coalfield. Field surveys and measurement data indicate that air leakage occurs in most of these structures, with the highest values recorded for ventilation doors, averaging 2.15 m^3/s, and ventilation gates, averaging 1.92 m^3/s. In contrast, retaining walls are generally well constructed and properly maintained, resulting in relatively low air leakage, with an average value of only 0.12 m^3/s.

Surface air leakage occurs mainly through the ventilation gates located at shaft entrances connected to the main fan stations. The average external air leakage was measured at 6.62 m^3/s, which corresponds to approximately 9.16% of the total fan airflow.

Although the air leakage rates recorded in the Quang Ninh coalfield are slightly higher than those specified in some international standards and guidelines, the difference is not considerable. In particular, the performance of retaining walls is close to international good practice due to their adequate construction quality and effective management.

Ventilation works play an important role in maintaining mine air quality and operational efficiency. To reduce air leakage, a comprehensive technical approach is required, covering all stages from design and construction to inspection, maintenance, and operation, with due consideration of the specific characteristics of each type of ventilation work. Such measures are essential for improving airflow distribution and enhancing the overall safety of underground coal mining operations.

Author contributions

Conceptualization: CVD; Data curation: CVD, TTV; Formal analysis: CVD, TTV; Investigation: CVD, TTV; Methodology: TTV; Project administration: CVD, TTV; Resources: CVD, TTV; Supervision: TTV; Validation: CVD; Visualization: CVD; Writing – original draft: TTV; Writing – review & editing: CVD, TTV. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Аңдатпа. Жерасты көмір шахталарындағы желдету жүйелерінің тұрақтылығы мен тиімділігі өндіріс қауіпсіздігін қамтамасыз ету және жұмысшылардың денсаулығын қорғау үшін шешуші маңызға ие. Ауа ағуы тазарту кенжарлары, тұйық қазбалар және ірі жерасты камералары сияқты жұмыс аймақтарына таза ауаның жеткізілу тиімділігін төмендетіп қана қоймай, көмірдің өздігінен жануы және метанның жиналуы сияқты жарылысқа әкелуі мүмкін қауіпті құбылыстардың туындауына да ықпал етеді. Сонымен қатар, ауа ағуы бас желдеткіш қондырғылардың жұмысы кезінде энергия тұтынуды айтарлықтай арттырады. Осыған байланысты жерасты көмір шахталарындағы ауа ағуын азайтуға бағытталған шешімдерді зерттеу және әзірлеу қажеттілігі туындайды. Тау-кен жұмыстарының сызбасын, желдету сызбасын және қолданыстағы желдету құрылыстарын талдау негізінде авторлар натурлық зерттеулер, өлшеулер, талдау және бағалау жұмыстарын жүргізді. Бұл шахталардың желдету құрылыстары арқылы болатын ауа ағуын азайту жөніндегі шараларды ұсынуға мүмкіндік берді. Сонымен қатар, Вьетнамдағы Куангнинь көмір бассейнінің жерасты көмір шахталарында қолдануға болатын желдету шлюздері, желдету есіктері және оқшаулағыш бөгеттер үшін конструктивтік шешімдер ұсынылды. Зерттеуде деректерді жинау, натурлық зерттеу, аспаптық өлшеу, шахталық талдау, сондай-ақ алынған нәтижелерді талдау және бағалау әдістері қолданылды. Ұсынылған шешімдер шахталық өндірісте енгізіліп, оң нәтижелер көрсетті, оның ішінде ауа ағуын азайту, желдету тиімділігін арттыру, бас желдеткіш қондырғылардың жұмыс режимдерін жақсарту және жалпы шахта бойынша желдету шығындарын қысқарту нәтижелері байқалды. Осы зерттеудің нәтижелері жерасты көмір шахталарында желдету жоспарларын әзірлеуге, сондай-ақ бүкіл шахта көлемінде ауа ағуын азайтуға бағытталған тиісті желдету құрылыстарын таңдау және орнату үшін негіз бола алады.

