ГІРНИЧИЙ ВІСНИК

Заснований у 1966 році
Періодичність випуску: 2 рази на рік

Том 58, № 2

Кривий Ріг
2024

ISSN 2306-5435
УДК 622

DOI: 10.31721/2306-5435-2024-2

Засновник:
Криворізький національний університет

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Криворізького національного університету
(протокол № 6 від 24 грудня 2024 р.)

Державна реєстрація:
Ідентифікатор медіа R30-04964.
Рішення Національної ради України з питань телебачення
і радіомовлення № 1501, протокол № 15 (09.05.2024 р.)

Науковий журнал включено до категорії «Б» Переліку наукових фахових видань України.
Спеціальності: 121 – Інженерія програмного забезпечення, 122 – Комп'ютерні науки, 123 – Комп'ютерна інженерія, 131 – Прикладна механіка, 133 – Галузеве машинобудування, 136 – Металургія, 151 – Автоматизація та комп'ютерно-інтегровані технології, 183 – Технології захисту навколишнього середовища, 184 – Гірництво, 192 – Будівництво та цивільна інженерія, 193 – Геодезія та землеустрій, 263 – Цивільна безпека, 274 – Автомобільний транспорт, 275 – Транспортні технології (за видами)
(наказ МОН України від 17 березня 2020 року № 409)

Журнал індексується в наукометричних базах даних:
Національна бібліотека України імені В. І. Вернадського (НБУВ), Google Академія, Інститут проблем реєстрації інформації Національної академії наук України, Dimensions, Бібліотека Університету Осло, Litmaps, Ulrichsweb, Open Ukrainian Citation Index (OUCI)

Контактна адреса:
Криворізький національний університет
50027, вул. В. Матусевича, 11, м. Кривий Ріг, Україна
E-mail: info@mining-journal.com.ua
https://mining-journal.com.ua/uk

MINING JOURNAL
of Kryvyi Rih National University

Founded in 1966
Frequency: 2 times a year

Volume 58, No. 2

Kryvyi Rih
2024

ISSN 2306-5435
UDC 622

DOI: 10.31721/2306-5435-2024-2

Founder:
Kryvyi Rih National University

Recommended for printing and distribution
via the Internet by the Academic Council
of Kryvyi Rih National University
(Minutes No. 6 of December 24, 2024)

State Registration:
Media identifier R30-04964.
Decision of the National Council of Television
and Radio Broadcasting of Ukraine No. 1501, Minutes No. 15, dated 09.05.2024

The scientific journal is included in category "B" of the List of scientific specialized publications of Ukraine.
Specialties: 0532 – Earth sciences, 0613 – Software and applications development and analysis, 0712 – Environmental protection technology, 0714 – Electronics and automation, 0715 – Mechanics and metal trades, 0724 – Mining and extraction, 0732 – Building and civil engineering, 1032 – Protection of persons and property, 1041 – Transport services

The journal is indexed in databases:
Vernadsky National Library of Ukraine (VNLU), Google Scholar, Institute of Information Registration Problems of the National Academy of Sciences of Ukraine, Dimensions, University of Oslo Library, Litmaps, Ulrichsweb, Open Ukrainian Citation Index (OUCI)

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E-mail: info@mining-journal.com.ua
https://mining-journal.com.ua/en

Редакційна колегія

Editorial Board

Зміст / Contents

Journal homepage: https://mining-journal.com.ua/en

MINING JOURNAL
of Kryvyi Rih National University

Vol. 58, No. 2, 2024

Received: 29.07.2024; Revised: 15.10.2024; Accepted: 24.12.2024

UDC 622.349:004.4.056.54

DOI: 10.31721/2306-5435-2024-2-10-20

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Opportunities and advantages of GIS for building three-dimensional models in mining

Abstract. The relevance of the study is driven by the need to optimise mining, monitoring and risk management, which requires the rapid introduction of advanced technologies to ensure the sustainable development of the mining industry. The purpose of this study was to analyse a new approach to the use of geographic information systems. The methods used include observation, description, comparison, modelling and other methods. The study analysed a new approach to the use of geographic information systems in mining to build three-dimensional models. By implementing this methodology in mining practice in Ukraine, significant positive changes have been achieved: the risks of emergencies have been reduced, mining processes have been optimised, and overall productivity has increased. It has also been shown that the use of geographic information systems can increase the accuracy of mining planning and reduce the cost of mining operations. Compared to traditional modelling methods, the new GIS-based approach provides more accurate and reliable data on geological structures and mineral distribution. The study has confirmed that the introduction of such technologies can significantly increase the competitiveness of mining companies by providing them with tools for more accurate forecasting and management of mining processes. The practical significance of this study is to establish an effective method of using geographic information systems to build three-dimensional models in mining, which opens new opportunities to improve the efficiency and safety of mining operations, in particular in Ukraine, contributing to the sustainable development of the industry and the country's economy

Keywords: exploration network; technology; mining; minerals; computer modelling; maps

Introduction

The study of the use of geographic information systems (GIS) in mining is extremely important in terms of improving the efficiency and safety of mining operations, which are key aspects for the sustainable development of the industry. GIS enables the analysis, modelling and forecasting of various geological and mining processes, which allows for optimising mine locations, planning to mine operations, monitoring the environment and managing risks. Given the strategic importance of mining for the country's economy, the development, and improvement of GIS applications in this area is essential for the competitiveness and sustainable development of the mining industry. The research was aimed at identifying the optimal methods of using GIS to build three-dimensional models in mining to improve the efficiency and safety of mining operations. This involves

Suggested Citation:
Kunytska, M. (2024). Opportunities and advantages of GIS for building three-dimensional models in mining. *Mining Journal of Kryvyi Rih National University*, 58(2), 10-20. doi: 10.31721/2306-5435-2024-2-10-20.

*Corresponding author

developing and implementing new technologies for accurate geological structure modelling, mineral resource identification, and mining process optimisation. It also includes establishing methods for monitoring and risk management. It should be borne in mind that the methods of using geographic information systems in mining need to be adapted to the conditions of specific regions, including Ukraine, due to its unique geological and geographical features. For example, when implementing such methods in mining projects in the Carpathians, it is necessary to consider the peculiarities of the mountainous terrain and the location of water sources, which may affect the risks of environmental disruption and employee safety. In addition, in areas with high seismic activity, such as the western regions of Ukraine, it is important to develop methods that consider the possible effects of earthquakes on mining facilities and infrastructure.

According to the study by N. Zuievska & T. Hrebeniuk (2024), the integration of geographic information systems in mining helps to reduce risks and improve the accuracy of mineral location. This integration allows miners to plan their work more efficiently, avoid unforeseen situations and optimise mining processes. The study highlighted the importance of using modern technologies to increase productivity and safety in mining. In their work, S. Andrieiev *et al*. (2021) investigated the need to develop new methods for analysing geographic data to build three-dimensional models in mining. Existing data analysis methods may not be effective enough to fully utilise geographic information in mining. The study highlighted the importance of finding new approaches to processing and analysing geographic data to build more accurate and reliable three-dimensional models in mining.

The study by E. Ivanov *et al*. (2023) examines the importance of using geographic information systems to optimise the location of mining facilities and planning of mining operations. The use of GIS allows for more efficient placement of mining infrastructure, reducing costs and risks. The study emphasised the importance of GIS as a tool for improving the efficiency of mining operations and reducing the negative impact on the environment. Yu. Velikodsky *et al*. (2023) point out the possibilities of using GIS to monitor and reduce the environmental impact of mining. GIS can be a powerful tool for systematically tracking changes in the natural environment and effectively managing the impact of mining activities. The study emphasised the importance of introducing GIS into mining to ensure sustainable development and conservation of natural resources.

A study conducted by M. Lubishtani & F.B. Lubishtani (2024) highlights the use of GIS in optimising the selection of locations for solar and wind power plants. By analysing geodetic parameters, such as elevation, land cover, and geographic coordinates, GIS aids in identifying the most suitable areas for energy installations. The integration of GIS in decision-making processes enhances the efficiency of site selection, leading to more effective management of renewable energy projects. The study underscores the importance of modern technologies, such as GIS, for improving the accuracy of planning and maximising the potential of renewable energy resources. In the work of B. Sobko *et al*. (2021), the authors explored the possibilities of using geographic information systems to reduce mining costs and optimise resource use. GIS can be effectively used to plan mining routes, locate infrastructure, and optimise workflows in mining. The study highlighted the importance of using modern technologies, such as GIS, to ensure effective management of mining projects and reduce their costs.

The purpose of this study was to evaluate a new approach to using geographic information systems to create three-dimensional models in mining to improve the productivity and safety of mining operations in Ukraine.

Materials and Methods

The Surpac integrated system enabled the creation of a digital deposit model, taking into account the latest advancements in geotechnology, and streamlined the process of identifying an efficient method for volumetric modelling of mining objects in open-pit operations. Geostatistical 3D modelling comprised various essential steps: establishment of a database, creation of a geometric orebody model, composition and delineation, statistical analysis, block modelling, and resource estimation. Additionally, by integrating with other software tools, Surpac became part of an advanced mining automation system, enhancing the efficiency and accuracy of the production process. Block modelling generated a three-dimensional representation of the sites by filling in a three-dimensional wireframe and dividing the terrain into elementary blocks. The block model was then imported into GEOVIA MineSched for analysis, where mining zones were defined, and mining equipment was allocated. The structure of the block model is similar to a table, with each column representing an object's attributes and each row representing a record.

The method of observation used in the study was to track mining processes and their impact on the environment. This method allowed for the collection of thorough data on various aspects of mining activities, such as the size and nature of explosions, changes in geological structures, and the quality of materials produced. This information has been used to develop strategies to reduce the negative environmental impact of mining operations and improve the overall efficiency of natural resource use.

The description method was used to describe in detail each stage of the mining process, from prospecting for deposits to production and processing of minerals. This made it possible to understand the geological structure of the region, identify potential risks and determine the best strategies for their management. A detailed description of mining operations provided the basis for further analysis of the efficiency and safety of mining sites and helped to develop recommendations for their optimisation and improvement.

The benchmarking method helped to identify the advantages and disadvantages of different approaches to mining, including the use of geographic information systems. This allowed identifying the best methods and strategies that can be applied to improve the efficiency and safety of mining operations. In addition, the benchmarking method allowed defining potential opportunities for further development and improvement of mining technologies.

The modelling method was a useful tool for forecasting various scenarios for the development of mining operations and their environmental impact. The modelling method gave the possibility to develop virtual models of mining sites and operations, which allowed effectively determining optimal resource management strategies and minimising negative environmental impacts. Furthermore, the modelling method has become the basis for exploring the possibilities of introducing new technologies and approaches in mining.

The measurement method provided precise data on the geometry of deposits, their dimensions, and the location of various mining facilities. Laser scanning made it possible to create detailed three-dimensional models of mines, walls, ceilings and other elements of mining structures with high accuracy. Photogrammetry was used to examine photographs from different angles to measure the dimensions and distances between objects, while geodetic measurements helped to obtain data on heights, angles, and distances across the mine site. This precise data helped to build more detailed engineering solutions, improve planning of mining operations and reduce risks during operations. The use of measurement in mining has enabled a more complete understanding of the geometry of deposits and the efficient management of mining resources to achieve better results.

Results and Discussion

Geographic information systems are computer systems created to gather, store, analyse, and visualise geospatial data. Geospatial data includes information that has a spatial location on the earth's surface, such as geographical coordinates, heights, location of objects. GIS allows using this data for a variety of analytical operations, visualising geographical patterns and solving geospatial problems in various fields, including geology, geodesy, ecology, architecture, transport, and many others. GIS consists of three main components: hardware, software and data. Hardware includes the computers and other devices used to run GIS, such as personal computers, servers, and GPS. Software is used to collect, store, analyse and visualise geospatial data, including applications for creating and editing maps, analysing spatial relationships and modelling. The data used in GIS includes geographic coordinates, attribute data about objects, elevation data and satellite imagery, which are the main inputs for mapping and analysis. GIS works by integrating data from a variety of sources, such as maps, satellite imagery, GPS data and census data. This data is used to create maps, layers, and models that allow users to understand and analyse spatial relationships. GIS allows visualising data in the form of maps, edit and analyse geographic information to make management decisions, plan routes, determine optimal locations for facilities, and much more.

The principles of GIS can be summarised in three key aspects. GIS operates with spatial data, which means using information that is geographically located, such as map coordinates, geographical objects and their properties. Furthermore, GIS can analyse this data, revealing various patterns, relationships, and trends occurring in space. Finally, GIS allows for the visualisation of geospatial data in maps, models, or other visual representations, which helps users to better understand spatial relationships and make informed decisions. GIS diagrams represent different types of visual representation of geospatial data. There are several various types of GIS diagrams that are used to represent different aspects of geospatial information. Common types of GIS diagrams include point diagrams, which are used to display point data such as the location of trees or buildings; line diagrams, which are designed to represent linear features such as roads or rivers; and polygonal diagrams, which are used to display areas or zones such as countries or parcels of land. Each type of GIS schema has its own unique properties and applications in the analysis and visualisation of geodata. GIS offers several benefits that make them indispensable for a variety of activities. They increase efficiency by simplifying and automating tasks, which saves time and money and improves decision-making. GIS provides increased accuracy of analysis by giving users access to up-to-date and accurate data, which helps in making informed decisions. In addition, they facilitate communication by visualising geographic information on maps, which promotes better communication between project participants and facilitates easy collaboration.

Geographic information systems are used in many areas of activity, including mining, urban planning, forestry and agriculture (Shvorov *et al.*, 2018). GIS provides convenient and efficient tools for analysing and managing geographic information, helping to improve processes in these industries. In forestry, they are used to managing forest resources and monitoring forest fires. In agriculture, GIS helps with soil mapping, crop rotation planning and yield monitoring. In urban planning, they are used for city planning, infrastructure development and environmental monitoring. Geographical information systems offer great opportunities for miners to obtain detailed information about the location of various elements of mining infrastructure and mining deposits. Thanks to GIS, miners can analyse the location of various components of mining facilities in virtual space, which contributes to a better understanding of the geological features and structures of the territory (Krawczyk, 2023). This is important for effective planning and development of mining strategies, as it allows for a variety of geological and geomorphological conditions to be considered. In addition, GIS provides miners with an opportunity of considering various risk and safety factors in mining operations. Analysis of spatial data helps to identify potential hazards and determine the best ways to avoid or minimise them. This helps to improve the safety of working conditions and reduce the likelihood of accidents. Thanks to spatial analysis using GIS, miners can efficiently plan and execute various mining operations, optimising resource use and increasing mining productivity. In general, the use of GIS in mining allows for a deeper understanding of natural processes and maximising the potential of mining resources, contributing to the sustainable development of the industry.

One of the key benefits of visualisation is the ability to display complex geological structures in three dimensions. This gives miners the ability to virtually delve into the depths of the earth and explore the location of mineral deposits, which contributes to a better understanding of geological conditions and the formation of mining strategies. In addition, GIS visualisation allows miners to plan and manage mining operations more efficiently. By displaying various elements of mining infrastructure and production facilities on three-dimensional models, miners can carry out more accurate production planning, develop optimal mine layout strategies and development routes. By visualising data using GIS, miners can implement more transparent and predictable management of mining processes. Visualisation graphically displays complex geological and mining data, making it more understandable and accessible for analysis and decision-making (Yousefi *et al.*, 2021). Thus, visualisation of geological structures and mineral deposits using GIS is an integral part of efficient mining production, which contributes to increased productivity and reduced risks in the mining industry.

One of the main advantages of using GIS in modelling is the ability to display the location and structure of mineral deposits in three dimensions. This gives miners the ability to virtually explore the depth and size of rock deposits, which is key to developing mining strategies and determining the best mining methods. In addition, GIS provides miners with an opportunity of optimising mine locations and developing optimal mining strategies. The analysis of spatial data allows for a variety of factors, such as sediment depth, geometry, and geological properties, to be considered to determine the optimal location of infrastructure and equipment (Smith *et al.*, 2023). Finally, GIS can be used by miners to plan long-term investments in mining projects, considering the geological and geomorphological features of the area. Modelling the operation of deposits helps to make informed decisions on the development and operation of mining facilities, ensuring optimal use of resources and maximising product yields. Thus, GIS plays an important role in modelling the operation of mineral deposits, providing miners with the means to effectively plan and manage mining processes, which contributes to the increase in productivity and efficiency of mining production.

GIS allows for real-time tracking of various geological and hydrogeological processes that can be a source of risk to mining operations. For example, they can monitor ground movements, changes in topography and hydrogeological conditions, which can prevent the possibility of landslides, flooding or other negative events. GIS can analyse and predict risks associated with the location of mining infrastructure (Ruhela *et al.*, 2022). They help to determine the optimal locations for mines, equipment and other mining facilities, considering potential hazards. GIS can be used to predict and model different risk scenarios and develop risk management strategies. They can consider various factors, such as geological conditions, climatic factors and other variables that affect risk, which helps to develop effective measures to minimise risks and ensure safe working conditions in mining. Therefore, the use of GIS for monitoring and managing risks in mining is critical, as it helps to ensure safe working conditions, reduce the likelihood of hazardous situations and increase the efficiency of mining operations.

GIS allows miners to analyse the geographical and geological features of the region where mining infrastructure is planned to be located. This includes studying the terrain, geological structure, climatic conditions, as well as accessibility to transport networks and other infrastructure facilities. Analysing these factors helps miners determine the best locations for mining facilities. GIS allows modelling different scenarios of infrastructure placement and assessing their impact on various aspects of mining operations, such as productivity, safety, and cost-effectiveness (Hosseinpour *et al.*, 2022). This allows miners to make informed decisions about the best infrastructure location. Finally, the use of GIS in the process of optimising the location of mining infrastructure contributes to improved planning and management of mining operations. This makes possible the efficient use of resources, reduction of costs, and increased overall productivity of mining enterprises. Hence, GIS holds significance in optimising the positioning of mining infrastructure, assisting miners in making well-informed decisions regarding optimal locations. This ensures enhanced efficiency and competitiveness for mining companies.

GIS can automate certain operations that used to require considerable effort and time. For example, GIS can be used to automatically analyse geological data and determine the best locations for mining facilities. GIS can improve the planning and coordination of mining operations. This is achieved through the ability to create detailed three-dimensional models of mining facilities and their environment (Choi *et al.*, 2020). Such models allow miners to better understand the topography of the area, the location of minerals and other factors affecting mining processes, which in turn contributes to more accurate and efficient planning of operations. Finally, the use of GIS helps to reduce losses and optimise the use of resources in mining. GIS allows miners to track and control the movement of minerals, determine optimal transportation routes, and plan the use of equipment and labour. This helps to reduce costs and increase productivity of mining companies, which has a direct positive impact on their competitiveness and profitability. Therefore, the use of GIS in mining is a key factor in improving the efficiency of mining processes, which contributes to better management and workflows, reducing losses and optimising resource use.

Surface mining is a form of mining activity that takes place on the earth's surface and involves the operation of open pit mines. This type of mining activity is characterised by the fact that it takes place directly on or slightly below the surface of the earth, i.e. without the need for adits or shafts. Surface mining is a specific form of mining activity that takes place on or slightly below the surface of the earth. It encompasses a variety of mining activities conducted in the open, without the need for adits or shafts to access the minerals. Among the most common methods of open pit mining are quarries, open pits and surface mining. Quarries are large open pit mines where minerals are extracted directly from the surface of the earth. Open pits, in turn, are mining operations that also take place on the surface. Surface mining usually involves the extraction of metals such as gold, silver, copper, nickel and other minerals. These forms of open pit mining have their own specific features and requirements, but they are all characterised by openness and the absence of the need to construct mines or adits for mining. This method of exploitation has its advantages and limitations and is used in various mining industries for the extraction of various minerals. In open pit mining, there is no need to construct or operate adits or shafts, as mining operations take place directly on or slightly below the ground surface. This feature is a key difference from other mining methods, which often require the construction and operation of deep adits or shafts to access mineral resources. The absence of the need for adits or shafts in open pit mining simplifies the operation process and reduces the cost of building and maintaining mining infrastructure. Instead, minerals are extracted directly from open pits, quarries, or other open workings located on the surface of the earth. This feature makes open pit mining attractive to businesses, as it is often more efficient and cost-effective, especially when extracting large volumes of minerals. In addition, the absence of mines helps to reduce the environmental impact and risks associated with the construction and operation of mining infrastructure.

Large-scale operations are one of the key features of open-pit mining. This means that this method of mining allows large areas to be covered for the extraction of minerals such as coal, metals, or construction materials. One of the advantages of large-scale operations is their ability to provide large volumes of production, which makes them particularly attractive to the mining industry. This is particularly important when a large demand for minerals needs to be met or when there is a need to develop infrastructure for construction or other needs. Large-scale operations also allow for efficient use of resources, ensuring that the areas for mining are optimally utilised. This may include spreading a variety of mining operations over large areas to maximise productivity and efficiency. In addition, large-scale operations can contribute to economic benefits by ensuring that economies of scale arising from large volumes of production can be taken advantage of. This can help reduce mining costs and increase the profitability of mining projects.

Modelling and assessing the effectiveness of open-pit mining operations represent fundamental abilities within GIS. Leveraging GIS in this domain enables thorough analysis and enhancement of diverse facets within mining operations. Design organisations use digital systems to address various issues related to planning and designing surface mining operations. These digital systems include a variety of tools and features that empower mining engineers to construct and evaluate intricate geological models, evaluate economic viability, and formulate operational strategies for mining activities. One significant benefit of these digital systems is their capability to generate and expand geospatial information support. This assistance streamlines the development of detailed maps and diagrams of mining facilities, including the interactive generation of horizontal plans. Beyond geospatial data, these digital systems can also model and configure complex mine environments using various technical and economic data inputs.

Mining operations in the field can be illustrated using models of dynamic objects influenced by technical processes. Software automation utilises wireframe and block models of the deposit, which include data on the distribution of rock types and mineral composition in the mining area. These models also incorporate a borehole wireframe that offers detailed information about the surface structure (Kotenko & Kunytska, 2023). Based on this, the process of implementing a digital model for open-pit mining and its components is demonstrated through the development and analysis of a digital representation of a mineral deposit using a specialised integrated system. The core of the information-technological database is a three-dimensional digital model comprising various elements such as topographic surfaces, geological structures, site planning schemes, models of mineral block components, and additional digital attributes specific to open-pit mining (Fig. 1).

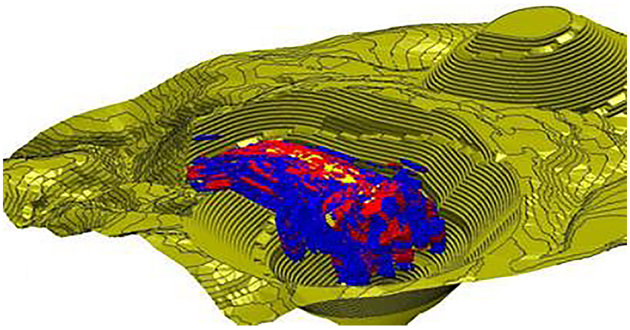

Figure 1. *Three-dimensional models depicting mineral deposits with diverse valuable components*
Source: *developed by the author*

The integrated Surpac system enables the creation of digital ore body models incorporating cutting-edge geotechnological advancements, facilitating the identification of efficient volumetric modelling methods for mining objects in open pit environments. Geostatistical 3D modelling involves several essential stages: establishing a database, geometrically modelling the ore body, defining its composition and boundaries, conducting statistical analysis, performing block modelling, and estimating resources. Moreover, Surpac has the capability to be integrated with other software tools within sophisticated mining automation systems, enhancing both the efficiency and precision of production processes.

The geological database serves as a critical component of the Surpac software, forming the foundation for all subsequent calculations and modelling tasks. Surpac utilises a relational database model that establishes connections between various information systems. The geological database comprises several tables, with the interface table (Table 1) and the study table (Table 2) being crucial for optimal functionality. The contiguity tables offer detailed information regarding the positions of drill holes, while the exploration tables provide data on the orientation and direction of these holes. These tables form the foundation for geological modelling, resource estimation, and mine planning. Surpac's geologic database can store a wide range of additional data types, such as assay results, petrologic descriptions, and geophysical data. Furthermore, the software enables users to generate and manage custom tables, ensuring that the geologic database can be customised to meet the specific requirements of each mining project.

Table 1. *Coordinates of the well entrance*

Hole_id	x	y	z	Maximum drilling depth	Path
371	52,498	71,061.21	388.1	40	curved
375	52,502.41	71,084.07	386.12	30.3	curved
382	52,524.07	71,045.16	387.11	35.5	curved

Source: *developed by the author based on M. Kunytska et al. (2023)*

Table 2. *Coordinates of points in the drilling space*

Hole_id	max	Dip	Azimuth
371	40	-90	0
375	30.3	-90	0
382	35.5	-90	0
387	35.2	-90	0
389	34	-90	0
390	34	-90	0
391	34	-90	0

Source: *developed by the author based on M. Kunytska et al. (2023)*

By utilising the "Help" feature, the anticipated geological database permits the generation of reports based on object location using coordinates, borehole depth, azimuth, and drilling angle for either specific boreholes or all available ones. Moreover, it simplifies the extraction of reports concerning tables and database information, offers data on minimum and maximum assigned coordinates, creates lithological columns in dwf format for chosen wells, and generates reports on intervals surpassing specified content thresholds.

The process of establishing weighted average intervals encompasses two primary phases. Initially, it entails identifying the positions of new intervals neighboring existing ones in the database using drill hole data. Subsequently, the second step entails computing the values of the new intervals acquired through compositing, thereby ascertaining the metal composition. The outlines of the ore body are delineated through the integration of compositional data gathered from individual drill holes. The wireframe model of the ore body is composed of interconnected polygonal shapes that form polygonal objects, with vertices aligning with existing string points. The combination of these triangles within the wireframe model constitutes the orebody, creating a completely enclosed structure.

The strategy for designing a wireframe model involves the creation of a triangulation of geological sections covering the longest distances in the longitudinal direction. The triangulation of all segments of these geological sections provides the framework of the orebody (Fig. 2). This geological body structure enables volume calculations considering the working horizon. Surpac streamlines triangulation and inverse distance methods, while grid operations facilitate the computation of mineral reserves.

Figure 2. *Ore deposit framework*
Source: *developed by the author*

Block modelling involves generating a three-dimensional representation of the site by using a 3D wireframe and partitioning it into fundamental blocks. Subsequently, the block model is imported into GEOVIA MineSched for assessment, where it is used to define the mining zones and allocate mining equipment. The block model is structured as a table, where columns represent site attributes and rows represent individual data entries (Fig. 3).

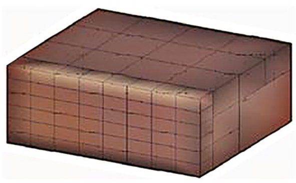

Figure 3. *Modelling objects using the block approach*
Source: *developed by the author*

The resultant block model visually illustrates the distribution of valuable components within the orebody through colour coding (Fig. 4). Creating histograms and modelling variograms assists in determining if the orebody should be segmented into homogeneous zones. The variogram considers parameters like thickness, slope, and strike of the orebody to identify spatial variations in heterogeneity.

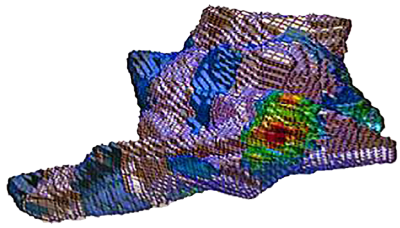

Figure 4. *Distribution of valuable components within the orebody*
Source: *developed by the author*

The dynamic aspect of the simulation involves tracking the displacements of fragmented material within the block model caused by explosions that lead to the formation of cracks in the rock mass (Fig. 5). Tracking particle movement offers insights into the dispersion of valuable components during fragmentation, thereby enhancing the reliability of data for addressing production challenges.

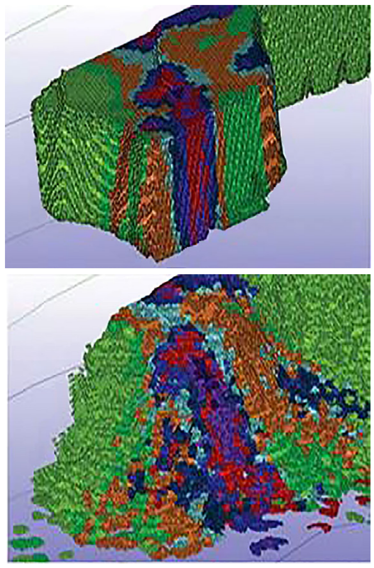

Figure 5. *Modelling of rock destruction by explosives*
Source: *developed by the author*

Therefore, the application of GIS is crucial in the planning, management, and monitoring of surface mining operations, contributing to their efficiency and sustainability. Geographical information systems play a significant role in the modern mining industry, providing extensive opportunities for building three-dimensional models that reflect the geological structures of a deposit and mining facilities. GIS allows building three-dimensional models with high accuracy and detail. With the help of geodetic data and geological information, models can be created that represent the topography, geological formations, mineral locations and mining structures with great accuracy. Three-dimensional models constructed in GIS enable miners to gain deeper insights into the geological composition of a deposit and strategise and streamline mining operations with greater efficiency. This helps to increase mining productivity and reduce resource consumption. Using three-dimensional models in GIS, it is possible to assess the risks associated with mining operations and take measures to prevent them. This helps to reduce the likelihood of accidents and incidents at mining sites and ensure the safety of employees. GIS enables efficient use of resources at all stages of the mining cycle. This encompasses planning the development of a deposit, controlling the operation of mining facilities, and optimising the processes of restoring the natural environment after mining operations. Three-dimensional models in GIS allow for a better understanding of the geological structure and structure of deposits, which can help identify new mineral deposits and plan further development of the mining industry. In summary, the use of GIS to build three-dimensional models in mining has several advantages that contribute to the efficiency, safety and economic viability of mining operations. They are becoming an important tool for modern mining production, allowing for a deeper understanding of geological processes and optimising mining operations.

According to the study by G. Szujó *et al.* (2023), the introduction of 3D web applications in the mining industry opens great opportunities to improve the productivity and efficiency of mining operations. These web-based applications allow for the creation of dynamic and interactive 3D models of mining facilities, deposits, and structures that can be viewed and analysed from any device with an internet connection. This approach allows miners, engineers, and management to instantly access critical information and make informed decisions about mining operations. These findings are consistent with the points made in the previous section. 3D web applications allow visualisation of the geological structure of deposits, which helps to identify new mineral deposits and plan optimal mining routes. Such applications can also recreate real mining conditions and situations, which allows for staff training in a virtual environment and increases the level of safety while working at the mine. In addition, 3D web applications can be used to monitor the status of equipment and production processes in real time, which allows for timely detection of problems and avoidance of unforeseen failures.

In conformity with a study by J. Yang *et al.* (2024), risk monitoring technologies at mining enterprises are becoming increasingly important in managing safety and improving mining efficiency. The use of advanced technologies, such as geoinformation systems, allows not only tracking potential risks but also managing them effectively. This means that companies can actively use these technologies to analyse and predict risks, which helps to avoid hazards and ensures a safer and more productive environment for workers and equipment. It is worth noting that one of the most promising technologies is the use of satellite imagery to monitor the condition of mining areas. The high-resolution images that can be obtained through this technology allow for timely detection of changes in the landscape, including landslides, erosion, and other potentially dangerous phenomena. Such data can be used to develop risk management strategies and prevent accidents.

Researchers Ya. Zheng *et al.* (2023) showed in the course of their work that the adaptation of the space industry for three-dimensional modelling of mineral prospects is an innovative approach that provides unique opportunities for studying and assessing geological structures and resources on the Earth's surface. Satellite data, such as high-resolution imagery and radar data, can be used to create three-dimensional models of mountain ranges, ore deposits and other natural formations. It can be agreed that this approach allows mining companies and research organisations to gain a more complete understanding of rock structure and resource distribution. It also helps to optimise exploration and development processes, reducing risks and improving mining efficiency. In addition, three-dimensional models based on satellite data can be used to predict potential finds and determine the best locations for drilling and subsequent production.

As noted by Yu. Cao *et al.* (2023), modelling and dynamic analysis of an integrated vertical transport system for deep-sea mining in three dimensions is an important aspect of the modern mining industry. This approach allows engineers and researchers to more effectively plan and manage mining operations at great depths, where traditional methods are not effective enough. By analysing the results and conclusions obtained, such models allow considering various aspects of production, including the geological structure of deposits, physical properties of rocks, pressure, and temperature conditions at depth, as well as technical parameters of the equipment and infrastructure used. Dynamic analysis allows predicting the behaviour of the system in different conditions and optimising its operation for maximum productivity and safety. This is especially relevant for mining in deepwater fields, where there is a risk of various man-made and environmental problems.

Researcher H. Fan *et al.* (2021) determined that a new model for three-dimensional deformation extraction using single-track interferometric radar sensing (InSAR) opens opportunities for researchers to more accurately monitor and analyse deformations resulting from mining operations. Single-track InSAR is based on the principle of radar interferometry and allows measuring changes in the distance between the satellite and the Earth's surface with high accuracy. InSAR works by measuring the interference between signals reflected from the Earth's surface, which are received at different times. This technique makes it possible to detect changes in the relief and movements of the Earth's surface with high accuracy. The advantages of InSAR include high resolution, the ability to monitor large areas and high sensitivity to micrometric changes. Compared to other methods, such as GPS or total station, InSAR can be more efficient and convenient for measuring changes in the terrain over a large area. InSAR technology has a wide range of applications, including detecting deformations in oil fields, studying tectonic movements, monitoring volcanic activity, analysing geological processes, and more. This makes it an indispensable technique for many research and practical applications in the field of land management and geoinformatics. In addition, this model provides information on the characteristics of subsidence in mining operations, such as the rate of movement of rock masses, the extent of deformation and its spatial distribution. Three-dimensional deformation extraction allows for a more complete and accurate assessment of the impact of mining operations on the environment and infrastructure, such as roads, buildings, and communications. This helps to reduce the risk of accidents and improve the planning and management of mining projects.

Conclusions

The study found that geographic information systems are extremely useful and effective tools for building three-dimensional models in mining. They made it possible to accurately visualise mining operations before they begin, which helped analyse potential risks and develop optimal mine exploitation strategies. This has reduced the likelihood of accidents and incidents at mining operations and helped to improve their efficiency and safety. Attempts were made to automate the detection of landslide hazard zones using the latest computer technology.

Consequently, the integrated Surpac system enables the generation of digital ore deposit models incorporating advanced geotechnologies, streamlines the identification of effective volumetric modelling methods for open pit mining objects, and enhances overall process efficiency and accuracy through integration with other software tools. In addition, GEOVIA MineSched's block modelling facilitates efficient analysis and allocation of mining equipment based on a three-dimensional representation of the object. One of the primary advantages of GIS in mining is its capability to generate intricate 3D models that accurately depict complex geological structures and mineral locations. This allows miners to understand the minefield and optimise mining processes to achieve maximum productivity and efficiency. Additionally, an important advantage of using GIS is its ability to integrate with other technologies, such as satellite imagery and automated control systems, which allows for a more complete and accurate view of mining processes and their management with great precision.

Overall, the study results confirmed the importance and prospects of using GIS in mining. These technologies have the potential to improve the safety, efficiency, and profitability of mining enterprises, making them an integral part of modern mining production. It is important to conduct additional research on the impact of the development of new technologies on the cost and availability of GIS for mining companies. Estimating costs and studying trends in this area will help to understand how technological progress can affect the cost of implementing and operating GIS in mining, as well as their overall accessibility for mining companies of different sizes and levels of technological development.

Acknowledgements

None.

Conflict of Interest

None.

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Можливості та переваги ГІС для побудови трьохвимірних моделей у гірництві

Анотація. Актуальність проведення дослідження зумовлена необхідністю оптимізації видобутку корисних копалин, моніторингу та управління ризиками, що вимагає швидкого впровадження передових технологій для забезпечення сталого розвитку гірничої промисловості. Метою даного дослідження був аналіз нового підходу до використання географічних інформаційних систем. Серед використаних методів слід зазначити метод спостереження, метод опису, метод порівняння, метод моделювання та інші. У рамках дослідження був проведений аналіз нового підходу до використання географічних інформаційних систем у гірництві для побудови тривимірних моделей. Шляхом впровадження цієї методики в гірничу практику в Україні досягнуті значні позитивні зміни: зменшено ризики надзвичайних ситуацій, оптимізовано процеси видобутку, підвищено загальну продуктивність. Також виявлено, що використання географічних інформаційних систем дозволяє збільшити точність планування гірничих робіт і знизити витрати на їх виконання. Порівняно з традиційними методами моделювання, новий підхід заснований на географічній інформаційній системі, і дозволяє отримувати більш точні та надійні дані про геологічні структури та розподіл корисних копалин. У результаті дослідження було підтверджено, що впровадження таких технологій може суттєво підвищити конкурентоспроможність гірничих підприємств, забезпечуючи їм інструменти для більш точного прогнозування та управління процесами видобутку. Практичне значення цього дослідження полягає в установленні ефективного методу застосування географічних інформаційних систем для побудови тривимірних моделей у гірництві, що відкриває нові можливості для підвищення ефективності та безпеки гірничих операцій, зокрема в Україні, сприяючи сталому розвитку галузі та економіки країни

Ключові слова: розвідувальна мережа; технології; видобуток; копалини; комп'ютерне моделювання; карти

Journal homepage: https://mining-journal.com.ua/en

MINING JOURNAL of Kryvyi Rih National University

Vol. 58, No. 2, 2024

Received: 05.08.2024; Revised: 11.11.2024; Accepted: 24.12.2024

UDC 622.271.012.3

DOI: 10.31721/2306-5435-2024-2-21-29

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Substantiation of the depth of the open pit employing the in-pit crushing and conveying technology as a determinant of the pit development at the subsequent stage of mining

Abstract. The constant increase in the depth of open pits employing the in-pit crushing and conveying technology applied to mining steeply dipping deposits causes an increase in the height of the ore lifting and transportation distance, and results in an increase in the cost of ore transportation to the surface. This, in turn, affects the depth of the subsequent stage of reconstruction of the pit transportation system. The present research aimed to substantiate the depth of the subsequent stage of iron ore pit mining applying the in-pit crushing and conveying technology using a generalising estimation figure for various consecutive time intervals during the stage-by-stage mining, which should improve the quality of design operations. The article employed methods of statistical-logical, causal and comparative analysis and the method of system-structural approach to determine the generalising figure for estimating the subsequent stage of mining by the in-pit crushing and conveying technology. When substantiating the depth of the subsequent stage of open pit reconstruction, the dependency was proposed to determine the maximum operating stripping ratio. The dependency takes into account the increase in transportation costs caused by the increased lifting height and the extension of the distance of transporting ore to crushing and reloading points of conveyor lifts located in the pit as a result of its deepening. In addition, the dependency of the position of the mined ore mass centre on the open pit depth was used in calculations. Considering the fact that in modern deep open pits, the volume of ore mined and transported by the truck-conveyor complex can reach 30 Mt annually, the search for ways to improve cargo flows of the pit transport complexes becomes one of the important designer tasks. In this connection, an estimated figure was proposed to determine the depth of the subsequent stage of mining the open pit employing the in-pit crushing and conveying technology complex, which takes into account the increased cost of ore transportation, the cost of marketable mineral products, and the current stripping ratio. At the same time, the increase in costs caused by the increased height of ore lifting due to mining deepening is taken into account to consider the increase in transport costs when designing further development of the in-pit crushing and conveying technology complex. In

Suggested Citation:
Kostyanski, O., & Zhukov, S. (2024). Substantiation of the depth of the open pit employing the in-pit crushing and conveying technology as a determinant of the pit development at the subsequent stage of mining. *Mining Journal of Kryvyi Rih National University*, 58(2), 21-29. doi: 10.31721/2306-5435-2024-2-21-29.