Негізгі сөздер: *ауа ағуы, ауа ағуын төмендету, желдету құрылыстары, негізгі желдеткіш қондырғылар, көмір шахталары, Куангнинь көмір бассейні.*

Снижение утечек воздуха в угольных шахтах: на примере угольного бассейна Куангнинь, Вьетнам

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Аннотация. Стабильность и эффективность вентиляционных систем подземных угольных шахт имеют решающее значение для обеспечения безопасности производства и защиты здоровья работников. Утечки воздуха не только снижают эффективность подачи свежего воздуха к рабочим зонам, включая очистные забои, тупиковые выработки и крупные подземные камеры, но и способствуют возникновению таких опасных явлений, как самовозгорание угля и накопление метана, которые могут привести к взрывам. Кроме того, утечки воздуха значительно увеличивают энергопотребление при работе главных вентиляторов. В связи с этим возникает необходимость исследования и разработки решений, направленных на снижение утечек воздуха в подземных угольных шахтах. На основе анализа схемы горных работ, схемы вентиляции и существующих вентиляционных сооружений авторами были проведены натурные обследования, измерения, анализ и оценка, что позволило предложить меры по снижению утечек воздуха через вентиляционные сооружения шахт. Кроме того, предложены конструктивные решения для вентиляционных шлюзов, вентиляционных дверей и изоляционных перемычек, которые могут быть применены на подземных угольных шахтах угольного бассейна Куангнинь, Вьетнам. В исследовании использованы методы сбора данных, натурных обследований, инструментальных измерений, шахтного анализа, а также анализа и оценки полученных результатов. Предложенные решения были внедрены в шахтное производство и показали положительные результаты, включая снижение утечек воздуха, повышение эффективности вентиляции, улучшение режимов работы главных вентиляторов и сокращение вентиляционных затрат по шахте в целом. Результаты данного исследования также могут служить основой для разработки вентиляционных планов на подземных угольных шахтах, а также для выбора и установки соответствующих вентиляционных сооружений, направленных на снижение утечек воздуха в масштабе всей шахты.

Ключевые слова: *утечки воздуха, снижение утечек воздуха, вентиляционные сооружения, главные вентиляторные установки, угольные шахты, угольный бассейн Куангнинь.*

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Grapho-analytical optimization of ore drawing parameters from barrier pillars with field preparation in inclined deposits under caving conditions

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Abstract. This article presents the results of a grapho-analytical study aimed at optimizing technological parameters for ore drawing from barrier pillars (BP) in inclined ore deposits under caving conditions. The extraction of reserves remaining within barrier pillars is one of the most challenging tasks in underground mining, as it requires a balance between maximizing ore recovery and maintaining the geomechanical stability of the surrounding rock mass. Particular attention is paid to substantiating the rational spatial position of drill-haulage drifts (DDW) during field preparation in caving zones. The research methodology is based on geometric and grapho-analytical modeling of ore drawing processes under various mining and geological conditions. The study considers ore body thicknesses ranging from 6 to 12 m and dip angles from 15° to 51°. Several variants of left-asymmetric displacement of the DDW axis relative to the central axis of the barrier pillar were analyzed to determine their influence on ore recovery efficiency, ore losses, dilution, and the stress-strain state (SSS) of the surrounding rock mass. The results show that displacement of the DDW axis significantly affects both extraction performance and geomechanical safety. The rational displacement interval was found to be 1.5-2.0 m in the direction of the ore body dip. Further displacement leads to deterioration of the stress-strain state of the host rocks, reduction of the protective rock layer between the drift roof and the stoping floor, and the need for additional deepening of mine workings. Such modifications increase development volumes in waste rock and, consequently, mining costs. The effectiveness of asymmetric drift placement is most pronounced in deposits with dip angles up to 30°, whereas for steeper ore bodies with dip angles of 40-51°, its practical significance decreases due to the predominance of gravity-controlled ore flow. The obtained results provide a scientific basis for improving mining layouts and can be used in the design of underground mining systems to enhance ore recovery, reduce losses and dilution, and ensure geomechanical stability during the extraction of reserves from barrier pillars.

Keywords: *barrier pillar, inclined deposit, ore drawing, drill-haulage drift, caving zone, grapho-analytical modeling, stress-strain state.*

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1. Introduction

The effective extraction of mineral reserves remaining in barrier and panel-to-panel pillars is a critical issue for the mining industry of Kazakhstan. Recent studies show that the transition from open-pit to underground mining, especially in deposits with complex morphology, requires an in-depth analysis of geomechanical processes to ensure the stability of mine workings [1, 2]. During the repeated extraction of barrier pillars (BP) in caving zones of inclined deposits, the risk of rock mass destabilization increases, which necessitates the application of advanced monitoring and modeling methods [3, 4].

The fundamental aspects of ensuring the stability of open-pit slopes and underground structures have previously been considered using major deposits such as Vasilkovskoye and Akzhal as examples [2, 5]. It has been established that the accuracy of stress-strain state (SSS) prediction directly depends on the quality of geomechanical justification of mining system parameters [4, 6]. At the same time, minimizing ore losses and dilution remains a priority, as these factors determine the economic efficiency of production [7, 8].

Under the conditions of inclined deposits with dip angles of 15-51°, conventional approaches to the placement of preparatory workings are often insufficiently effective. Studies of ore drawing processes and the interaction between broken ore and caved rock indicate the need to optimize the spatial position of drill-haulage drifts (DDW). The use of modern support materials, including innovative shotcrete mixtures that improve stability under complex mining and geological conditions, also plays an important role in ensuring the long-term stability of such workings [9, 10].

The study of asymmetric field-preparation schemes is of particular scientific interest. Previous investigations of the SSS during repeated BP extraction have shown that the asymmetric arrangement of field workings makes it possible to shift zones of maximum stress concentration and thereby

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protect the structural elements of the mining layout [4]. In addition, high-energy methods of rock mass impact, such as hydraulic fracturing, provide additional opportunities for controlling the behavior of difficult-to-cave roofs [11].

In recent years, considerable attention has been paid to improving ore recovery technologies in caving mining systems [12, 13]. The efficiency of ore extraction from barrier pillars depends not only on the geological characteristics of the deposit, but also on the configuration of mine workings and the interaction between the fragmented ore mass and the surrounding rocks. Practical experience from underground mines shows that even minor changes in the location of production openings can significantly affect ore losses, dilution, and the overall economic performance of mining operations [14]. Therefore, the optimization of mining layouts remains an important scientific and engineering task.

The application of grapho-analytical methods provides an effective tool for investigating ore flow behavior under various mining and geological conditions. Unlike purely numerical approaches, grapho-analytical modeling enables the visualization of draw zones, the identification of stagnant areas, and the assessment of the influence of excavation geometry on extraction indicators [12, 15]. Such methods are particularly useful at the preliminary design stage, when rapid evaluation of several technological alternatives is required. Moreover, graphical models can serve as a basis for subsequent geomechanical analysis and engineering decision-making.

For inclined ore bodies, determining the optimal position of drill-haulage drifts is especially important, since gravity-driven ore movement is strongly affected by the deposit dip angle [13, 16]. As the dip angle increases, the geometry of ore flow zones changes considerably, which may influence both recovery efficiency and the stability of mining structures. Consequently, identifying rational displacement parameters for drill-haulage drifts is essential for achieving a balance between maximum ore recovery and geotechnical safety.

Despite the considerable amount of accumulated research data, issues related to the grapho-analytical optimization of left-asymmetric DDW displacement parameters for different ore body thicknesses of 6-12 m remain insufficiently studied. Therefore, the objective of this study is to determine rational parameters for the left-asymmetric displacement of drill-haulage drifts located beneath the barrier pillar and to assess their influence on ore recovery and geomechanical stability under various mining and geological conditions. The obtained results are intended to provide a scientific basis for optimizing field-preparation schemes and improving the efficiency of ore extraction from barrier pillars within caving zones.

2. Study area and proposed mining technology

Considering the current mining conditions at the Zhezkazgan deposit and the specific features of intact ore bodies located within the caving zone, the use of an underground mining technology based on a continuous caving system with end discharge of ore is proposed [3, 10]. This recommendation is based on the analysis of mining experience under similar geological and geotechnical conditions. Further testing of the proposed underground technology is planned at the Annenskaya mine of VZhR [4, 8, 11, 12].

According to the proposed technology, the extraction of intact ore bodies within the caving zone does not involve the formation of a conventional stoping chamber. Therefore, direct access of personnel and mining equipment to the unsupported stoping space is excluded. Safe mining operations are ensured by driving small-cross-section drill-haulage drifts (DDW), which allow the installation of rock bolts [13] and, where required, additional support using steel arch frames made of SVP-22 special profiles [9]. These workings provide access for drilling fan-shaped borehole patterns for ore breaking, as well as for loading and transporting the broken rock mass to the local ore pass.

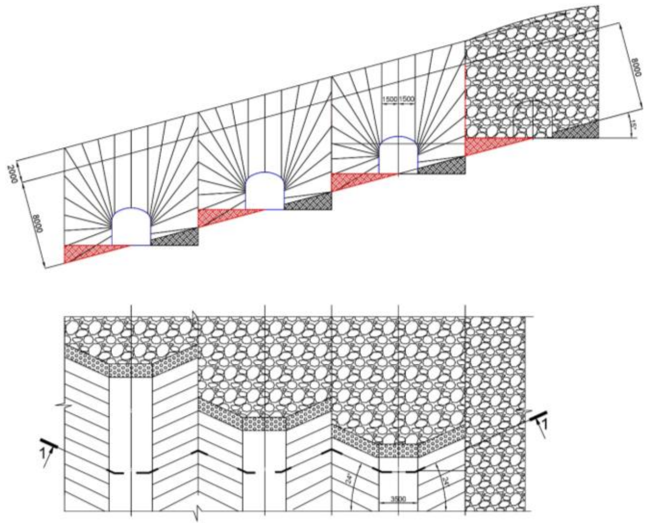

Figure 1. General view of the proposed technology for mining intact ore bodies using a continuous caving system with end discharge of ore mass within the caving zone: drilling pattern of fan-shaped boreholes in three planes and placement of the DDW along the ore–rock contact on the footwall side of the deposit