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the open pit, the depth of which is determined according to the proposed methodology, the value of the current stripping ratio will not exceed the maximum operational one at the subsequent stage. This approach allows quick estimation of the depth of an iron ore open pit that mines steep deposits when designing the subsequent stage of reconstruction to provide its breakeven finalisation

Keywords: open pit working; maximum operational stripping ratio; open pit deepening; mining step

Introduction

When developing modern iron ore open pits, large volumes of rock mass are excavated, this often amounting to more than 50 Mt annually. At that, a significant proportion of the mass is transported from deep horizons. The final depth of many iron ore open pits reaches 500-700 m. It should be noted that mining inclined and steep deposits by deep open pits is characterised by a number of features that influence the development of the open pit and transport complex. The main problem affecting open pit operations consists in the fact that working conditions of open pits are continuously complicated during the entire period of deposit development due to the increase in the operation depth, the height of the working zone and the current stripping ratio value. This results in a significant increase in the height of the mining lift by transport complexes and, as a consequence, an increase in a lifting cost share in ore extraction costs. The solution to the transportation problem in a difficult situation is most often found in the wide application of complexes of the in-pit crushing and conveying technology (ICCT).

According to A. Adamchuk (2021), the traditional ICCT scheme is as follows: the rock mass is transported by a truck from the face to the concentration level where a conveyor hopper with a primary crusher is installed. The costs of transporting the rock mass by dump trucks are higher than by an inclined conveyor, so to use combined truck and conveyor transport effectively, the reloading point should be relocated every 90-105 m deepwards over time. When mining operations go deeper, further deepening of the ICCT complex is provided to reduce the distance of ore transportation from lower levels to crushing and reloading points and the in-pit journey of vehicles usually at the subsequent stage of open pit development.

N. Sarybayev *et al.* (2021b) draw attention to the current trend in ICCT development that, when deepening mining operations, extraction of ore from deep horizons requires making adjustments in the design of the open pit transport system. Yu. Hryhoriev *et al.* (2021a) noted that in the past, application of the ICCT required consideration, but now mining-technical and technical-economic conditions require search for and substantiation of the choice of the most rational parameters and the dimension-type of extraction and loading equipment of road and conveyor transport. Thus, the present work focused on technological parameters of the in-pit crushing and conveying technology at iron ore open pits, neglecting the conditions of forming cargo flows to the ICCT reloading points.

V. Azarian (2019) argues that it is important to develop a comprehensive efficiency estimation of the quality management technology of a generalised complex of ore flows of a mining and concentration plant (GZK in Ukrainian) that links the actual volume of ore sent for concentration, the concentrate yielded from it and the cost of processing. But GZK profits are secured by not only the quality of the iron-bearing material of the flows, but also the functioning of the transport complex that forms ore flows to concentration plants, parameters of which depend on an open pit size. In this respect, V. Monastyrskyi & A. Smirnov (2021) studied ore flows in Kryvyi Rih open pits at M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine. However, the mentioned work considered heavy-duty trucks and belt conveyors of the ICCT, leaving the complex of the Inhulets Mining and Concentration Plant, one of the largest in Kryvyi Rih Basin, unaddressed.

O. Shustov *et al.* (2021) emphasised that the increase in mining costs caused by the growing depth of development affected the cost of transporting the rock mass and recommended that the cost of transporting the rock mass should be taken into account with the increasing value depending on the depth of mining. However, the transportation cost also depends on distribution of the transported rock mass relative to the working zone of the open pit, which also should be taken into account. Generally, the growing depth of mining operations in iron ore open pits leads to the increase in the transport distance; the share of ore mass transportation costs in the cost structure also increases steadily, adding to an inevitable increase in the ore cost and raising the question of practicability of further pit deepening.

Yu. Hryhoriev *et al.* (2021b) analysed the basic computational principles and techniques for determining the final boundaries of the open pit and identified the methods of Lerch-Grossman, the floating cone, Seymour, dynamic programming methods, special neural networks, graph theories, network flows and other approaches. Based on these methods, K-Mine, SurpacN-PVSheduler, Four-X, MineShed software packages, as well as integrated three-dimensional CAD systems (Gemcom, MineScape, Data-Vulcan, MineSight, etc.) are widely used. The shortcomings of the mentioned techniques include complexity of implementation, a large amount of input data, and lack of reliable means of method evaluation. From the above, it can be concluded that the mentioned approaches to solving the problem require further development taking into account the current trends.

V. Slobodianiuk & I. Maksymov (2021) propose using the economic effect, equal to the difference of total costs for transporting the rock mass to the main conveyor at one crushing and reloading point and during development at their optimal quantity, as a criterion of the truck-conveyor transport optimisation. The analytical dependency is established to determine the optimal number of reloading points at their uniform deployment throughout the height of the working zone of the open pit. However, this work considers parameters that directly characterise the operation of the ICCT complex only when choosing an effective strategy for ICCT development. At the same time, the economic result of GZK activities, i.e. the cost of marketable products (concentrate, pellets), is also influenced by the amount of overburden per unit of mined minerals.

Therefore, to choose the strategy of the ICCT development, it is more correct to take into account the current stripping ratio and economic indicators of the GZK marketable product value in the estimation figure, as the open pit and the concentration plant are a single technological complex. In this regard, to design subsequent stages of open pit mining, a new estimation figure should include expenses for GZK marketable products, and along with that increased costs for transporting ore by the ICCT collecting transport at each stage of deposit development should be predicted. The present work aimed to improve the method of substantiating the depth of the open pit with the ICCT that develops steep deposits at the subsequent stage of its mining by means of an estimation figure for various consecutive periods of the open pit mining duration.

Materials and Methods

To achieve the goal set in the work, a systemic approach is applied considering the previous experience in mining science. Depth is one of the defining parameters in developing an open pit and its working zone. At that, calculations and selection of equipment for the ICCT schemes are performed taking into account their development by open pit methods until the end of life of mine. However, when designing, the final depth of large open pits is often and repeatedly reconsidered and adjusted. As a result, there is uncertainty when determining other parameters of other open pits with ICCT complexes as well.

Specialists and designers reconsidered initial projects and changed operational (design) stripping ratios to align the parameters of the development system with the design (Kovalchuk *et al.*, 2015). This results in the necessity of finding a method of pre-design substantiation of the depth when mining the open pit by stages on the breakeven principle. Theoretically, the basic principle of substantiating the open pit depth is based on the comparison of one of the stripping ratios with the marginal (economically expedient) one. For open pits developing inclined and steep deposits, boundaries are set by the contour stripping ratio numerically equal to the boundary one. But the bench-based analysis of mined mass volumes and stripping ratios is inconvenient due to the fact that when initial conditions change while designing, there emerges a need to recalculate the volumes.

The method of V. Rzhevskyi (1956) is widely used in calculations to solve the main design issues and determine the final depth of the open pit. The method is based on the comparison of current (K_c) and marginal of economically expedient (K_e) stripping ratios, i.e. $K_c \leqslant K_e$. Thus, the indicator (K_e) is decisive in determining the depth of surface mining operations. However, the mentioned estimation figures are proposed directly to determine the final boundaries of the open pit, while parameters of its subsequent stage of mining are interim.

Different options for forming subsequent stages of open pit mining may differ in depth without changing the basic parameters of the design decisions. In this case, one of the main parameters that determines operation of the ICCT complex in the open pit is the ore lifting height and transportation distance. Thus, the estimation figure, with which parameters for the subsequent stages of further development of open pits are to be compared, should take into account the increase in the costs of ore lifting and transportation. This is due to the fact that at steep deposits, the depth of ore extraction is constantly increasing resulting in the growth of costs for its transportation to the surface.

To determine the depth of the subsequent stage of mining the open pit within a particular period of its development, the present work suggests the maximum operational stripping ratio considering the value of GZK marketable products as an estimated figure. As accurate prediction of parameters of the subsequent mining stage is rather difficult, it is important to perform analytical work involving elements of the theory of similarity in order to determine the required parameters of ore flows of the working zone of the open pit. The depth of the subsequent stage of open pit development is determined on the example of the Inhulets Mining and Concentration Plant ("InGZK"), where one of the largest ICCT projects in Kryvyi Rih iron ore basin was implemented.

Available statistical materials (data on horizontal distribution of annual production volumes for the past period of the open pit operation) enabled calculating the coordinates of the mass centre of the ore working zone according to the depth of the open pit over a sufficiently long period of time. This dependency was studied on the material for the period from 1974 to 2011, as the said period is most fully represented by the available statistical data due to a large amount of the research performed on the InGZK open pit within this period.

According to technological design standards, when analysing parameters of transportation schemes for open pits under reconstruction with an annual rock mass output of more than 40 Mt, the calculation period is taken equal to 7-10 years, and 5-7 years for smaller productivity. With this in view, the estimated figure was determined for 2030. For calculations on the InGZK open pit, the existing ICCT complex, where motor vehicles are used as assembly equipment, and other parameters were taken into account (Information on production…, n.d.).

Mathematical processing of statistical data through approximation (the least squares method) enabled finding the dependency of the mass centre of the ore working zone on the depth of the open pit (Tamrazov, 1987; Semerikov *et al.*, 1998). Thus, a relationship was established between the depth of the mass centre of the ore working zone and the depth of the open pit. The obtained dependency helped predict the depth of the mass centre location of the distribution of the ore production volumes at the subsequent stage of the open pit development. Substituting the obtained value of the mass centre of the ore working zone in the proposed maximum operational stripping ratio formula enabled obtaining its value for the subsequent stage of the open pit development. Next, this value was compared with the current stripping ratio, which varies depending on the depth of the open pit, and finally, the sought-for depth of the open pit is found.

Results and Discussion

Based on the generalising nature of the methodology of substantiating the depth of subsequent stages of mining iron ore open pits with the ICCT complex that develop steep deposits, it can be considered that the obtained dependencies and recommendations are acceptable for designing the subsequent stages of reconstructing iron ore open pits with the ICCT complex by relevant design and research organisations.

The indicator reflecting the breakeven operation of the open pit-concentration plant complex, provided that the profit from the sale of marketable products is spent on stripping, is the maximum operational stripping ratio. The mentioned ratio $K_{o.m}$ was determined as the sum of the current stripping ratio and its increase due to the difference between the price and the cost of marketable products, which is taken as an indicator to substantiate the depth of the subsequent stage of the open pit development and calculated according to the formula, m^3/t:

$$K_{\mathrm{o.m}} = \frac{(P_{\mathrm{c}} \cdot P_{\mathrm{s}} - C_{\mathrm{c}} \cdot P_{\mathrm{p}}) \cdot (1-i) \cdot \gamma - \Delta I_{\mathrm{tr}} \cdot P_{\mathrm{p}}}{C_{\mathrm{o}} \cdot P_{\mathrm{p}}} + K_{\mathrm{C}}, \qquad (1)$$

where P_c, C_c – the price (excluding VAT) and the cost of marketable products (e.g. concentrate) of the GZK, UAH/t; P_s, P_p – the volume of sold and produced marketable products for the calculation period, t; γ – the concentrate yield from ore, unit fr.; C_o – the cost of a unit of overburden, UAH/m^3; K_c – the current stripping ratio for the recent period of the open pit operation, m^3/t; ΔI_{tr} – the increase of costs for transporting ore when deepening the open pit at the stage under consideration, UAH/t; i – the income tax, unit fr.

Comparison of the value of the current stripping ratio K_c with the maximum operational one $K_{o.m}$ calculated for the subsequent stage of the open pit development indicates the degree of approximation of the current open pit parameters, in particular its depth to the value of the depth at the subsequent stage of its development. Thus, while designing the stage-by-stage mining of the open pit, it is expedient to apply the principle when the current open pit depth is gradually increased until the current stripping ratio K_c reaches the value of the maximum operational stripping ratio $K_{o.m}$ and, accordingly, the current position of the open pit bottom reaches the depth of the subsequent stage of mining.

When input data for determining the value of the increase in the cost of ore transportation and lifting (ΔI_{tr}) during the deepening of the open pit at the stage is not available, this value can be found applying the methods of the similarity theory (Serdiuk, 2005) and approximation (Semerikov *et al.*, 1998). It is expedient to predict ore production distribution parameters on the basis of statistical data and technical and economic indicators achieved at the time of designing. At that, the process of designing an open pit within a steep deposit will be simplified if the parameter influencing significantly the operation of the ICCT complex in the open pit – the height of ore lifting at the subsequent stages of its development – is determined in advance. The intensive open pit deepening contributes to the continuous increase of this value: from the current depth ($h_{c.i}$) to the depth of the open pit at the subsequent stage of its development ($h_{s.s}$). The height of ore lifting in the open pit is functionally related to the depth of the open pit itself, the parameters of the ore working zone and the nature of distribution of horizon production volumes along the depth of the open pit.

According to B. Isakov & M. Chetveryk (2021), when designing the transition to stripping the next horizon using the in-pit crushing and conveying mining technology, a certain amount of time passes from the beginning of designing to commissioning, and the depth of the open pit can be significantly increased compared with the one at which it should have been commissioned according to the project. As this expands the transportation distance for trucks that should be maintained in the proper working condition (Savin & Sokolenko, 2024), and also reduces the economic efficiency of the designed scheme, this factor should be taken into account in the calculations.

In accordance with the Standard of the Organisation of Ukraine No. 73.020-078-1:2007 (2007), parameters of transportation schemes (weighted average lifting height, weighted average transportation distances) are analysed for the open pits to be reconstructed. Based on the input data, the amount of increase in ore transportation costs (ΔI_{tr}) at the subsequent stage of open pit deepening compared with its current state is determined. The calculation value ΔI_{tr} is determined from expression (2) (UAH/t):

$$\Delta I_{tr} = C_v \cdot \Delta L_t = C_v \cdot h_p \cdot k_{r.d}/i_t, \quad (2)$$

where C_v – the cost of 1 t·km for technological vehicles, UAH/t·km; ΔL_t – the increase in the distance of ore transportation by trucks to the ICCT reloading points due to lowering the mass centre of the ore working zone and deepening the open pit, km; h_p – the increase in the ore lifting height which is defined as the difference between the depth of the weighted average position of the mass centre of distribution of horizon production volumes in the current year and the same parameter at the subsequent stage of mining, m; $k_{r.d}$ – the road development index for open pits, unitless value; i_t – the inclination of technological roads in the open pit, %.

The study of the influence of the pit depth on the depth of the weighted average centre of mass of horizon volumes of ore extraction allows (Table 1) a dependency of changes in one factor when the other changes.

Table 1. *Changes in open pit depths and ore mass centres of the ore working zone by years of InGZK open pit operation*

Year	Open pit depth, m	Depth of mass centre of ore working zone, m
1974	170	127
1975	185	127
1976	185	134
1977	185	139
1978	200	153
1979	215	157
1980	215	162
1981	215	162
1982	215	176
1983	215	182
1984	230	184
1985	230	194
1986	245	194
1987	260	182
1988	260	188
1990	275	191
1991	290	203
1992	290	201
1993	305	203
1994	305	220
1996	320	228
1997	320	236
1998	335	236
1999	350	242
2000	350	235
2001	350	227
2002	365	242
2003	365	248
2004	365	252
2005	365	265
2006	380	284
2007	380	290
2008	395	292
2011	440	307

Notes: *surface marking accepted +50 m*
Source: *developed on the basis of the data collected personally by the authors*

The dependency describing the effect of the depth of the InGZK open pit on the depth of its ore working zone mass centre is obtained by approximation. Linear regression is as follows, m:

$$x_{mc.} = a \cdot h_{s.s} + b = a(h_{c.i} + \Delta h \cdot t) + b = 0.6421 \cdot h_{s.s} + 23.3, \quad (3)$$

where $x_{mc.}$ – the depth of the mass centre of the ore working zone, m; a, b – the empirical coefficients of the linear equation, unit; $h_{s.s}$ – the depth of the open pit at the subsequent stage of reconstruction, m; $h_{c.i}$ – the current depth of the open pit, m; Δh – the average annual rate of open pit deepening (for the InGZK open pit $\Delta h \approx 7$ m/year, but up to 1980 it was $\Delta h \approx 9$ m/year); t – the duration of the period from the current year to the subsequent stage of the open pit development, years.

It is proposed to assume that the preliminary depth of the open pit at the subsequent stage of its development is equal to $h_{s.s} = h_{c.i} + \Delta h \cdot t$, m. Approximation quality indicators ($r_{xy} = 0.9706$, $R^2 = 0.9421$, $A = 4.646\%$) of the obtained equation (3) allow asserting that it is adequate to mining and engineering factors being investigated, and as a simple model it can be used to solve some mining problems. With the help of the obtained dependency (3), it is possible to predict the depth ($x_{mc.}$) of the centre of mass distribution of ore production at the subsequent stage of the open pit development. If the value of this parameter for the current year is written as $x_{c.i}$, then $h_p = x_{mc.} - x_{c.i}$, m. The increase in ore transportation costs according to the formula (2) is as follows, UAH:

$$\Delta I_{tr} = C_v \cdot k_{r.d} \cdot (a \cdot h_{s.s} + b - x_{c.i})/i_t = C_v \cdot k_{r.d} \cdot (a \cdot [h_{c.i} + \Delta h \cdot t] + b - x_{c.i})/i_t. \quad (4)$$

By substituting the value of ΔI_{tr} (4) in the formula (1) and considering the case when $P_s = P_p$, the dependency is obtained that determines the value of the maximum operational stripping ratio for the subsequence stage of the open pit development, t/m^3:

$$K_{o.m} = \frac{(P_c - C_c)\cdot(1-i)\cdot\gamma - C_v\cdot k_{r.d}\cdot(a\cdot[h_{c.i}+\Delta h\cdot t]+b-x_{c.i})/i_t}{C_o} + K_c. \quad (5)$$

Due to the continuous deepening of the open pit developing a steep deposit from the current depth ($h_{c.i}$) to the depth ($h_{s.s}$) of the subsequent stage of its development, the current stripping ratio (K_c) is increased to a value equal to the maximum operational stripping ratio $K_c = K_{o.m}$ at the subsequent stage of the open pit development determined by formulae (1) or (5). The design process also determines the open pit depth $h^1_{s.s}$, which is adequate to the maximum operational stripping ratio $K_{o.m}$.