As shown in Figure 1, the proposed technological scheme is intended for inclined ore bodies with dip angles greater than 15° and thicknesses ranging from 6 to 12 m. The extraction block is formed along the strike of the ore body within a designated area up to 12 m wide. The DDW is driven along the ore–rock contact on the footwall side of the deposit. The drift is supported by rock bolts and, if necessary, by steel arch frames made of SVP-22 special profiles. Vertical fan-shaped boreholes are drilled from the roof and sidewalls of the DDW, while inclined fans are drilled to form a triangular undercut. After drilling, one fan of boreholes is blasted, followed by ventilation of the block. According to the end-discharge technology, the broken ore and host rock are then loaded and transported by self-propelled LHD equipment to the local ore pass.

The DDW is advanced section by section. Drilling-and-blasting operations are carried out in parallel with preparatory and cutting operations in subsequent DDW sections, while the broken rock mass is discharged accordingly. At the beginning of operations and throughout each working shift, all safety measures aimed at identifying and eliminating hazardous situations within the technological area must be strictly observed under the constant supervision of the shift foreman.

To extract reserves remaining in intact ore bodies, underground mining is therefore proposed using a continuous caving system with end discharge of ore and host rock [3, 10]. In this system, the block height is assumed to be equal to the ore body thickness, while the thickness of the caved ore layer is taken as equal to the line of least resistance of the blasted borehole fan. To reduce the seismic effect of blasting, one fan is detonated at short-delay intervals.

For preparatory operations, drill-haulage drifts are used for each panel within the block. Depending on mining and geotechnical conditions, the DDW may be driven either without additional support or with rock-bolt reinforcement combined with steel arch-frame support made of SVP-22 special profiles [9].

3. Research methods

The research methodology is based on grapho-analytical modeling aimed at justifying the rational parameters for the location of drill-haulage drifts (DDW) driven in the rock mass beneath the floor of barrier pillars (BP). The main focus of the study is to determine the rational magnitude of the left-asymmetric displacement of the DDW axis relative to the central axis of the BP. Such displacement makes it possible to adapt the technological scheme to the conditions of inclined ore bodies and to reduce the negative influence of the caving zone on the stability of preparatory workings.

To achieve this objective, a series of graphical models was developed for a wide range of mining and geological conditions. The variable parameters included ore body thicknesses of 6, 8, and 10 m at dip angles of 15°, 20°, and 30°. Particular attention was also paid to ore bodies with a thickness of 12 m, for which the range of analysis was extended to dip angles of 40° and 51°. This made it possible to evaluate changes in ore drawing conditions during the transition from gently inclined to steeply inclined ore bodies. During the modeling process, the displacement of the DDW axis relative to the BP axis was varied from 1 to 4 m with an increment of 1 m.

The optimization procedure was based on a comprehensive analysis of the geometry of the formed ore-drawing funnels and the corresponding slope angles of the caved rock mass. During graphical construction, the DDW positions were determined to ensure the most favorable relationship between ore recovery indicators and the safety of preparatory workings. Particular attention was paid to maintaining a stable stress-strain state (SSS) of the surrounding rock mass and preventing a critical reduction in the protective rock layer between the DDW roof and the floor of the stoping space.

At the final stage of the study, the obtained graphical solutions were generalized and the rational parameters of left-asymmetric DDW displacement were determined for different combinations of ore body thickness and deposit dip angle. These parameters were further used to substantiate the effectiveness of the selected geometric proportions of outlet workings during the repeated extraction of reserves from barrier pillars within the caving zone.

Thus, the proposed methodological approach makes it possible to compare alternative DDW displacement schemes, identify rational geometric parameters for different mining and geological conditions, and provide a basis for further graphical interpretation of the obtained optimization results.

4. Results and discussion

The grapho-analytical study was carried out to optimize the location parameters of drill-haulage drifts (DDW) driven in the rock mass beneath the floor of barrier pillars (BP). The analysis covered ore body thicknesses of 6, 8, and 10 m at dip angles of 15°, 20°, and 30°. In addition, for ore bodies with a thickness of 12 m, the study was extended to dip angles of 15°, 20°, 30°, 40°, and 51°. This made it possible to evaluate the influence of ore body geometry on the rational displacement of the DDW axis under different mining and geological conditions.