It is possible that the previously accepted depth $h_{s.s}$ at the next stage of the open pit development will be greater than the depth $h^1_{s.s}$, i.e. $h_{s.s} \geqslant h^1_{s.s}$. In this case, the maximum operational stripping ratio is determined by formulae (1) and (5), but taking into account the depth $h^1_{s.s}$ and the corrected maximum operational stripping ratio $K^1_{o.m}$ adequate to the open pit depth $h^1_{s.s}$ at the subsequent mining stage.

The opposite situation is possible when the assumed previous depth $h_{s.s}$ of the open pit will be less than the depth $h^1_{s.s}$, i.e. $h_{s.s} \leqslant h^1_{s.s}$. In this case, the maximum operational stripping ratio $K^1_{o.m}$ is also calculated taking into account the depth $h^1_{s.s}$. In both cases, the duration of the period t from the current date to the subsequent stage of the open pit development will be $t^1 = (h^1_{s.s} - h_{c.i})/\Delta h$, years. In the case where $h_{s.s} = h^1_{s.s}$, $K^1_{o.m}$ is not calculated.

According to formula (5) at $t = 19$ years for 2030, for the InGZK open pit where vehicles are used, the calculated maximum operational ratio is equal to $K_{o.m} = 0.66$ m^3/t. In this example, it is considered that the maximum operational ratio $K_{o.m} = 0.66$ m^3/t is adequate to the previously accepted depth of the open pit, i.e. $h_{s.s} = h^1_{s.s} = 573$ m.

Thus, the principle of finding a substantiated open pit depth at the subsequent stage of its development is that when deepening the open pit to the depth of the subsequent development stage ($h^1_{s.s}$), the current stripping ratio will not exceed the maximum operational ratio ($K_c \leqslant K^1_{o.m}$), which will allow the fullest use of the advantages of open pit mining. Application of the proposed estimation figure – the maximum operational stripping ratio – is appropriate for different consecutive periods of time when solving the design issues of each subsequent stage of reconstruction during the stage-by-stage open pit development.

This method of approximating the open pit depth at the subsequent stage of its development can be used to substantiate prospective design solutions. Yu. Hryhoriev *et al.* (2021a) argue that mining conditions of mineral deposits will be characterised by further increases in the open pit depth and transportation distances. This can be fully agreed with and taken into account when studying ICCT parameters at the subsequent stage in the open pit development. One of the main challenges in open pit designing is its sustainable development and minimisation of costs, and given the long development time of the deposit and variable mining and engineering conditions of open pits, correction of previously made decisions is an inevitable step to increase their efficiency. At the same time, revision of even one of the essential parameters of open pits at the subsequent stage, such as depth, can affect efficiency of the decisions made, especially at the pre-design stage. Therefore, this factor is essential for prospective decisions.

N. Sarybayev *et al.* (2021a) indicate that the area of the most economical use of the ICCT method with belt conveyors of the standard inclination (up to 16°) is provided within the range of technological parameters – the capacity of 10-25 Mt/year and the lift height of 250-600 m. At the same time, when designing a new technological transportation scheme, it is necessary to delineate the efficient area of its application, which can be done with the help of the estimation figure proposed in this work. S. Kuzmenko *et al.* (2019) believe that one of the most important conditions to use a conveyor lift is provision of the transport with the rock mass for the payback period of 10-20 years. The ICCT schemes employed at Kryvyi Rih open pits largely depend on specific mining conditions. According to N. Sarybayev *et al.* (2021b), deepening of mining operations will require adjustment of the transport system of the open pit. However, the examples show that the economic effect of this technology is always positive.

V. Slobodianiuk & I. Maksymov (2021) suggest the use of mobile crushing and reloading points. However, the authors believe that construction of a new stationary crushing and reloading point is inefficient, since it is not possible to create an area of the required size with a lifetime that justifies relevant construction costs. In this case, it is also necessary to assess the mining and engineering situation in the open pit using an estimation figure. Yu. Hryhoriev *et al.* (2021b) state that mining conditions of mineral deposit development in the coming years will be characterised by a further increase in the open pit depth and transport distances, with which one can fully agree and take into account when studying the parameters of the ICCT at the subsequent stage of the open pit development.

Thus, summarising the above, it is possible to conclude that when transiting to the subsequent stage of the open pit development, it is necessary to assess the mining and engineering situation using an estimation figure to outline the rational field of applying the technological transport complex and determine the ways of further improvement of ICCT parameters at the subsequent stage of the open pit development. In this regard, in order to perform approximate estimates of the open pit depth at the pre-design stage, the use of the maximum operational stripping ratio to substantiate the subsequent stage of the open pit development is proposed.

Conclusions

In the course of solving the problem using the similarity theory, a method has been proposed that allows a more deep approach to the study and evaluation of such important parameters as the depth of the subsequent stage of developing with the ICCT complex, determination of the value of the maximum operational stripping ratio for this stage and its adequate open pit depth and substantiation of the economic expediency of the subsequent stage development of the open pit the pre-design stage. Application of dependencies determined using the similarity theory makes it possible to solve the tasks necessary for the further development of the ICCT complex and substantiate the depth parameter for the subsequent stage of the open pit development, which ultimately allows obtaining the designed technological and economic result in a given period. The methodological approach to determining the depth of the subsequent stage of mining the iron ore open pit with the ICCT complex during the stage-by-stage development can be used by design organisations and research institutes when designing reconstruction of open pits in steeply dipping deposits. The issue of how the nature of ore distribution throughout the height of the open pit working zone affects the provision of optimal operational conditions for each of the applied types of the ICCT complex still remains unaddressed, which may be the subject of further research. It is also useful to analyse the influence of open pit deepening and changes in the depth of the mass centre in distributing ore production volumes on the dynamics of stripping ratios.

Acknowledgements

None.

Conflict of Interest

None.

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Обґрунтування глибини кар'єру з циклічно-потоковою технологією як визначальної величини його відпрацювання в черговому етапі розробки

Анотація. Постійне збільшення глибини кар'єрів з циклічно-потоковою технологією, що розробляють круто падаючі родовища, викликає зростання висоти підйому та відстані перевезення руди, і як наслідок, збільшення витрат на її доставку на поверхню, що впливає на величину глибини чергового етапу реконструкції транспортної системи кар'єру. Метою даної роботи було обґрунтування глибини чергового етапу відпрацювання залізорудного кар'єру з комплексом циклічно-потокової технології за допомогою узагальнюючого показника оцінки для різних послідовних відрізків часу при поетапній розробці кар'єру, що має покращати якість проектних робіт. В статті використовувалися методи статистично-логічного, каузального і компаративного аналізу та метод системно-структурного підходу, щодо визначення узагальнюючого показника оцінки чергового етапу відпрацювання кар'єрів з комплексом циклічно-потокової технології. Запропоновано при обґрунтуванні глибини чергового етапу реконструкції кар'єру залежність для визначення максимального експлуатаційного коефіцієнту розкриву, в якій враховано збільшення транспортних витрат через зростання висоти підйому та подовження відстані транспортування руди на дробильно-перевантажувальні пункти конвеєрних підйомників розташованих в просторі кар'єру внаслідок його поглиблення. В розрахунках також використано залежність положення координати центру мас видобутої руди від глибини кар'єру. Враховуючи, що в сучасних глибоких кар'єрах обсяги руди, що видобувається і транспортується автомобільно-конвеєрним комплексом протягом року можуть становити 30 млн. т, одне з важливих завдань проектувальників полягає в пошуку шляхів вдосконалення вантажопотоків транспортних комплексів кар'єру. У цьому з'вязку запропоновано оціночний показник для визначення глибини чергового етапу відпрацювання кар'єрів з комплексом циклічно-потокової технології, в якому у взаємозв'язку враховано збільшення витрат на доставку руди, вартість товарної продукції гірничозбагачувального комбінату, поточний коефіцієнт розкриву. При цьому береться до уваги збільшення витрат через збільшення висоти підйому руди при пониженні гірничих робіт в кар'єрі, що дозволяє врахувати приріст транспортних витратат при проектуванні подальшого розвитку комплексу циклічно-потокової технології. У кар'єрі, глибина якого визначається по запропонованій методиці, значення поточного коефіцієнту розкриву не перевищуватиме максимального експлуатаційного коефіцієнту розкриву в черговому етапі. Даний підхід дозволяє оперативно оцінити глибину залізорудного кар'єру, що розробляє крутопадаючі поклади при проектуванні чергового етапу реконструкції за умови беззбиткового його доопрацювання

Ключові слова: відкрита гірнича виробка; максимальний експлуатаційний коефіцієнт розкриву; поглиблення кар'єру; сходинка відпрацювання

Journal homepage: https://mining-journal.com.ua/en
MINING JOURNAL
of Kryvyi Rih National University
Vol. 58, No. 2, 2024

Received: 06.06.2024; Revised: 06.10.2024; Accepted: 24.12.2024

UDC 622.765:553.546 DOI: 10.31721/2306-5435-2024-2-30-39

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Development a new flotation refining technology for magnetite concentrates at the Northern Mining and Processing Plant Private Joint-Stock Company

Abstract. The purpose of this study was to develop a new flotation refining technology for magnetite concentrates at the Northern Mining and Processing Plant Private Joint-Stock Company to produce a final commercial product with a total iron content of at least 69.0% and silica content not exceeding 4%. Mineralogical analysis was used to study mineral liberation, chemical analysis to determine the qualitative composition of the raw material, and sieve analysis to determine the granulometric composition of the material. The study also employed methods of processing, analysing, and synthesising research results to establish optimal conditions for separating mineral grains by size. The results showed that achieving the maximum total iron content in the concentrate and minimising the silica content, while ensuring maximum iron recovery, depends on grinding conditions, which are determined by the degree of mineral grain liberation. It was found that the flotation rate constant for quartz depends on the mass fraction of quartz in the feed and ranges from 0.05 to 0.10 min^{-1}. Mineralogical studies of the raw concentrate revealed that, in addition to monomineral magnetite particles, it includes aggregates of magnetite-quartz (up to 2.52%), magnetite-quartz-silicate, magnetite-quartz, silicate-carbonate (up to 7.5%). Carbonates are mainly represented by sideroplesite and calcite; silicates by cummingtonite, biotite, and chlorite. Gangue particles consist of monomineral quartz or silicate-quartz, carbonate-silicate-quartz aggregates. According to quantitative mineralogical calculations, monomineral magnetite particles are concentrated in the fine-grained fraction, with 92.3% in the -0.045 + 0.02 mm class and 98.1% in the -0.02 mm class. Laboratory tests of the magnetic-flotation refining of the concentrate demonstrated the feasibility of obtaining high-quality concentrate from the magnetite concentrates of the Northern Mining and Processing Plant Private Joint-Stock Company with a total iron content of 69.0% and silica content of 3%, achieving an 88.9% yield and 92.9% iron recovery in the concentrate from the operation. The practical significance lies in the development of a technological scheme for refining raw magnetite concentrate under the conditions of the Northern Mining and Processing Plant Private Joint-Stock Company to produce high-quality concentrate with

Suggested Citation:
Oliinyk, T., & Bezsmertnyi, Ye. (2024). Development a new flotation refining technology for magnetite concentrates at the Northern Mining and Processing Plant Private Joint-Stock Company. *Mining Journal of Kryvyi Rih National University*, 58(2), 30-39. doi: 10.31721/2306-5435-2024-2-30-39.

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maximum yield, a total iron content above 69.0%, and silica below 4.0%, while ensuring iron recovery in the concentrate of more than 90%

Keywords: iron ore concentrate; reverse cationic flotation; magnetic separation; mass fraction; granulometric composition

Introduction

As of 2024, Ukraine holds a prominent position in the global market for the extraction and processing of iron ore quartzites. Mining and processing enterprises in the Kryvyi Rih Iron Ore Basin play a significant role in this sector. The Kryvyi Rih plants supply raw materials to ferrous metallurgy enterprises both within Ukraine and abroad. However, the quality of iron ore concentrates from Kryvyi Rih beneficiation plants, with an iron content of 65-68% and SiO_2 content of 6.0-9.0%, is considerably lower than that of similar plants in Canada, Sweden, and the USA. Such factors reduce the marketability of Kryvyi Rih enterprises and diminish the competitiveness of Ukrainian products.

The quality of iron ore concentrate is crucial for further processing and is primarily determined by two key factors: the content of the useful component and the level of harmful impurities. Hence, there is a growing demand for high-quality concentrates with a high content of the useful component and low silica content, suitable for direct iron reduction. However, Ukrainian plants face challenges due to beneficiation technologies developed in the 20th century, which do not ensure the production of competitive quality concentrate for the global market. Thus, the development of new enrichment methods and techniques has become a pressing issue. This challenge is being addressed by both mining and processing enterprises and researchers.

The study by M.M. Bulayani *et al.* (2024) highlights that the beneficiation of low-grade ores is a critical area of research in the mineral processing sector. Despite their lower iron quality and high impurity levels, low-grade iron ores constitute a significant portion of global iron ore reserves. The beneficiation of low-grade iron ore is an essential process for utilising ore deposits, especially as demand for iron and its alloys continues to grow due to rapid industrialisation and the depletion of high-quality reserves. The mineralogy of iron ore and impurity levels dictate the beneficiation pathways for obtaining high-quality iron ore concentrate. Effective beneficiation processes not only enhance the economic viability of low-grade ore deposits but also promote sustainable resource management and environmental conservation. The study discusses various methods of low-grade iron ore beneficiation, including grinding, gravity separation, flotation, and magnetic separation.

In the work of A.F.D.V. Rodrigues *et al.* (2023), it was proven that reverse cationic flotation technology is the most widely used method for fine iron ore beneficiation. However, this technology faces numerous inefficiencies in the technological cycle, including fine grinding, desliming, flotation, and product thickening. The study explores new advances in crushing and grinding technologies, as well as magnetic separation and gravity methods, as alternatives or complete replacements for reverse flotation technology. Researchers have demonstrated that innovative approaches to iron ore beneficiation will play a decisive role in the transition of the global industry to so-called "green steel".

In the work of X. Zhang *et al.* (2019), it was established that flotation is considered the most promising method for obtaining high-quality iron from low-grade, finely disseminated iron ores. Flotation can be used as a standalone method or as a complement to other separation techniques, such as gravity separation and magnetic separation. Flotation is highly dependent on the chemical composition of the mineral surfaces to be separated. Reverse flotation is the most promising flotation pathway for further development. The choice between cationic or anionic reverse flotation depends on the mineralogy and available reagents. Cationic reverse flotation offers advantages over anionic flotation due to its higher flotation speed, simpler reagent systems, operational simplicity and reliability, and suitability for operation at low temperatures. However, cationic collectors have relatively poor selectivity, foaming properties, and high toxicity, which can lead to product losses and environmental pollution. Anionic reverse flotation is less sensitive to slimes, has a lower collector cost, and higher selectivity due to calcium activators, which have an activating effect on quartz and a depressing effect on iron ore. However, anionic reverse flotation requires significant quantities of activators, as well as high temperatures and alkalinity of the process.

In the study by B. Luo *et al.* (2021), the new amphoteric surfactant LDEA was investigated. The research showed that during froth flotation, the properties of the collector, especially its solubility in the pulp, adsorption on the mineral surface, and hydrophobicity, play a crucial role in achieving optimal iron content and recovery rates. It was determined that pH stabilisation affects not only the chemical composition of the surface but also the ionisation state of the collector, which determines its adsorption mechanism on mineral surfaces and the efficiency of particle separation.

In the work of J.T.G. Junior *et al.* (2023), it was proven that flotation is the most widespread method for processing iron oxides in the typical size range of -150+40 μm. The study noted that ultrafine particles below 40 μm exhibit low collision rates with air bubbles, which risks the loss of fine and ultrafine magnetite and haematite particles alongside quartz. Researchers demonstrated that the use of cationic surfactants, such as diamine LILAFLOT-811M and monoamine ether LILAFLOT-919, showed high efficiency in processing ultrafine particles. Both biodegradable collectors effectively separate magnetite and quartz. At pH-9, both collectors facilitated quartz recovery of 95.9% (with diamine LILAFLOT-811M) and 97.7% (with monoamine ether LILAFLOT-919) and exhibited relatively similar flotation kinetics.

In the study by T. Oliinyk *et al.* (2023), researchers examined the challenges of developing efficient iron ore beneficiation technologies and applying various enrichment methods, including gravity, magnetic, and flotation techniques. The ore under investigation contained particles below 74 μm. The flotation enrichment reagent regime consisted of Lilaflot-811M, Lilaflot-D817M, and Lilaflot-D819M as collectors, dextrin as a depressor for iron ore minerals, and caustic soda as a medium regulator. It was proven that the most efficient beneficiation schemes included two stages of ore grinding, wet magnetic separation, and reverse flotation in two steps with regrinding of the froth product. Another effective scheme involved pre-enrichment of the ore using dry magnetic separators, two-stage grinding to a fraction below 74 μm, wet magnetic enrichment, and reverse cationic flotation in two steps with regrinding of the froth product.

The technological potential for enriching magnetite quartzites of the Northern Mining and Processing Plant Private Joint-Stock Company (PJSC “Northern MPP”) has been studied between 2021 and 2024 but remains inconclusive. This allows for a more detailed investigation of the magnetic, flotation, and magnetic-flotation refining technologies to produce a competitive product. Therefore, the aim of this work was to determine the optimal technological scheme for flotation refining of magnetite concentrates at PJSC “Northern MPP” to obtain a final commercial product with a total Fe content of at least 69.0% and SiO_2 content not exceeding 4%.

Materials and Methods

To determine the feasibility and necessity of refining magnetite quartzites under laboratory conditions, experiments were conducted on the beneficiation of raw concentrate from PJSC “Northern MPP”. The chemical composition of the concentrate revealed the following: total iron content – 66.0%, magnetite iron content – 62.3%, iron oxide – 27.6%, harmful impurities: silica (SiO_2) – 6.79%, titanium dioxide (TiO_2) – 0,041%, aluminium dioxide (Al_2O_3) – 0.18%, manganese oxide (MnO) – 0,038%, calcium oxide (CaO) – 0.47%, magnesium oxide (MgO) – 0.53%, phosphorus oxide (P_2O_5) – 0,018%, sulphur (S) – 0.07%, carbon dioxide (CO_2) – 0.33%, potassium oxide (K_2O) – 0,053%, sodium oxide (Na_2O) – 0.15%, loss on ignition (LOI) – 0,062%. The granulometric composition of the raw concentrate is presented in Table 1.

Table 1. *Granulometric characteristics of ordinary concentrate*

Size class, mm					
+0.071	-0.071 +0.056	-0.056 +0.045	-0.045 +0.02	-0.02	Total
0.7	1.1	2.4	36.5	59.3	100

Source: *authors’ development*

The tests were conducted at the laboratory of PJSC “Northern MPP” and the Department of Mineral Processing at Kryvyi Rih National University. The pre-grinding of the concentrate was performed using a laboratory mill of the “Rollgang” type, designed to simulate the grinding processes of industrial mills. Magnetic beneficiation was carried out using a laboratory magnetic analyser AM-2A (NTC MAGNIS LTD, Luhansk, Ukraine) with a magnetic field induction of 1,000 G. Flotation tests on the concentrate were conducted using a laboratory flotation machine “237 FL” (SCMA Lab, Kryvyi Rih, Ukraine), equipped with interchangeable cells of 0.5 and 1.0 litres capacity. Laboratory studies were performed based on three technological schemes for enriching the raw concentrate: 1. Magnetic refining scheme. This scheme included preliminary grinding of the entire raw concentrate, classification in hydrocyclones, and magnetic beneficiation. The scheme is illustrated in Figure 1. 2. The flotation refining scheme. This scheme involved a reverse cationic flotation cycle. The froth product of the main flotation cycle was classified in a closed circuit with the mill, enriched using a magnetic separator with low magnetic induction, processed in a control flotation cell, and returned to the main flotation process. The flotation process was carried out with the addition of the amine reagent Lilaflot 811M. The scheme is illustrated in Figure 2. 3. The magnetic-flotation refining scheme. This scheme involved the classification and grinding of raw concentrate in a closed circuit. The classifier overflow was directed to magnetic separation and subsequently to the main flotation cells, followed by the enrichment of the cell product using magnetic separators. The froth product was classified and ground in a closed circuit. The hydrocyclone overflow, after magnetic beneficiation and control flotation, was returned to the main flotation cycle. The main flotation process was conducted with the addition of the amine reagent Lilaflot 811M. The scheme is illustrated in Figure 3.

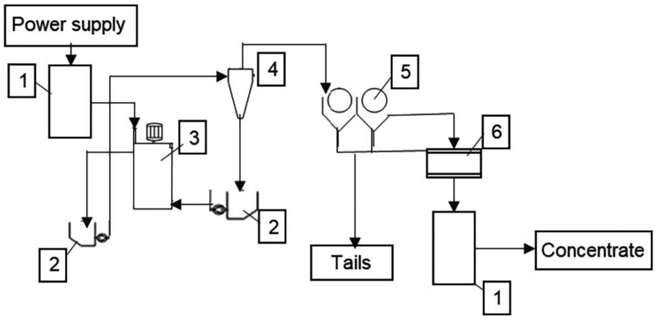

Figure 1. *Technological scheme No. 1 for magnetic refining of raw concentrate*
Notes: *1 – mixer (homogeniser) for feed product; 2 – technological sumps with pumps; 3 – vertical mill; 4 – hydrocyclone battery; 5 – wet magnetic separation; 6 – magnetic desliming unit*
Source: *authors' development*

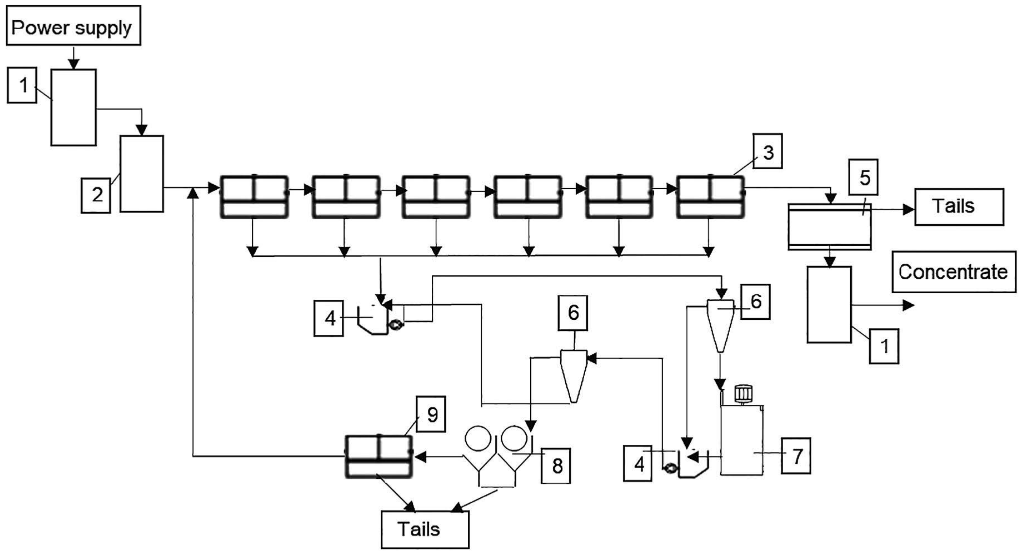

Figure 2. *Technological scheme No. 2 for flotation refining of raw concentrate*
Notes: *1 – mixer (homogeniser) for feed product; 2 – contact tank with reagent; 3 – main flotation cells; 4 – technological sumps with pumps; 5 – magnetic desliming unit; 6 – hydrocyclone batteries; 7 – vertical mill; 8 – wet magnetic separation; 9 – control flotation cell*
Source: *authors' development*

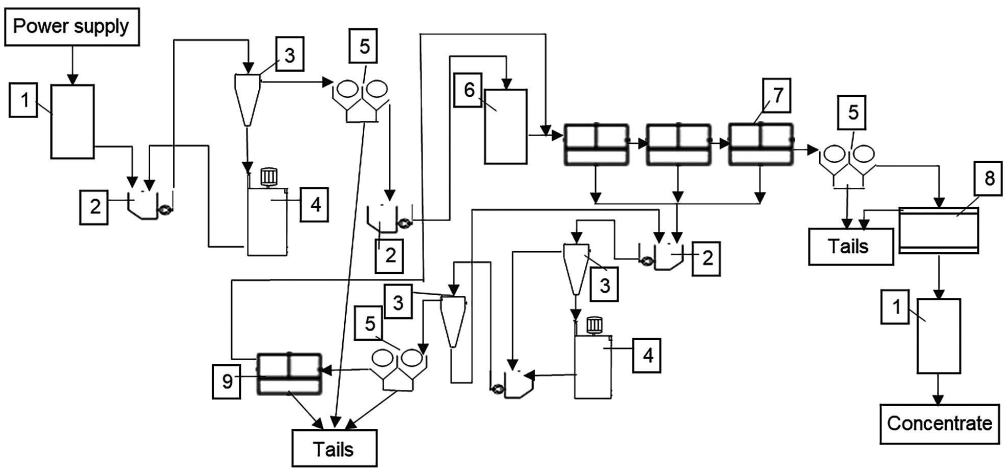

Figure 3. *Technological scheme No. 3 for magnetic-flotation refining of raw concentrate*
Notes: *1 – mixer (homogeniser) for intermediate product; 2 – main flotation cells; 3 – hydrocyclone batteries; 4 – vertical mill; 5 – wet magnetic separation; 6 – contact tank with reagent; 7 – main flotation cells; 8 – magnetic desliming unit; 9 – control flotation cell*
Source: *authors' development*

The research was conducted using the reverse cationic flotation method, employing the cationic reagent amine Lilaflot 811M, produced by AKZO NOBEL. The process did not include the addition of hydrolysed starch as an iron depressant due to the presence of poor, non-liberated aggregates in the flotation feed, which are susceptible to the depressing action of hydrolysed starch, negatively affecting concentrate quality. Additionally, no pH stabiliser was used.

Flotation and reagent conditions were identical across all experiments and included:

1. Amine dosage: 200 g/t;
2. Contact time: 1 minute;
3. Solid content in the flotation feed: 30-35%;
4. Flotation duration: 10 minutes.

Standard research methods applied:

1. Sieve analysis was conducted in accordance with DSTU 3704:2013 (2013).
2. Flotation analysis was conducted in accordance with DSTU 8811.1:2018 (2018).
3. Chemical analysis was conducted in accordance with DSTU 8811.0:2019 (2019).

Results

An analysis of comparable plant operations demonstrated that achieving high beneficiation efficiency depends on improving concentrate quality, optimising raw material utilisation, and reducing specific beneficiation costs. These goals are achieved through various methods, including flotation refining (Bulayani *et al.*, 2024). The feasibility of implementing and selecting a technological refining scheme depends on multiple factors, including the physico-chemical properties and characteristics of the feed material, plant capacity and productivity, available space for refining operations, and the essential testing, especially semi-industrial trials. The beneficiation technologies currently used in Ukraine, particularly at PJSC "Northern MPP" are incapable of producing high-quality concentrates and require improvement. Enhancement efforts focus on incorporating additional refining operations for raw concentrate, such as extra grinding, fine screening, using magnetic separators with varying field gradients and intensities, hydraulic separation, and flotation methods. The Kirkenes plant in Norway refines its raw concentrate through additional grinding and reverse cationic flotation, achieving iron content levels up to 70%. Plants such as Adams (USA), Sherman and Griffith Mines (Canada), the Poltava Mining and Processing Plant, and the Ingulets Mining and Processing Plant (Ukraine) have effectively improved the quality of magnetite concentrate by integrating reverse cationic flotation operations into their technological schemes. Hydraulic fine screening operations are also widely used in mining and processing plants in the USA and Canada, first introduced in 1967 at the Erie Mining plant in the USA. This technology has also been implemented at the Central Mining and Processing Plant (Ukraine), leading to increased quality and productivity (Hubin *et al.*, 2016).

All beneficiation processes, including flotation, are based on the differences in the properties of the minerals being separated. The primary phenomena utilised in flotation are surface tension and wettability. Under specific conditions, these properties ensure the effective progress of flotation. For efficient flotation, selecting the appropriate flotation equipment is critical. Each type of flotation machine has unique characteristics and structural features, and specific machines are used for the flotation of various minerals (Bulayani *et al.*, 2024). Flotation machines are enrichment devices used to separate minerals during the flotation process in a water-mineral pulp. The flotation process is influenced by factors such as flotation time, stirring, and aeration methods. These parameters determine the type, volume, and number of flotation machine cells as well as compliance with energy consumption standards (Smirnov & Biletskyi, 2010).

At PJSC "Northern MPP" raw magnetite concentrate is produced through magnetic beneficiation. The raw material composition for magnetite concentrate exhibits unstable quality indicators (Dovhiy *et al.*, 2017). The composition of the iron ore feed is characterised by mineralogical varieties such as magnetite, haematite-magnetite, silicate-magnetite, and magnetite-silicate. The structure is fine- and microcrystalline, with aggregates of heavy ore grains of magnetite and haematite bound with gangue minerals such as quartz, silicates, and carbonates (Filenko, 2011). The material also contains martite, biotite, iron mica, amphiboles, and cummingtonite. Due to variations in the proportions of easily, moderately, and poorly beneficiated ore minerals, as well as differing levels of harmful gangue impurities, the concentrate displays variable characteristics in its mineralogical, chemical, and granulometric composition (Morkun *et al.*, 2017).

Mineralogical studies revealed that the concentrate predominantly consists of the ore mineral magnetite (82.6%). The samples also contain iron hydroxides, silicates, and carbonates (totalling 4.14%). The gangue component is quartz, with a content of 6.63-7.5%. Harmful impurities include sulphides and apatite, with contents around 0.16%. Mineralogical studies of the raw concentrate also identified aggregates such as magnetite-quartz (up to 2.52%), magnetite-quartz-silicate, magnetite-quartz, and silicate-carbonate (up to 7.5%). The carbonates are primarily represented by sideroplesite and calcite, while silicates include cummingtonite, biotite, and chlorite. Non-ore particles include monomineral quartz or silicate-quartz, carbonate-silicate-quartz aggregates. Quantitative mineralogical calculations revealed that monomineral magnetite particles accumulate in fine fractions class -0.045+0.02 mm: 92.3%; class -0.02 mm: 98.1%. In coarser fractions, the proportion of monomineral particles decreases, while the proportion of poor aggregates and gangue particles increases. For instance, class +0.071 mm: 62.7% poor aggregates, and 6.9% gangue particles; class -0.071+0.056 mm: 41.7% poor aggregates, and 6.2% gangue particles; class -0.056+0.045 mm: 16.8% poor aggregates, and 2.6% gangue particles.

Laboratory studies demonstrated a direct correlation between silica content and iron content: as the proportion of ore minerals increases, the proportion of gangue minerals decreases, and vice versa. The results are presented in Figure 4.

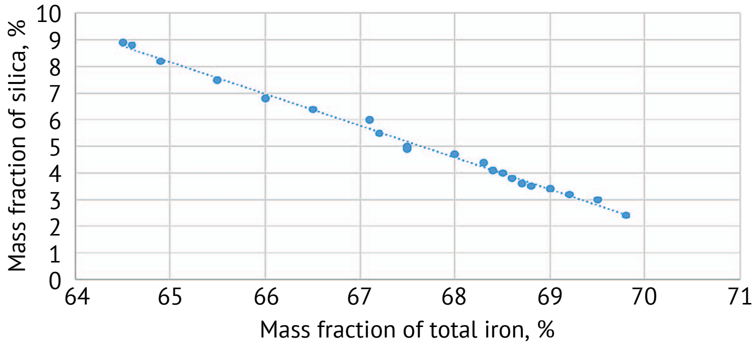

Figure 4. *Relationship between the mass fraction of total iron and silica*

Source: *authors' development*

The analysis of the studies demonstrated that using magnetic, magnetic-flotation, and flotation refining methods for raw concentrate with the reagent collector Lilaflot 811M makes it possible to obtain a final concentrate with a total iron mass fraction ranging from 68.0 to 69.0%, recovery rates between 92.9 and 95.7%, and silica content in the concentrate from 3.4 to 4.7%. The results of the studies are presented in Tables 2 and 3.

Table 2. *Results of raw concentrate refining for technological schemes No. 1-3*

No. of technological scheme	Quality indicators, %								
	Output power supply			Concentrate			Dump tailings		
	Mass share Fe_{total}, %	Removal Fe_{total}, %	Exit Fe_{total}, %	Mass share Fe_{total}, %	Removal Fe_{total}, %	Exit Fe_{total}, %	Mass share Fe_{total}, %	Removal Fe_{total}, %	Exit Fe_{total}, %
1	66.0	100	100	68.3	94.9	91.7	40.6	5.1	8.3
2				68.0	95.7	92.9	40.0	4.3	7.1
3				69.0	92.9	88.9	42.1	7.1	11.1

Source: *authors' development*

Table 3. *Granulometric characteristics of ordinary concentrate finishing according to technological schemes No. 1-3*

No. of technological scheme	Size class, mm						Product
	+0.071	-0.071 +0.056	-0.056 +0.045	-0.045 +0.02	-0.02	Total	
1	-	0.3	1.1	31.7	66.9	100	Concentrate
2	0.5	0.9	3.5	34.2	60.9	100	Concentrate
3	-	0.6	0.9	22.0	76.5	100	Concentrate

Source: *authors' development*

An analysis of the granulometric composition of the concentrates indicates that those obtained in tests 1 and 3 consist of finer material than the sample from test 2. The content of the -0.045 mm fraction in these tests was 98.6 and 98.5%, respectively. Since pure ore minerals are mainly found in the -0.045+0 fraction, the total iron content is higher in samples 1 and 3 than in sample 2, with values of 68.3 and 69.0% compared to 68.0%. This confirms that the overall quality indicators of concentrates obtained using technological schemes that involve vertical mills for feed grinding are superior to schemes where the feed is not ground. This is due to the more effective liberation of grains, which positively impacts the quality parameters of the concentrate.

Discussion

The findings of this study are supported by a substantial body of scientific research. The magnetic-flotation refining method has been identified as the most promising and economically viable approach for raw concentrate beneficiation. The selection of beneficiation equipment and the reagent regime depends on the mineralogy and level of harmful impurities. The current trend in the metallurgical industry, coupled with the rapid growth of "green energy", demands that iron product manufacturers reduce the silica content to 2%. Magnetic or hydraulic separation alone cannot achieve this due to the presence of locked silica minerals. In the work of M. Ma (2012), a comparison of reverse anionic and cationic flotation highlighted that the advantages of anionic flotation include lower reagent costs and better iron recovery. However, the author noted that reverse cationic flotation remains the most widely used method for iron ore beneficiation.

In the work of F. Dehghani *et al.* (2022) demonstrated that the final ore grinding size depends on the nature of mineralisation, mineral distribution within ore deposits, and associated gangue minerals. The researchers examined two technological schemes for magnetic-flotation concentrate refining: 1) Magnetic separation with a magnetic field intensity of 2,000 G, grinding to a particle size of less than 74 μm, followed by a flotation cycle; 2) Grinding the entire flotation feed, flotation beneficiation, and subsequent wet magnetic separation with a magnetic field intensity of 1,000 G. During flotation, a collector reagent, depressant, and pH stabiliser were applied. The study determined that wet magnetic separation prior to flotation was more effective than using flotation as the primary beneficiation operation. Magnetic separation before flotation reduced grinding costs, the number of flotation cells, and reagent consumption, resulting in a higher-quality product with fewer impurities. In contrast, using flotation as the initial beneficiation step increased the number of flotation cells, raised reagent consumption, and complicated the process.

In the work of S.O. Bada *et al.* (2012) also employed an initial grinding stage to a particle size of less than 75 μm, followed by magnetic separation, a control grinding stage to achieve 95% of particles below 25 μm, wet magnetic separation, and reverse cationic flotation with the collector reagent Lilaflot-817M and starch (iron depressant). The operations increased the iron mass fraction in the concentrate to 65.5%, with reverse cationic flotation further increasing the iron content to 70.0%.

H.D.G. Turrer *et al.* (2007) studied the impact of synthetic flocculants on the beneficiation of fine iron ore fractions. They found that enriching iron ore fractions smaller than 44 μm could increase iron recovery by 7.8% with the addition of non-ionic polyacrylamides combined with a cationic collector, depressant, and pH stabiliser. However, using non-ionic polyacrylamides also increased silica content in the concentrate by 0.12-1.58% due to the presence of polyacrylamide-induced flocs. J.-O. Gustafsson & O. Lima (2013) evaluated the foam formation and stability of cationic collectors, as foam structure and stability are critical factors in mineral flotation. Their work compared the effects of ether diamine Lilaflot-D817M and Lilaflot-628M and found that ore type, water quality, and collector type significantly influence foam properties during magnetite quartzite beneficiation. Water with higher ion content produced more voluminous foam.

In the work of K.P. Babu & M. Aminuddin (2020) studied the impact of low-grade iron ore particle size and changes in reagent regimes on concentrate quality and yield. The study showed that increasing the collector dosage and pulp density reduced concentrate yield while increasing iron content. They also found that pH stabilisation affected concentrate yield and iron content. At lower pH levels, negatively charged silicates electrostatically interact with positively charged cation ions, reducing concentrate yield while increasing iron content. At higher pH levels, silicates become less negatively charged, decreasing interaction with cations, which increases concentrate yield but decreases iron content.

N.P. Lima *et al.* (2013) examined the size-based separation of flotation feed. They divided the feed into two fractions: -150÷+45 μm and below 45 μm and compared the results with an undivided sample of less than 150 μm. The study found that iron recovery was highest for the fraction below 45 μm with lower reagent consumption. However, increased collector dosage reduced iron recovery and silica content. The researchers demonstrated that size-based feed separation in iron ore flotation improved iron recovery by nearly 3%, reduced silica content, and decreased iron content in tailings. G.M. Rocha *et al.* (2022) studied flotation without starch addition and at lower pH levels. They compared amide-amines and etheramines as collectors, finding that increasing amide-amine dosage by 50%, without starch addition, improved iron recovery by up to 9% and concentrate yield by up to 5%. However, this reduced the iron mass fraction in the concentrate by 1%.

To enhance the flotation efficiency for magnetite quartzite beneficiation, H. Hubin *et al.* (2018) found that the initial concentrate contained many technological aggregates formed during grinding, increased pulp viscosity, and the growth of the ground material's total surface area into magnetic flocs, causing mechanical entrapment of natural particles. They demonstrated that ultrasonic treatment improved flotation properties and increased final concentrate yield by 2-5% without compromising product quality by altering pulp viscosity.