At the first stage, graphical models were developed for several variants of left-asymmetric DDW displacement relative to the BP axis. The displacement values were taken as 1, 2, 3, and 4 m in the direction of the ore body dip. An example of such graphical constructions for an ore body thickness of 6 m is shown in Figure 2. These schemes made it possible to compare the geometry of the formed ore-drawing funnels, the position of stagnant zones, and the relationship between the DDW roof and the floor of the stoping space.

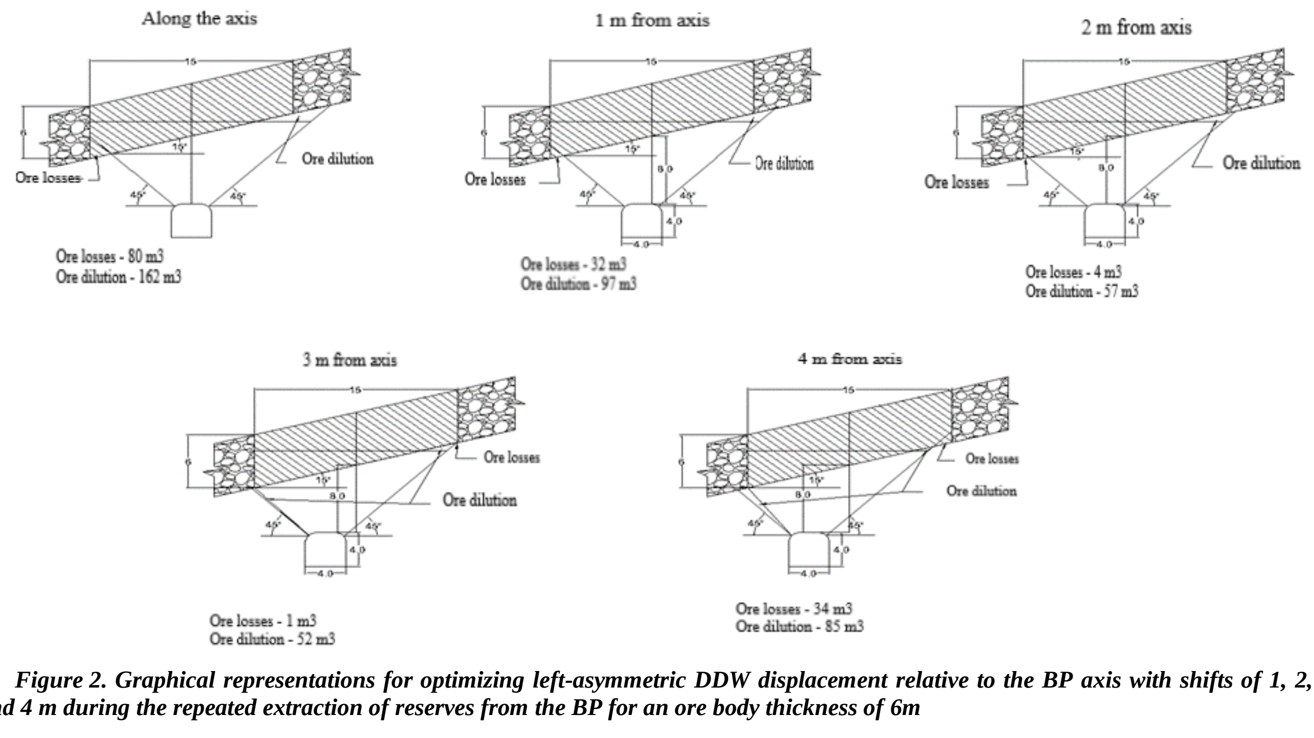

Figure 2. Graphical representations for optimizing left-asymmetric DDW displacement relative to the BP axis with shifts of 1, 2, 3, and 4 m during the repeated extraction of reserves from the BP for an ore body thickness of 6m

The obtained graphical results show that the displacement of the DDW axis has a nonlinear influence on the efficiency of ore drawing. A small displacement of 1 m does not always provide a sufficient correction of the ore flow geometry in inclined deposits, especially when the dip angle causes noticeable asymmetry in the movement of the broken ore mass. In contrast, excessive displacement of 3-4 m leads to distortion of the ore-drawing funnel, displacement of stagnant zones, and an increased risk of ore losses and dilution. Therefore, the DDW position cannot be selected only on the basis of maximum approach to the ore body; it must also take into account the stability of the surrounding rock mass and the preservation of a sufficient protective layer above the working.

The most favorable results were obtained when the DDW axis was shifted by approximately 1.5-2.0 m from the BP axis in the direction of the deposit dip. Within this interval, the geometry of the ore-drawing funnel remains technologically acceptable, while the protective rock layer between the DDW roof and the floor of the stoping space is not critically reduced. This provides a rational balance between ore recovery, dilution control, and geomechanical stability of preparatory workings.

Based on the graphical analysis, a left-asymmetric DDW shift of 2 m from the BP axis was adopted as the rational technological solution for the considered inclined deposits with dip angles up to 30°. The corresponding optimized parameters are presented in Figure 3a-f.

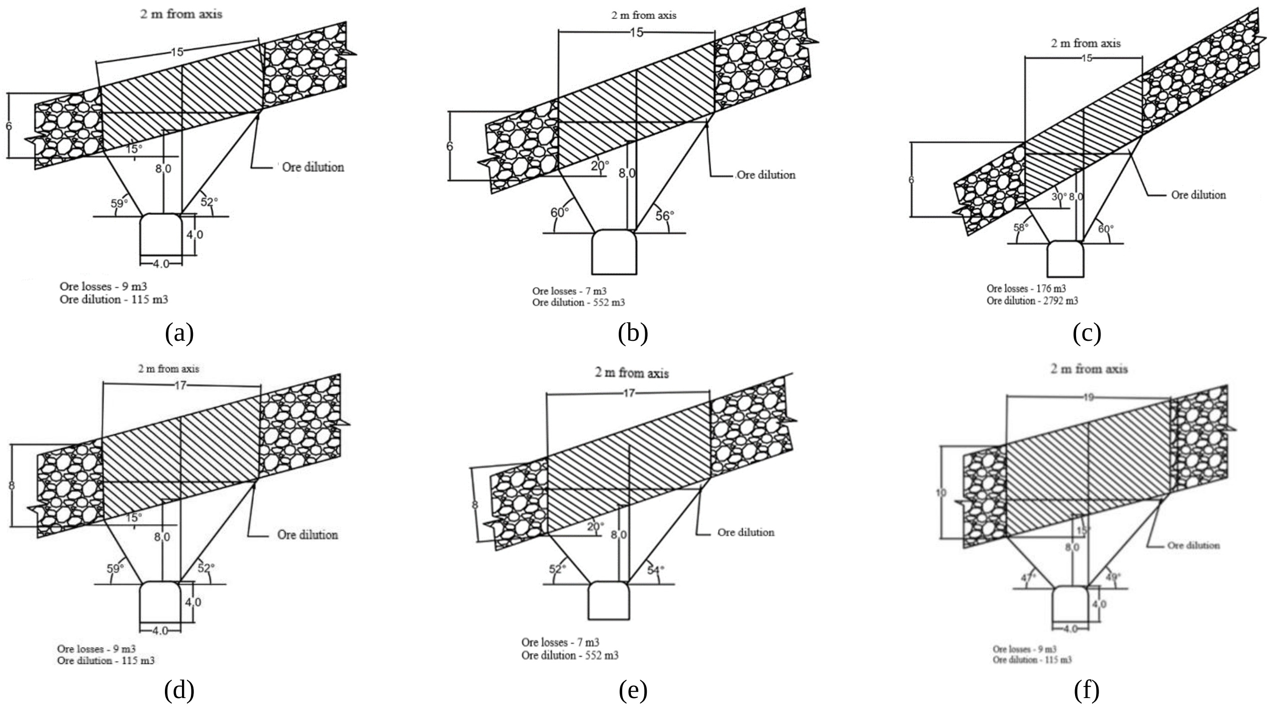

Figure 3. Optimal technological parameters for a left-asymmetric DDW shift of 2 m from the BP axis and the corresponding slope angles of the waste-rock outlet funnel: (a) ore body thickness of 6 m and deposit dip angle of 15°; (b) ore body thickness of 6 m and deposit dip angle of 20°; (c) ore body thickness of 6 m and deposit dip angle of 30°; (d) ore body thickness of 8 m and deposit dip angle of 15°; (e) ore body thickness of 8 m and deposit dip angle of 20°; (f) ore body thickness of 10 m and deposit dip angle of 15°

The comparison of the graphical schemes confirms that the practical efficiency of left-asymmetric DDW placement is most pronounced for inclined ore bodies with dip angles of 15-30°. Under these conditions, the ore mass movement is affected both by gravity and by the spatial configuration of the outlet workings. Therefore, a rational shift of the DDW axis makes it possible to improve the formation of the drawing funnel and reduce the probability of stagnant zones in the broken rock mass.