To sum it all up, the study, along with an analysis of other scientific works, confirmed that reverse cationic flotation is the most promising method for iron ore beneficiation. However, the technological and economic performance of this process depends on the proper selection of beneficiation equipment and an optimal reagent regime.

Conclusions

Magnetic beneficiation methods do not yield high-quality concentrates due to ore depletion and the inclusion of silicate minerals, which degrade concentrate quality. The concentrate is fine-grained and comprises aggregates that are challenging to separate using magnetic separators. An analysis of flotation beneficiation processes at the Poltava and Ingulets Mining and Processing Plants, as well as enterprises in the USA and Canada, demonstrated that reverse cationic flotation is more efficient. Depending on feed quality, it can increase iron content to 69% or higher while reducing silica content to 3%.

Laboratory studies revealed that additional grinding operations in a closed circuit, combined with wet magnetic separation, can increase the iron mass fraction to 68.0-68.3% and reduce silica content to 4.3-4.6%. The flotation refining scheme that omits grinding the initial feed but includes froth product grinding in a closed circuit showed the poorest qualitative results for the final concentrate. The reduced iron mass fraction in the final concentrate was attributed to the presence of non-liberated grains with a particle size of +0.045÷+0.071 mm, containing 28.2-45.2% total iron. In this technological scheme, the total iron content did not exceed 68.0%.

The most efficient refining scheme for the raw concentrates of PJSC "Northern MPP" is the magnetic-flotation refining scheme with classification and grinding of the raw concentrate in a closed circuit. Laboratory tests confirmed that this approach can produce a concentrate with a total iron content exceeding 69.0% and silica content below 3%. Producing high-quality concentrate will enable its use in the production of DRI-class pellets, which is critical for the global steel industry's transition to "green energy". Future research will focus on improving the technological chain, particularly by determining the optimal feed particle size for flotation cells to enhance the quantitative and qualitative performance of the magnetic-flotation technology and optimise reagent consumption.

Acknowledgements

None.

Conflict of Interest

None.

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Розробка технології флотаційного збагачення магнетитових кварцитів приватного акціонерного товариства «Північний гірничо-збагачувальний комбінат»

Анотація. Метою роботи була розробка нової технології флотаційного доведення магнетитових концентратів на основі приватного акціонерного товариства «Північний гірничо-збагачувальний комбінат» для отримання кінцевого товарного продукту з массовою часткою заліза загального не менше 69,0 % і кремнезему не більше 4 %. Використано мінералогічний аналіз для дослідження розкриття мінералів, хімічний аналіз – для визначення якісного складу досліджуваної сировини та ситовий аналіз – для визначення гранулометричного складу матеріалу. В роботі також застосовано методи обробки, аналізу та синтезу результатів досліджень зі створення оптимальних умов розділення мінеральних зерен за крупністю. У результаті визначено, що досягнення максимальної масової частки заліза загального у концентраті та мінімальної масової частки кремнезему, при максимальному вилученні заліза, залежать від умов подрібнення, які визначаються ступенем розкриття мінеральних зерен. Встановлено, що константа швидкості флотації кварцу залежить від масової частки кварцу в живленні і становить 0,05-0,10 $хв^{-1}$. Мінералогічні дослідження рядового концентрату виявили, що до його складу входять, окрім мономінеральних частинок магнетиту, зростки магнетиту – кварцу (до 2,52 %), магнетиту – кварцу – силікату, магнетиту – кварцу, силікату – карбонату (до 7,5 %). Карбонат здебільшого представлений сидероплазитом, кальцитом; силікати – кумінгтонітом, біотитом, хлоритом. Нерудні часточки – мономінеральні кварцові або силікат – кварцові, карбонат – силікат – кварцові. Згідно з кількісним мінералогічним розрахункам, мономінеральні частинки магнетиту накопичуються в тонкозернистій фракції в класі -0,045 + 0,02 мм – 92,3 % та в класі -0,02 мм – 98,1 %. В результаті проведення лабораторних випробувань магнітно-флотаційного доведення концентрату доведено можливість отримання з магнетитових концентратів приватного акціонерного товариства «Північний гірничо-збагачувальний комбінат» високоякісного концентрату з масовою часткою заліза загального 69,0 % і оксиду кремнію 3 %, 88,9 % за виходом і 92,9 % вилученням заліза загального у концентрат від операції. Практична значимість полягає у розробці технологічної схеми доведення рядового магнетитового концентрату в умовах приватного акціонерного товариства «Північний гірничо-збагачувальний комбінат» для отримання високоякісного концентрату з максимальним виходом та масовою часткою заліза загального вище 69,0 % і кремнезему менше 4,0 % при вилученні заліза загального у концентрат більше 90 %

Ключові слова: концентрат залізорудний; флотація катіонна зворотна; сепарація магнітна; частка масова; склад гранулометричний

Journal homepage: https://mining-journal.com.ua/en

MINING JOURNAL
of Kryvyi Rih National University

Vol. 58, No. 2, 2024

Received: 23.07.2024; Revised: 11.11.2024; Accepted: 24.12.2024

UDC 622.2

DOI: 10.31721/2306-5435-2024-2-40-49

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Analysis and problems of the world's practical experience in the extraction of minerals by the combined open-pit and underground method

Abstract. The purpose of this paper was to review and analyse the world practice of combined open-pit and underground mining with further justification of its application at mining enterprises in Kryvyi Rih. The following methods have been used: analysis of practical experience in mining by the combined open-pit and underground method of the world's most famous mines; generalisation of the shortcomings of technogenically destructive technologies of open-pit mining of iron ore raw materials and modern environmental problems of open-pit mining; calculations of the multifactorial structure of dependence in the operation of a mining enterprise on environmental losses; methods of analysis. It has been established that it is necessary to develop a comprehensive strategy for the transition from the existing open-pit mining technology to the technologies of open-pit and underground mining, taking into account the stress-strain state of the rock mass. The relationship between iron ore production at mining enterprises and environmental costs was established. The results of the calculations showed that 99.74% of the variability of environmental costs is explained by changes in the factors affecting the environment, which are calculated in the presented structure, and the remaining residuals are due to the effect of unaccounted factors. The paper investigated and developed transitional technologies with the formation of an underground mining complex on the side of a quarry. A review and analysis of the problems of transition from open-pit mining to the technology of combined open-pit and underground mining of iron ore raw materials was carried out. It was established that in the long-term planning of the development of mining enterprises for the future, preference should be given to the combined or underground mining method. Based on the practical experience of world mines with combined production, a comprehensive strategy for the transition from the existing open-pit mining technology to the technology of open-pit and underground mining has been developed, taking into account the stress-strain state of the rock mass. The practical significance is to develop the optimal technology in the future, taking into account the identified shortcomings and problems of the combined open-pit and underground method at world mines for the conditions of the Kryvyi Rih iron ore basin

Keywords: technology; research; working; mining; ore; scheme

Suggested Citation:
Shepel, O. (2024). Analysis and problems of the world's practical experience in the extraction of minerals by the combined open-pit and underground method. *Mining Journal of Kryvyi Rih National University*, 58(2), 40-49. doi: 10.31721/2306-5435-2024-2-40-49.

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Introduction

In 2022-2024 in Kryvyi Rih iron ore basin there was such situation, that actually there are no executed basic researches concerning definition and management of stresses and deformations at a transition period on mining operations opencast on a complex underground extraction of deposits. Also, not enough scientific researches on the combined mining operations which provide working of chambers of the second turn under an opencast bottom under protection of a pillar with hardening backfill and the further filling of a niche of opencast with the fulfilled barren rocks. Therefore, mining of the basic hypotheses of definition and management of the main stresses and deformations which arise under a bottom of working opencast with transition on underground an extraction of minerals, research, and also mining complex resource saving up technology thanks to which it is possible to provide the combined way of the further extraction of minerals, is the important practical problem.

Mining operations in the world has led to that practically in all developed mining countries deterioration mining and specifications is observed. There is a constant change of depth of mining operations, thickness of ore deposits decreases, power inputs increase by extraction 1 tonnes of minerals. To gradual fall of depth of mining of minerals there is a sharp increase in volumes of barren rocks and the cost price of the further opening of deposits considerably increases, that considerably worsens the general economic indicators at mining operations opencast. It would be expedient to apply a parallel deposit opening to maintenance of a solution of the given questions in the underground way together with working opencast which gradually stops the activity, on achievement of critical depth by it.

Authors S. Pysmennyi *et al.* (2023) noticed that necessity of application of the open-pit or underground excavation methods are defined taking into account geological conditions of burial of deposits and necessary productivity of the enterprise. At transition to the combined ways of working of ore deposits it is possible to allocate following most typical cases of association of the open-pit and underground mining operations in time: the combined working of reserves by the open-pit and underground way within one deposit; completion of reserves of a deposit by the open-underground way with gradual transition exclusively for an underground way of working and the termination of open-pit excavation method; working of reserves of perspective blocks of a deposit by open-pit way and completion of unpromising regions by open-underground and underground ways. For maintenance of safety of operations in developments at transition from open-pit mining operations to combined or an underground extraction the technique of definition of parameters which is put forward to the future underground workings is offered. Also, certain destructive processes which arise at underground mining operations are described.

Concerning a location of mine and opencast from mineral reserves it is possible to allocate the basic ways of conducting mining operations: with combination of model opencast-mine on axis Y where underground mining operations occur below coffin; with combination of model opencast-mine on axis X where underground mining operations occur in a pit wall; it is combined on axes Y and X. The design procedure of the general geometry of opencast according to the further mining of a deposit (Marchelli *et al.*, 2023). According to a problem of systematic transition from open-pit mining operations to underground mining operations, or to the combined working of mineral deposits the methodology of an establishment of the is intense-deformed condition of a massif (Stupnik *et al.*, 2024). Thanks to the resulted dependences of stresses and deformations which are established, it is possible to establish effective depth and parameters of the further mining of mineral deposits.

By authors R.M. Nisaa & N.I. Fawzi (2023) it is established that the coal mining considerable rates increases in the open-pit way, however it leads to deterioration and degradation of the earths which become unsuitable for their further use. Considerable influence of open-cast mining is confirmed in city Bontang in Indonesia which leads to air contamination in its suburbs. In such conditions problems with health can receive the majority of people. In article are specified requirement for the big necessity of recultivation of the earths at development of mining operations. It is one of harmful indicators on whom it is possible to assert, that transition to the combined or underground excavation method of minerals is safer for a surface.

Authors A. Salkynov *et al.* (2023) bring results of mathematical modelling with calculations of parameters of an actual mining. According to received data the basic dependences which describe a stress and deformations in a massif near a working excavation are revealed. On the basis of these results of the resulted calculations practical solutions for application directly on a deposit are recommended. Also, it is specified, that at the basic calculations it is necessary to consider the main influencing physic mechanical properties of rocks and ores. A. Driouch *et al.* (2023) specified that safe further mining by underground way needs application of a method of mining with application 2D or 3D geotechnical numerical modelling. For research of the is intense-deformed condition of a massif the finite element method which gives the chance to receive more exact results of research will be offered. By means of the software it is recommended to carry out calculations of the is intense-deformed condition of a massif of transitional technologies from open-cast mining to an underground extraction. The mathematical approach to the description of stresses which arise in chambers under an opencast bottom at consecutive open-underground mining is offered.

By means of software H. Luo *et al.* (2024) recommend to carry out calculations of the is intense-deformed condition of a massif in tunnels which are exposed to a rock pressure. By such principle it is possible to apply the given approach at calculation of transitional technologies from open-pit mining to an underground extraction. The mathematical approach to the description of stresses which arise in a massif is offered agrees three key indexes. Scientist B. Rakishev (2023) notices that at mining of mineral deposits probably application resource saving up technologies which provide further a decrease of a contamination and losses of minerals. Thanks to technical solutions the considerable production efficiency is reached. Also, possibility of application of a variant of selective extraction of minerals which will improve mining quantity indicators is created. On the basis of such base terms as selective and resource saving up technologies of mining of deposits it will be developed effective practical solutions for working complex structural deposits.

The purpose of the study was to substantiate the use of the open-pit mining method in the Kryvyi Rih iron ore basin as the main method of deposit development, given that there is an urgent need for advance planning of deposit opening under existing mine pits.

Materials and Methods

Methods of research which were used in work: the analysis of practical experience on mining operations by the combined open-pit and underground methods of the famous world ore mines; generalisation of lacks of technogenic destructive technologies of open-pit mining iron of ore raw materials and modern environmental problems of open-pit mining of minerals; carrying out of calculations of the multifactorial form of dependence in work of the ore mining enterprise on ecological losses by means of settlement value of Student's coefficient; methods of analysis of the received data.

The analysis of practical experience on mining operations by the combined open-pit and underground methods of the famous world ore mines as problems which the world ore mining enterprises face will appear and in Kryvyi Rih iron ore basin was the basic method of research. At introduction in operation of extraction chambers which are under an opencast bottom, or in a pit wall, it is necessary to understand an overall picture of distribution of the main stresses and deformations which arise in a rock mass. Thus, it is possible to warn in advance extreme situations and to provide the future consequences at transition from the open-pit mining on combined technology.

Based on the practical experience of mining enterprises, the article summarises the disadvantages of technogenic and destructive technologies of open-pit mining of iron ore raw materials and modern environmental problems of open-pit mining. Understanding the main consequences for the ecology of the area caused by open-pit mining, it is possible to recommend effective resource-saving technologies for combined or separate underground mining. Based on the data from Official website of the Dnipropetrovsk Regional State Administration (n.d.), and also on the basis of the main problems and the reasons which arise, and consequences of application of open-pit mining of a deposit calculations of the multifactorial form of dependence in operation of the ore mining enterprise on ecological losses by means of settlement value of Student's coefficient are carried out. Indicators which directly or indirectly influence environment at open-pit mining of deposits were initial data for calculations.

For the purpose of revealing of the main dependences between indicators of interaction of mining iron ore mines on environment Kryvyi Rih iron ore basin and financing in nature protection functionality, had been applied the multifactorial form with one productive indicator Y and N causal indicators ($x_1, x_2, \ldots, x_n$). As causal indicators it is expedient to accept following key parameters of activity of factories: x_1 – the stored volume of overburdens (million m^3); x_2 – amount of the concentrated waste which remain on object (million tonnes); x_3 – amount atmospheric emissions (thousand tonnes); x_4 – the selected water (including water from storage reservoir) (million m^3); x_5 – downthrow or removal of recirculated waters (million m^3); x_6 – amount of the degraded daylight area (thousand tonnes); x_7 – the basic investments for protection of a surrounding habitat (million UAH). The analysis of the received results is carried out and the further effective of open-underground development of mining operations is offered.

Results

At carrying out of the analysis of practical experience on mining operations by the combined open-pit and underground way it is specified, that such ore mine as Ruttan Mine developed a copper deposit at first opencast, and then in the underground way. By underground operations in extraction chambers there was a backfill which warned displacement and daylight area destruction. Kamoto Mine in Katanga worked with long interruptions in operation, however since 2020 the mine again left on the planned volumes of a mining of copper and cobalt (Katanga Mining Limited..., 2019). The deposit most part is fulfilled by opencast. The basic underground reserves fulfil chamber systems with hardening backfill. Eight years were simultaneously conducted operations on extraction of a deposit by opencast and underground way. Hardening backfill requires additional expenses connected with its cost, preparation and transportation, however provides firmness day surface.

In Kazakhstan, an interesting example of the combined working of deposits is a Tishyn deposit ore. The deposit looks like some parallel steeply dipping ore bodies with names "Osnovne" and "Paralelne". Deposits have big enough fluctuation of the sizes of thickness. Deposit reserves have started to fulfil opencast with gradual transition to the combined mining. Accordingly carrying out of the uncovering main and air shafts, and also inclined ramps (Fig. 1) in advance has begun. On an ore mine the thick high-efficiency equipment on transportation, both in opencast, and in underground workings (Dyachkov *et al.*, 2021). The deposit of ore mine Finsch (Fig. 2) is one more interesting example of the combined mining. Ore mine Finsch concerns one of world leaders on extraction of diamonds. In this region there is one more thick ore mine Venetia, that also extracts diamond.

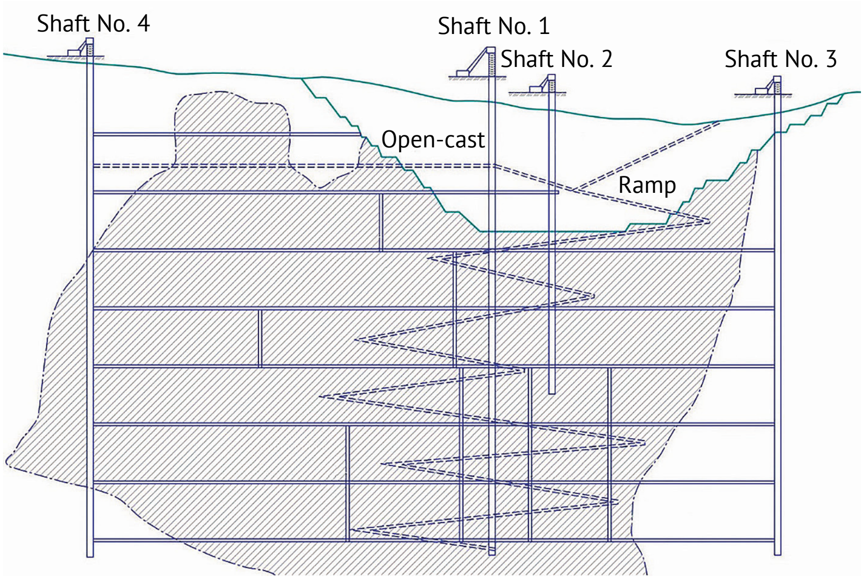

Figure 1. *Scheme of combined working of Tishyn ore reserves*

Source: *developed by the author*

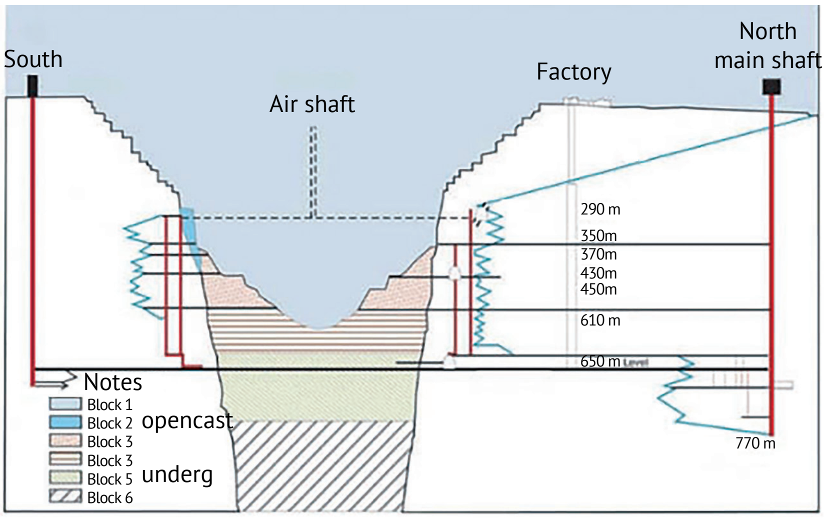

Figure 2. *Combined working of the deposit by the Finsch mine*

Source: *developed by the author*

In the beginning of a mining the deposit was fulfilled by opencast. Then consistently mining of a deposit was conducted by underground way under a coffin bowl. Opening of a block of underground mining operations is carried out from a surface by spiral ramps to level 680 m and shaft depth 763 m (Khati & Matabane, 2019). Operations are conducted by system of a floor induced caving on level of 630 m. On an ore mine apply highly heading equipment longwall sets of equipment, including – for drilling on complete section rising in diameter 2.9 m and more. On coal-face works for drilling of deep boreholes use a semi-automatic drilling complex "Tamrock" with dry drilling of boreholes (depth of boreholes more than 40 m).