At the same time, an increase in DDW displacement beyond 2 m is not technologically justified in most of the considered cases. Although such displacement may locally modify the ore drawing conditions, it causes an unfavorable approach of the DDW roof to the floor of the stoping space. This reduces the thickness of the protective rock layer and may destabilize the stress-strain state (SSS) of the surrounding rock mass. If a shift greater than 2 m is required, additional vertical deepening of the DDW becomes necessary. Such a solution can partially restore geomechanical safety, but it also increases the volume of development in waste rock and, consequently, the cost of mining operations.

For steeply inclined ore bodies with dip angles of 40° and 51°, the influence of asymmetric DDW displacement decreases. Under these conditions, gravity-controlled ore flow becomes dominant, and the drawing process tends toward a more symmetrical vertical discharge pattern. As a result, the practical significance of shifting the DDW from the BP axis is reduced, while the additional costs associated with asymmetric preparation become less justified.

Thus, the results of the grapho-analytical study confirm that the rational displacement of the DDW axis depends on the combined influence of ore body thickness, deposit dip angle, ore-drawing funnel geometry, and the geomechanical condition of the surrounding rock mass. For the considered mining conditions, the most reasonable technological solution is a left-asymmetric DDW shift of 1.5-2.0 m, with 2 m adopted as the optimal design value for deposits with dip angles up to 30°.

5. Conclusions

Based on the conducted grapho-analytical study, rational parameters for the left-asymmetric displacement of drill-haulage drifts during the repeated extraction of reserves from barrier pillars in inclined ore bodies were substantiated. The analysis considered the combined influence of ore body thickness, deposit dip angle, ore-drawing funnel geometry, and the geomechanical stability of preparatory workings.

It was established that the displacement of the DDW axis relative to the BP axis has a nonlinear effect on ore drawing conditions. Insufficient displacement does not fully compensate for the asymmetric movement of the broken ore mass in inclined deposits, whereas excessive displacement distorts the geometry of the drawing funnel, increases the probability of stagnant zones, and may lead to higher ore losses and dilution.

The rational interval of DDW displacement was determined to be 1.5-2.0 m from the BP axis in the direction of the ore body dip. This interval provides the most favorable balance between ore recovery, dilution control, and preservation of a stable stress-strain state of the surrounding rock mass. For practical design purposes, a left-asymmetric shift of 2 m can be adopted as the optimal technological parameter for inclined ore bodies with dip angles up to 30°.

It was shown that a DDW shift greater than 2 m is generally not advisable without additional vertical deepening of the working. Although such deepening may improve the geomechanical position of the drift, it increases the volume of development in waste rock and therefore leads to higher mining costs. The efficiency of the proposed asymmetric preparation scheme decreases as the deposit dip angle increases. For steeply inclined ore bodies with dip angles of 40-51°, gravity-controlled ore flow becomes dominant, and the need for DDW displacement from the BP axis is significantly reduced. Therefore, the proposed recommendations are most applicable to inclined deposits with dip angles of 15°–30°.

The obtained results can be used to improve field-preparation schemes, increase ore recovery, reduce dilution, and maintain the geomechanical stability of workings during barrier pillar extraction.

Author contributions

Conceptualization: BDK, ZRK; Data curation: BDK, ZRK; Formal analysis: OMN; Funding acquisition: ZRK, OMN; Investigation: BDK; Methodology: ZRK, OMN; Project administration: BDK; Resources: ZRK, OMN; Software: BDK, ZRK, OMN; Supervision: BDK, ZRK, OMN; Validation: ZRK, OMN; Visualization: BDK, ZRK; Writing – original, draft: BDK, ZRK, OMN; Writing – review & editing: ZRK, OMN, ASA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Еңіс кен денелерін опырылу жағдайында далалық дайындау кезінде тосқауыл кентіректерден кенді шығару параметрлерін графоаналитикалық оңтайландыру

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Аңдатпа. Мақалада опырылу жағдайында еңіс кенді шоғырлардағы тосқауыл кентіректерден (ТК) кен шығарудың технологиялық параметрлерін оңтайландыруға бағытталған графоаналитикалық зерттеу нәтижелері ұсынылған. Тосқауыл кентіректерде қалдырылған қорларды игеру жерасты кен өндірудегі ең күрделі міндеттердің бірі болып табылады, өйткені ол кенді барынша толық алуды және қоршаған тау жыныстары массивінің геомеханикалық тұрақтылығын сақтауды қатар қамтамасыз етуді талап етеді. Опырылу аймақтарында далалық дайындау кезінде бұрғылау-жеткізу қазбаларының (БЖҚ) ұтымды кеңістіктік орналасуын негіздеуге ерекше назар аударылған. Зерттеу әдістемесі әртүрлі тау-кен-геологиялық жағдайларда кен шығару процестерін геометриялық және графоаналитикалық модельдеуге негізделген. Қуаты 6–12 м аралығындағы кен денелері және 15°-тан 51°-қа дейінгі құлау бұрыштары қарастырылды. Кенді алу тиімділігіне, шығындарға, құнарсыздануға және қоршаған тау жыныстары массивінің кернеулі-деформацияланған күйіне (КДК) әсерін анықтау мақсатында БЖҚ осін тосқауыл кентіректің орталық осіне қатысты сол жақ асимметриялық ығыстырудың бірнеше нұсқалары талданды. Нәтижелер БЖҚ осінің ығысуы кенді алу көрсеткіштеріне де, геомеханикалық қауіпсіздікке де айтарлықтай әсер ететінін көрсетеді. Ығыстырудың ұтымды аралығы кен денесінің құлау бағыты бойынша 1.5–2.0 м құрайды. Ығыстыруды одан әрі арттыру жанас жыныстардың КДК-нің нашарлауына, қазба төбесі мен тазарту кеңістігінің табаны арасындағы қорғаныш тау жынысы қабатының азаюына, сондай-ақ тау-кен қазбаларын қосымша тереңдету қажеттілігіне әкеледі. Мұндай өзгерістер бос жыныстар бойынша қазба жүргізу көлемін ұлғайтып, тиісінше кен өндіру шығындарын арттырады. Қазбаларды асимметриялық орналастырудың тиімділігі құлау бұрыштары 30°-қа дейін болған жағдайда анағұрлым айқын байқалады, ал құлау бұрыштары 40–51° болатын тік кен денелері үшін оның практикалық маңызы кен массасының гравитациялық ағынының басым болуына байланысты төмендейді. Алынған нәтижелер дайындау сұлбаларын жетілдірудің ғылыми негізін қалыптастырады және тосқауыл кентіректерден қорларды игеру кезінде кенді алуды арттыру, шығындар мен құнарсыздануды азайту, сондай-ақ қазбалардың геомеханикалық тұрақтылығын қамтамасыз ету мақсатында жерасты игеру жүйелерін жобалауда қолданылуы мүмкін.

Негізгі сөздер: *тосқауыл кентірек, еңіс кен денесі, кенді шығару, бұрғылау-жеткізу қазбасы, опырылу аймағы, графоаналитикалық модельдеу, кернеулі-деформацияланған күй.*

Графоаналитическая оптимизация параметров выпуска руды из барьерных целиков при полевой подготовке наклонных залежей в условиях обрушения

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Аннотация. В статье представлены результаты графоаналитического исследования, направленного на оптимизацию технологических параметров выпуска руды из барьерных целиков (БЦ) в наклонных рудных залежах в условиях обрушения. Извлечение запасов, оставленных в барьерных целиках, является одной из наиболее сложных задач подземной разработки, поскольку требует обеспечения баланса между максимальным извлечением руды и сохранением геомеханической устойчивости окружающего породного массива. Особое внимание уделено обоснованию рационального пространственного положения буродоставочных выработок (БДВ) при полевой подготовке в зонах обрушения. Методика исследования основана на геометрическом и графоаналитическом моделировании процессов выпуска руды при различных горно-геологических условиях. Рассмотрены мощности рудных тел от 6 до 12 м и углы падения от 15° до 51°. Проанализированы несколько вариантов левоасимметричного смещения оси БДВ относительно центральной оси барьерного целика с целью определения их влияния на эффективность извлечения руды, потери, разубоживание и напряженно-деформированное состояние (НДС) окружающего породного массива. Результаты показывают, что смещение оси БДВ существенно влияет как на показатели извлечения, так и на геомеханическую безопасность. Рациональный интервал смещения составляет 1,5-2,0 м в направлении падения рудного тела. Дальнейшее увеличение смещения приводит к ухудшению НДС вмещающих пород, уменьшению защитного породного слоя между кровлей выработки и почвой очистного пространства, а также к необходимости дополнительного заглубления горных выработок. Такие изменения увеличивают объем проходки по пустым породам и, соответственно, повышают затраты на добычу. Эффективность асимметричного расположения выработок наиболее выражена при углах падения до 30°, тогда как для более крутых рудных тел с углами падения 40-51° его практическое значение снижается вследствие преобладания гравитационно обусловленного потока рудной массы. Полученные результаты формируют научную основу для совершенствования схем подготовки и могут быть использованы при проектировании подземных систем разработки с целью повышения извлечения руды, снижения потерь и разубоживания, а также обеспечения геомеханической устойчивости выработок при отработке запасов из барьерных целиков.

Ключевые слова: *барьерный целик, наклонная залежь, выпуск руды, буродоставочная выработка, зона обрушения, графоаналитическое моделирование, напряженно-деформированное состояние.*

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CONTENTS

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