One more classical technology combined open-underground mining deposits can be observed on ore mines Craigmont Mine in Canada (Fig. 3) and diamond mine Koffiefontein Mine (Fig. 4), located for 80 km from Kimberley in Southern Africa. Last is one of many mines Kimberley among which the most known neighbors are mine De Beers Consolidated Mine. By underground operations mining methods of a sublevel caving of ore and adjacent strata, in some cases of mining method with a caving of ore and strata are extended.

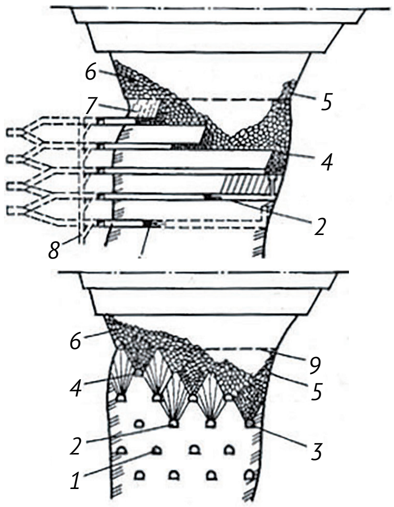

Figure 3. *Combined mining of deposits at the Craigmont Mine in Canada*
Notes: *1, 2 – blind gallery; 3 – drawing and loading of broken ore by self-propelled loading and transport machines; 4 – breaking; 5 – field boundaries; 6 – broken ore; 7 – boreholes; 8 – ore chute; 9 – contour of the lower border of the opencast*
Source: *developed by the author*

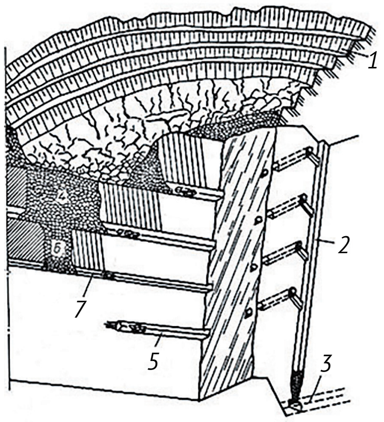

Figure 4. *Combined mining opencast-mine at mining of deposits at the diamond Koffiefontein Mine*
Notes: *1 – opencast bench; 2 – ore chute; 3 – haulage gate; 4 – broken ore of the second underground level; 5 – carrying out of loading and blind gallery; 6 – broken ore of the third underground level; 7 – drilling out of blastholes*
Source: *developed by the author*

One of high-efficiency mines with the combined mining operations is Kiruna mine. On an ore mine 30 million tonnes ore and accompanying raw materials is extracted annually almost. Until the 1960 mine produced ores opencast. Since 1961 mining of iron ores is carried out by underground way. The ore mine extracts rich magnetite ores. A development is conducted on level – 1,345 m. Deposit of iron ores on Kiruna mine is opened by the shafts driven on a lying side in barren rocks. From shaft on which ore to a deposit stands out crosscuts are spent. The mine field is divided into eight sections, everyone with own ore chute and ventilating system. Level reserves are allocated on sublevels in height of 28.5 m. From a surface to level which is fulfilled, there are driven spiral ramps for moving of the self-propelled equipment.

Ore mine Kidd Creek (Fig. 5) in Ontario, Canada is an example of conducting mining operations over 1,500 m. The ore mine develops complex ores. Along with copper and zinc here too extract indium, copper-nickel carbonate and other. A deposit has started to develop in 1966 in the open-pit way. Since 1968 the combined mining which occurred to gradual transition is applied. Carrying out of underground workings has begun for 100 m to final depth of opencast. Therefore, in advance all main workings before actual closing down in mining opencast have been spent. The transitional period lasted about ten years (Rankin *et al.*, 2024). The given ore mine is indicative in respect of performance of operations in some stages of opening. That is in parallel with opencast deposit working in the Stage 1 of opening has begun, depth to 1,400 m (Stage 2) gradually increased. Carrying out of underground workings to depth of level of the Stage 3 (level of 2,070 m) is gradually carried out.

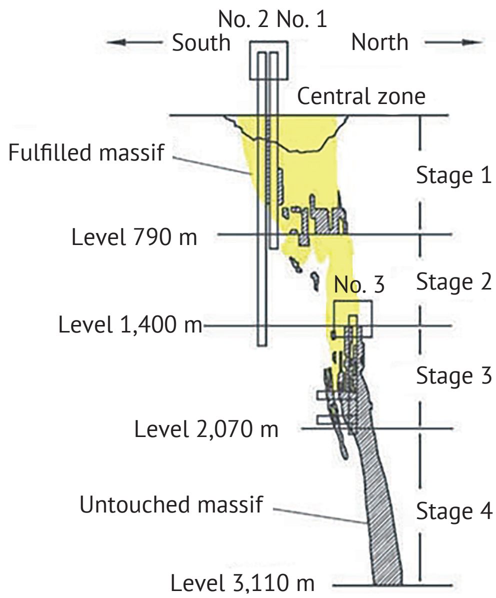

Figure 5. *Opening scheme of deposit Kidd Creek in the underground way*
Source: *developed by the author*

Also, the complex of capital ore chutes and two air raises (one is driven from opencast from depth 150 m) have been spent. In connection with considerable fluctuations of quality and irregularity of an ore mining in 2 times the capacity of sorting structure has been increased. In process of development of an underground mining capacity of opencast decreased, however the stable volume of an ore mining and constant load level of a preparation plant thus remained. The deposit is opened from a surface to level of 1,400 m. In carrying out there is a shaft No. 3, that working of reserves will provide the Stage 2 of opening to level of 2,070 m. In the long term is planned to depth of 3,100 m. The enterprise uses powerful drilling, loading, and transport equipment of the manufacturers "Ingersoll Rand", "Mission", "Cubex", "Tamrock" and others.

Analysis of the brought basic technologies gives the chance to tell, that at transition to the combined ways of working of mineral deposits under a bottom working, or the suspended opencast by the basic problem stabilisation of geodynamic processes in rock massif. Thus, there is a pressing question of transition on complex opencast-mine or underground working of deposits. Thus, there is a necessity of definition of parameters of technology of open-underground and underground mining operations, including with backfill of the fulfilled space, and regularities of the main stresses and deformations which define conditions of their application.

On the basis of the spent analysis it is established, that there is a necessity of carrying out of the review of the basic lacks of technogenic and destructive technologies of open-pit mining iron of ore raw materials and modern environmental problems of open-pit mining of minerals. The basic nature protection questions of mining regions are caused by the increased share of a contamination of environment. So, for example, the pivotal indicators which influence quality of air of the Kryvyi Rih, it is the caused industrial operations of mining ore mines and metallurgical plants, and also transport (Fig. 6).

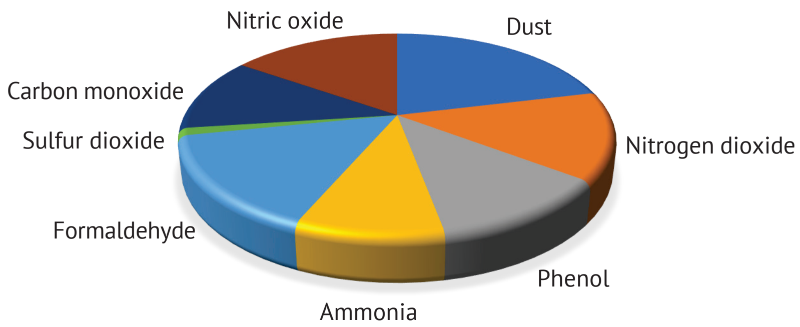

Figure 6. *Indicators of environmental contamination of territory Kryvyi Rih*
Source: *compiled by the author based on Ecological passport of Dnipropetrovsk region for 2023 (2024)*

For 2023, to atmosphere has got 16.3 million tonnes carbon dioxide which is the basic hotbed gas responsible for changes in a climate (Regional report..., 2024). The second dangerous environmental problem of mining regions are pollution of natural reservoirs. Pollution of water objects is carried out, as a rule, by downthrow of harmful impurities of mining objects and other. Removal of the polluted technical water in natural reservoirs for 2023 makes 515.964 million m^3 (the indicator has decreased for 4.7% in comparison with last year), consisting of: harmful – 106.637 million m^3; pure according to norms – 246.737 million m^3; cleaned – 162.59 million m^3 (Ecological passport..., 2024).

Working of deposits by open-pit way has considerable anthropogenic effect on surrounding habitat thus ecological position worsens. If to look the updated card Kryvyi Rih iron ore basin through Google maps with satellite display it is visually possible to see considerable breakages, downfalls, daylight area falls. The natural landscape which looks like huge breakages as after the bombardment, the forbidden zones with cavities and ledges because of direct action of open-pit mining, dumps, slime stores changes. Annual volumes of barren rocks which are transported to dumps, make 71 million m^3 which include of tailings and barren rock about 53 million tonnes, deformed the considerable area of a daylight area of 34,000 hectares, and from them annually recultivation only 100 hectares. Totally economic losses from described above factors for Kryvyi Rih iron ore basin can be estimated in some hundred million dollars.

Leaning against initial data it has been calculated plural to a determinant which has made size $R^2 = 0.9974$ and a multidimensional indicator of connection which is equaled accordingly $R = \sqrt{0.9974} = 0.995$. Calculations have shown that following results were approximately 99.74% variability of ecological expenses speaks change of factors which influence surrounding habitat which are calculated in the presented form and the rests – action of not considered factors. As $R > 0.9$, force of correlation is very strong. The calculated size of Student's coefficient above for tabular ($t_{tab} = 2.45$, attached to $n - m - 1 = 6$), hence a multidimensional indicator of connection R is the meaning. Other results calculations are brought in the Table 1.

Table 1. *Results of calculations of a multicomponent form of dependence in the work of a mining enterprise on environmental losses*

Index name		Calculated value	Indicator		Calculated value
Regression coefficients	y_0	-30,801.01	Reliability coefficients of regression coefficients (Student's coefficient value)	l_0	2.059
	y_1	1.59		l_1	3.83
	y_2	3.07		l_2	1.64
	y_3	0.26		l_3	2.83
	y_4	-0.53		l_4	0.48
	y_5	2.62		l_5	2.15
	y_6	4.07		l_6	1.17
	y_7	0.60		l_7	5.87
Errors of regression coefficients	S_0	14,959.787	Variance	v_1	7
	S_1	0.417		v_2	6
	S_2	1.874	Fisher adequacy criterion	f	167
	S_3	0.092	Table value of Student's coefficient	t	2.4469
	S_4	1.112			
	S_5	1.220			
	S_6	3.472	The tabular value of Fisher's test	f_{tab}	4.2150
	S_7	0.103			

Source: *developed by the author*

Thus, the executed researches allow to define an optimum direction of the further prospect of mining operations in region. The basic condition is necessity of gradual transition from the technogenic and destructive opencasts located on a daylight area, on modern ecologically safe technologies of the combined and underground mining operations (Veliyev, 2021). The basic advantages at working of mineral deposits by underground way or together with working opencast are following factors: reduction of losses of territories under formation of opencasts and waste heaps; improvement of an ecological condition of a daylight area of basin and cleanliness of air in areas of transition to complex technologies of mining operations; an intrusion of application of selective extraction at an ore mining; application, barren rocks from opening opencast, as accompanying material at manufacturing, for example the building goods; possibility of creation of reserved territories, recreational zones after achievement by opencasts of critical depth of mining.

So, results of the executed researches show, that in Kryvyi Rih iron ore basin, as well as in others iron extracted regions of Ukraine, underground excavation method not only does not concede opened for the basic technical and economic indicators, but also surpasses it for separately isolated factors, such as preservation of the environment. Therefore, at forward planning of development mines on the future it is necessary to prefer combined, or to underground excavation method. Technologies of mining of minerals are expedient for applying in cases when high efficiency of operation and considerable scales of manufacture get crucial importance in object view achievement. So, if mines of Ukraine with open-pit excavation method of iron ores do not take advantage of the nearest years of possibilities of halving of a complex mining in model opencast-mine next years they it is reached such cost price on which profitability of opencasts will come nearer to zero, and a number of opencasts become unprofitable.

Such conclusion is confirmed by calculations according to which combined open-underground, and in the future exclusively underground mining allows to reduce on the average on one opencast opening volume to 2.5-6.5 million m^3, considerably to reduce factor of opening with 3.0-3.5 to 0.1-0.2 m^3/tonnes, to lower a production cost on 35-55%, to increase by 20-35% profit. Except material advantages, improvement of an ecological condition of a daylight area of basin and cleanliness of air in areas of transition to complex technologies of mining operations is the core by environment preservation.

Discussion

S. Pysmennyi *et al.* (2022) notice that for reduction of the cost price of stripping at open-pit mining of mineral deposits it is expedient to form internal spoil heaps of barren rocks on boards of working opencasts. But there is actual enough problem of the further operation of opencasts in conditions when the significant number of barren rocks simply blocks in the volume access roads, the contamination of benches and other problems is created. Internal spoil heaps would be expedient for forming in opencasts provided that in them critical depth of mining is reached. That is, such conditions which opencasts without conducting underground mining operations do not allow to exploit further are created. Then it is possible to use not involved benches of opencasts under dumps of barren rocks. By researches in article it is proved, that it is necessary to use the complex approach of transition from open-pit mining operations to combined, or exclusively underground. The given approach will reduce outbursts of harmful substances, will improve ecological position of region, and also will give the chance to utilise a significant number of barren rocks which usually remained in dump.

In spent researches M. Byle *et al.* (2024) it is offered to investigate long working supervision features of formation on a daylight area of caving zones and displacement zones at mining of mineral deposits in the conditions of a karst deposit. It is offered to observe of a part of a daylight area which directly contacts to a working excavation of the bottom level which is fulfilled in more details. Thus, it is recommended to pay especially attention to physical and mechanical properties above lying soils, such as fracturing, humidity and other. Also, it would be possible to recommend working of the top part of a deposit by open-pit way. Further with application of the same systems with a caving of ore and adjacent strata. If insufficient durability above lying soils, it would be more expedient to form a pillar from hardening backfill between a daylight area and a working excavation to warn a caving.

In scientific paper Y. Zhang & G. Sun (2020) it is specified, that open-pit mining operations in opencast on a coal mining have rather low complexity of operations and a production cost. However, in scientific paper it is specified nothing about considerable ecological influence on environment, considerable outbursts of harmful substances, considerable zones of alienation of a daylight area under opencasts. In the scientific paper in the open-pit way without consequences of such type of mining of minerals the problem of increase in efficiency of a coal mining dared at environment and ecological aspect as a whole. An effective coal mining in the open-pit way it would be expedient to spend taking into account results of researches of influence of harmful factors on nature protection indicators. For example, it is possible to create the plural form, model or structure to calculate plural to a determinant which will generate a direction of the further researches.

Authors Y. Zhang & G. Li (2020) methods of optimisation which are based on technologies of an artificial intellect of systems of decision-making at open-pit mining of mineral deposits are offered. In their article the basic lacks of open-pit mining of mineral deposits is described, but the ecology problem here too is not considered at conducting such way. It would be interesting to learn about application of an artificial intellect in the conditions of the combined mining when it is necessary to fulfil the deposit most part in the future in the underground way with application of an industrial plane of opencast in the industrial purposes. In the conditions of difficult environmental problems which arise at conducting open-pit excavation method of deposits, the intrusion of bases of an artificial intellect in settlement program complexes would be original idea at a solution of some problems. For example, calculations of technical and economic indicators of the basic processes of underground mining operations with artificial intellect application.

Scientists Y. Lu *et al.* (2024) research of stresses and deformations of benches and a massif is considered at deposit working by open-pit way. It is proved, that mining of a mineral deposit by opencast has considerable destroying actions on an earth daylight area. In research the complex approach for a regular estimation of shifts of pit walls is used. It is one of operations devoted to consideration of a problem of the increased inflow of water of opencast which influences directly the further mining of a deposit by underground way in the conditions of deep levels. However, in operation it would be possible to consider in the form of multifactorial model and other influencing indicators which are not considered in research.

At analysis of considerable territories of a daylight region at mining of deposits by the ore mining enterprises it has been analysed and compared geologic structure of surfaces for the purpose of analysis of degree of influence on the ecological factor. At an extraction of minerals there are destroyed fields of a daylight region which require recultivation and restoration of natural balance. To such questions though and on an example of the Lviv-Volyn coal basin, researches have been devoted K. Baraban *et al.* (2023).

So, at the general estimation of environment at transition from open-pit mining operations to the combined or underground excavation method of deposits it is possible to use pictures of satellites which give the evident image of a problem. Thus, it is possible to consider invisible from a daylight region to a human eye indicator. In general, the environment estimation at influence of activity of mining operations should be complex. All factors, such both physical and mechanical properties of ore and soils, and the main stresses and deformations in a massif that will give the chance to apply safely at mining of mineral deposits the combined way should be considered.

Conclusions

For the purpose of definition of the basic dependences between indicators of interaction of a mining iron ore mines on environment Kryvyi Rih iron ore basin and financing in nature protection functionality, had been applied the multifactorial form, as factorial signs key parameters of activity of factories have been accepted, including the stored volume of overburdens, volume of washery refuses and harmful impurities which gets to air, considerable failures of the earths, capital investments into ecology of extracting areas and other. It has been calculated plural a determinant which has made $R^2 = 0.9974$ and a multidimensional indicator of connection which is equaled accordingly $R = \sqrt{0.9974} = 0.995$. Calculations have shown that results were approximately 99.74% variability of ecological expenses speaks change of factors which influence surrounding habitat, and the rests – action of not considered factors are calculated in the presented form. In the future transitional technologies with formation of an underground extracting complex in a pit wall and separately under a bottom of working opencast will be investigated and developed. It is confirmed, that combined open-underground, and in the future exclusively underground mining allows to reduce on the average on one opencast opening volume to 2.5-6.5 million m^3, considerably to reduce factor of opening with 3.0-3.5 to 0.1-0.2 m^3/tonnes, to lower a production cost on 35-55%, to increase by 20-35% profit. Except material advantages, improvement of an ecological condition of a daylight region of basin and cleanliness of air in areas of transition to complex technologies of mining operations. The further research will consist in definition of dependences of the main indicators of stresses and deformations in an opencast operative range at transition to an underground mining magnetite quartzites chamber mining methods with the combined backfill. Researches of the is intense-deformed condition of rock massif of an open-pit field will be carried out at mining operations by exclusively open-pit way.

Acknowledgements

None.

Conflict of Interest

None.

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Аналіз та проблеми світового практичного досвіду з видобутку корисних копалин комбінованим відкрито-підземним способом

Анотація. Метою даної роботи були розгляд та аналіз світової практики з видобутку корисних копалин комбінованим відкрито-підземним способом з подальшим обґрунтуванням його застосування на гірничих підприємствах Кривого Рогу. Використані наступні методи: аналіз практичного досвіду з видобутку корисних копалин комбінованим відкрито-підземним способом найвідоміших світових рудників; узагальнення недоліків техногенно-деструктивних технологій відкритого видобутку залізорудної сировини та сучасних екологічних проблем відкритої розробки корисних копалин; проведено розрахунки багатофакторної структури залежності в роботі гірничорудного підприємства на екологічні втрати; методи аналізу. Встановлено, що необхідна розробка комплексної стратегії переходу з існуючої відкритої технології видобутку сировини на технології відкрито-підземного та підземного видобутку корисних копалин з врахуванням напружено-деформованого стану гірського масиву. Встановлено залежність між показниками видобутку залізної руди на гірничорудних комбінатах та витратами в навколишнє середовище. Результати виконаних розрахунків свідчать, що 99,74 % варіативність екологічних витрат пояснюється зміною факторів, що впливають на навколишнє природне середовище, які розраховані в представленій структурі та інші залишки – дією неврахованих чинників. В роботі досліджено та розроблено перехідні технології з формуванням підземного видобувного комплексу в борту кар'єра. Виконано огляд та аналіз проблем переходу від видобутку корисних копалин відкритим способом на технології комбінованого відкрито-підземного й підземного видобутку залізорудної сировини. Встановлено, що при перспективному плануванні розвитку гірничодобувних підприємств на майбутнє слід віддавати перевагу комбінованому, або підземному способу розробки. На основі практичного досвіду світових рудників з комбінованим видобутком розроблено комплексну стратегію переходу з існуючої відкритої технології видобутку сировини на технології відкрито-підземного та підземного видобутку корисних копалин з врахуванням напружено-деформованого стану гірського масиву. Практична значимість полягає в розробленні оптимальної технології в майбутньому з врахуванням встановлених недоліків та проблем застосування комбінованого відкрито-підземного способу на світових рудниках для умов Криворізького залізорудного басейну

Ключові слова: технологія; дослідження; відпрацювання; розробка; руда; схема

Journal homepage: https://mining-journal.com.ua/en

MINING JOURNAL
of Kryvyi Rih National University

Vol. 58, No. 2, 2024

Received: 06.08.2024; Revised: 12.11.2024; Accepted: 24.12.2024

UDC 622.8

DOI: 10.31721/2306-5435-2024-2-50-55

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About the connection of the total porosity of fossil coal with metamorphic transformations of coal seams

Abstract. Studying the porosity of minerals, in particular coal, and understanding the relationship between its structure and characteristics and properties is necessary for rationalising the use of coal, optimising processing processes, and finding new methods of combating sudden emissions or gas release. The goal was to establish the level of correspondence between the calculated values of the total porosity of coal (according to the empirical equation) and their experimental determination by standard methods, as well as to determine the indicators of the closeness of the correlation dependence of the total porosity on the degree of metamorphic transformations. The research methodology was based on the analysis of the comparison of the compliance of the calculated values of the total porosity for each separate coal seam according to the empirical equation with their values established by standard methods. The results indicated that the physical characteristics of coal, in particular density and porosity, change with the increase in the degree of metamorphism. The porosity of coal, the structure of its porous system and the specific surface determine the filtration, diffusion and sorption processes both in natural conditions of occurrence and during their changes under the influence of various physical and chemical factors. It has been proved that there is a practical absence of correlation between the total porosity of fossil coal and metamorphic transformations of coal seams when assessing the impact of these processes, taking into account the volatile substances yield. The total porosity is a unique characteristic of a particular coal seam within a mine field and is only partially determined by the volatile content. The averaged empirical dependencies on the volatile matter yield provide only a general idea of the trends in coal porosity during metamorphic transformations of coal seams. The results of the experiments make it possible to develop proposals for improving the regulatory

Suggested Citation:
Rudniev, Ye., Antoshchenko, M., & Popovych, V. (2024). About the connection of the total porosity of fossil coal with metamorphic transformations of coal seams. *Mining Journal of Kryvyi Rih National University*, 58(2), 50-55. doi: 10.31721/2306-5435-2024-2-50-55.

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framework for predicting the manifestation of dangerous properties of coal seams during mining operations. The facts revealed in the research can be used in regulatory documents to predict the dangerous properties of coal seams, as they allow the development of proposals and methods for improving the regulatory framework for safe mining operations. This will lead to a decrease in the level of accidents with serious consequences, industrial injuries at coal mining enterprises

Keywords: coal seam; dangerous properties; coalification; labour protection

Introduction

The issue of coal porosity and related phenomena is of great practical importance, as it relates to the problems of gas capacity and gas carrying capacity of coal seams, the solution of which would make it possible to predict and manage the release of gases in mining operations. Management of gas release directly depends on the content of methane in mining products, the amount of which can be contained under certain conditions in fossil coal, is closely related to the structure of the coal substance. Porosity defines the physical properties of the rock, its overall strength, rate of propagation of elastic waves, compressibility, electrical and other characteristics.

Scientists T. Wang *et al.* (2023) emphasised in their work that the pore-related characteristics of coal include porosity, specific surface area, pore volume, pore size distribution and their relationship. Studying the porous structure of various fossil coals and establishing its relationship with other characteristics or features of coal, their properties is necessary for the rational use of coal, optimisation of their processing processes, and also, as noted by O. Bazaluk *et al.* (2024), to develop effective methods for suppressing hazardous emissions in coal or preventing emissions.

The nature of the hazardous properties of coal seams, namely the release of explosive gas and dust, unexpected gas and coal emissions, spontaneous combustion of coal, explosiveness of coal dust and other undesirable phenomena, has not been fully disclosed by 2024, therefore, ignoring occupational safety, using outdated mining technologies and methods results in accidents with serious consequences for workers. The problem of injuries and accidents at enterprises has been considered by many scientists (Nosal *et al.*, 2021), and is still at a fairly high level. As noted by V. Tarasov *et al.* (2021), the problem of endogenous fires and explosions of methane-air mixtures, which lead to deaths, is of particular importance in coal mining. M. Onifade & B. Genc (2020) noted that a number of different methods have been applied to minimise these cases, but the problem still remains. Accordingly, scientific research aimed at solving these problems is relevant for all coal-mining countries of the world.

The aim of the work was to evaluate the strength of the correlation between total porosity and the degree of metamorphic changes in coal.

Materials and Methods

All types of solid fuel have a porous structure. The actual sample density ($d_r^{\,d}$) is always greater than the apparent density ($d_a^{\,r}$). Their difference refers to the value of the actual density and is expressed as a percentage, which characterises the total porosity (P_r) of the coal:

$$P_r = \frac{d_r^d - d_a^r}{d_r^d} \cdot 100. \qquad (1)$$

According to the same dependence, the value of P_r was calculated for a set of 590 coal seams according to the catalogue of collector properties of hard coal and anthracite (Makiyivka State Research..., 1985). For this set of coal seams, the values of $d_r^{\,d}$ and $d_a^{\,r}$ were determined experimentally according to DSTU GOST No. 2160:2019 (2019) and ISO No. 5072:2021 (2021). For the second set of 186 coal seams, the values of P_r were calculated according to equation (1), but using the estimated values of $d_r^{\,d}$ and $d_a^{\,r}$ according to empirical dependencies. The catalogue (Makiyivka State Research..., 1985) does not provide indicators of the closeness of correlation for these dependencies. The total volume of pores $P_{r(p)}$ in absolute terms for coal unloaded from rock pressure according to the catalogue (Makiyivka State Research..., 1985) was determined using the values of the actual ($d_r^{\,d}$) and apparent ($d_a^{\,r}$) densities according to equation (2):

$$P_{r(p)} = \frac{d_r^d - d_a^r}{d_r^d \cdot d_a^r}, \text{cm}^3/\text{g}. \qquad (2)$$

When determining $P_{r(p)}$ according to equation (2) for a set of 590 coal seams, the experimental values of $d_r^{\,d}$ and $d_a^{\,r}$, were used, established in a standard way in accordance with the requirements specified by V. Tarasov *et al.* (2021). For the second set of 186 coal seams, their values were calculated according to empirical equations. In addition, the values of $P'_{r(p)}$ were calculated in parallel to control the accuracy of calculations, according to empirical equation (3), depending on the yield of volatile substances during the thermal decomposition of coal in a vacuum (V^{daf}):

$$P'_{r(p)} = 0.114 - 0.006V^{daf} + 0.00013(V^{daf})^2, \text{cm}^3/\text{g}. \qquad (3)$$

The degree of compliance of the calculated values of $P_{r(p)}$ according to empirical equation (3) with their experimental determinations by standard methods was not established. For a long period of time, V^{daf} was the only indicator of metamorphic transformations of seams when determining the consumer qualities of coal in accordance with the geological and coal-chemical map of the Donetsk basin (Donetsk State Coal Research Institute, 1954). It remains one of the main criteria in the modern classification of coal by genetic and technological parameters according to DSTU No. 3472:2015 (2015), and is also the main indicator of metamorphism in determining the susceptibility of coal seams to gas-dynamic phenomena (Order of the Ministry of Energy and Coal Industry of Ukraine No. 868, 2011). For these reasons, the V^{daf} indicator has been studied to a greater extent than other criteria, and its values are given in the catalogue (Makiyivka State Research..., 1985). This makes it possible, using the value of V^{daf}, to estimate the degree of influence of metamorphic transformations of the seams on changes in the total porosity of coal.

The methodology is based on a comparative analysis of the relationship between the calculated values of the total porosity $P'_{r(p)}$ for each of the set of 590 coal seams according to empirical equation (3) and their value $P_{r(p)}$, determined by standard methods using equation (2). For the analysed set of 590 coal seams, the closeness of the correlation with the volatile yield V^{daf} was determined by statistical processing by the least squares method of the total porosity values calculated using the experimental values of the real (d_r^d) and apparent (d_a^r) densities according to equations (1) and (2).

Results and Discussion

The graph comparing the calculated values of the total porosity $P'_{r(p)}$ according to empirical equation (3) with their determination by standard methods $P_{r(p)}$ according to equation (2) showed significant differences in the analysed ratios, as shown in Figure 1.

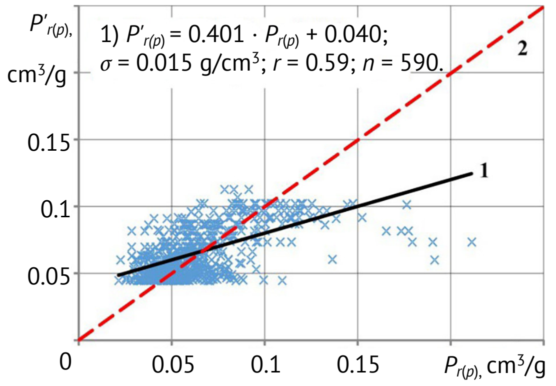

***Figure 1.** Interrelation between the calculated values of total porosity and their determination for a set of 590 coal seams according to the methodology of current standards*

***Notes:** × – the established ratio for each coal seam between the values of $P'_{r(p)}$ and $P_{r(p)}$; 1 – averaging line; 2 – bisector of the coordinate grid; r – correlation coefficient; σ – root mean square deviation; n – the number of processed data pairs*

***Source:** authors' development*

In this case, there is no presence of high correlation interdependence ($r = 0.59$). The presence of maximum distances of points in relation to the bisector of the coordinate grid when $P_{r(p)} > 0.15$ cm³/g (2), which determines the equality of $P'_{r(p)}$ and $P_{r(p)}$, indicates insufficient accuracy in determining the total porosity of $P'_{r(p)}$ using the empirical equation (3). The direction of changes in the total porosity of coal ($P_{r(p)}$ – equation (1) and $P'_{r(p)}$ – equation (2)) during metamorphic transformations for a set of 590 coal seams is illustrated by graphs of their dependence on the yield of volatile substances (V^{daf}), which are shown in Figure 2.

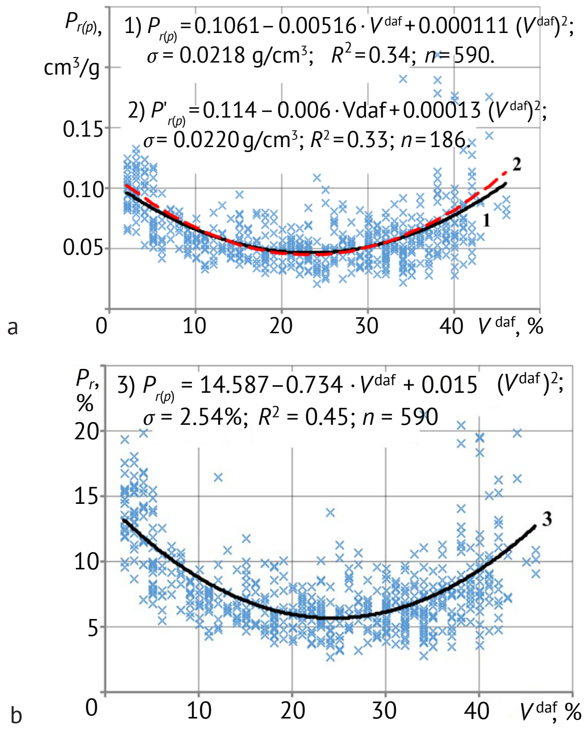

***Figure 2.** Dependence of the values of the total porosity of coal ($P_{r(p)}$ and P_r), determined according to the methods of generally accepted standards for a set of 590 coal seams on the release of volatile substances (V^{daf})*

***Notes:** × – values of total porosity $P_{r(p)}$ (a) and P_r (b), determined according to equations (2) and (1) using real (d_r^d) and imaginary (d_a^r) density; 1 – empirical average curve of the second-order polynomial obtained by the least squares method for a set of 590 coal seams; 2 – the average curve of the calculated values of the total density ($P'_{r(p)}$) for a set of 186 coal seams according to equation (3); 3 – the empirical average curve of the second-order polynomial obtained by the least squares method for a set of 590 coal seams; σ – root mean square deviation; R^2 – coefficients of determination; n – number of processed data pairs*

***Source:** authors' development*

The second-order polynomial shown in Figure 2(a), curve 1, characterises a rather low, practically absent, correlation between total porosity and volatile yield. The tightness of the connection (R^2 and σ) for the analysed complex of 590 coal seams is 0.34 and

0.0218 cm^3/g, respectively. Curve 2 is characterised by approximately the same correlation indices ($R^2 = 0.33$ and $\sigma = 0.0220$ cm^3/g), in relation to the set of 590 coal seams. This curve corresponds to empirical equation (3). Almost identical correlation indicators for curves 1 and 2 indicate that the use of averaged calculated values of $P'_{r(p)}$ according to equation (3) did not affect the overall accuracy of determining $P_{r(p)}$ according to equation (2).

The obtained results show that the total porosity of fossil coal is a strictly individual characteristic of a particular coal seam, which is slightly dependent on the yield of volatile substances. The average empirical dependences on this indicator give only partial insight about the direction of change in the total porosity of fossil coal during metamorphic transformations of coal seams.

The task of determining the volume of fossil coal is characterised by the problems of gas capacity and gas content of coal seams. The work by W. Han *et al*. (2020) indicate that the pore structure of coal is an important indicator for measuring the occurrence of coalbed methane and the actual operational capacity of coal mines. Despite a huge number of works in the field of coal physics, there is no single theory for the structure of fossil coals. According to the most general idea, based on X-ray diffraction and electron microscopy, coals of various modifications are considered as systems constructed of small graphite-like fragments (crystallites) randomly oriented in volume and chain non-aromatic part, as indicated by J.H. Shinn (1984) and A. Oberlin (2021).

The porosity of coal, together with the structure of its pore system and specific surface area, plays a key role in regulating the processes of filtration, diffusion and sorption. These processes take place both in the natural conditions of coal deposits and during coal transformation as a result of various physical and chemical effects. In some cases, these factors include the processes of metamorphic transformations of coal seams. Under the influence of these processes, the ratio between porosity types may change. It is divided into three main types: general (or physical), effective and open. Physical porosity includes the volume of isolated and connected pores. An open porosity refers to the volume of interconnected pores that are filled with gaseous or liquid fluids when the rock is saturated in a vacuum. Open porosity is less than the total porosity per volume of isolated pores. The effective porosity determines the fraction of the volume occupied by a moving fluid when the pore space is sufficiently saturated with this fluid. B. Ma *et al*. (2020) noted that the effective porosity is defined as the ratio of the volume of interconnected pore space to the total volume of the porous sample.

The porous structure of fossil coal is directly related to its crystal structure. T. Wang *et al*. (2023) found that coal pores are mostly micropores and account for more than 90% of the total pores. As of 2024, the presence of pores with a size of 10^{-3}-10^{-9} m in the structure of fossil coal can be considered proven. Porosity determination methods based on grinding and pycnometry experiments give misleading results without taking into account closed porosity. The problem of closed porosity is studied from the standpoint of gas adsorption, small-angle X-ray and neutron scattering techniques.

Conclusions

The insufficient accuracy of determining the total porosity using the empirical equation was established, which is confirmed by the presence of maximum point removals with respect to the bisector of the coordinate grid at $P_{r(p)} > 0.15$ cm^3/g, which determines the equality $P'_{r(p)}$ and $P_{r(p)}$. The almost identical correlation coefficients of the dependences of the total coal porosity ($P_{r(p)}$ and P_r) on the volatile matter yield indicate that the use of the averaged calculated values of $P'_{r(p)}$ did not affect the overall accuracy of the determination of $P_{r(p)}$. The total porosity of fossil coal is a strictly individual characteristic of a particular coal seam, which to some extent depends on the volatile matter yield. Based on the averaged empirical dependences on (V^{daf}), it is possible to state the direction of change in the total porosity of fossil coal during metamorphic transformations of coal seams. For the first time, the practical absence of correlation between the total porosity of fossil coal and metamorphic transformations of coal seams was proved when assessing the impact of these processes using the volatile substance yield. Prospects for further research are the need to develop more accurate methods for determining the total and closed porosity of coal, in particular, taking into account its micropore structure and metamorphic changes, as well as studying the effect of porosity on filtration and sorption processes in mine operation conditions.

Acknowledgements

The authors express their gratitude to Doctor of Technical Sciences, Professor V. Tarasov for his interest in the work and valuable comments during the discussion.

Conflict of Interest

None.

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Про зв'язок загальної пористості викопного вугілля з метаморфічними перетвореннями шахтопластів

Анотація. Вивчення пористості корисних копалин, зокрема вугілля, та розуміння зв`язку його структури з характеристиками та властивостями необхідне задля раціоналізації застосування вугілля, оптимізації переробних процесів та знаходження нових методів боротьби з раптовими викидами або газовиділенням. Мета полягала у встановлені рівня відповідності розрахункових значень загальної пористості вугілля (відповідно до емпіричного рівняння) їх експериментального визначення стандартними методами, а також визначити показники тісноти кореляційної залежності загальної пористості від ступеня метаморфічних перетворень. Методика досліджень ґрунтується на аналізі порівняння відповідності розрахункових значень загальної пористості для кожного окремого шахтопласту відповідно до емпіричного рівняння їх значенням, встановленим стандартними методами. Результати свідчать, що з підвищенням ступеня метаморфізму змінюються і фізичні характеристики вугілля, зокрема щільність і пористість. Пористість вугілля, структура його пористої системи та питома поверхня визначають фільтраційні, дифузійні й сорбційні процеси як у природних умовах залягання, так і під час їх змін під впливом різноманітних фізичних та хімічних факторів. Було доведено практичну відсутність кореляційної залежності загальної пористості викопного вугілля від метаморфічних перетворень шахтопластів при оцінці впливу цих процесів, враховуючи показник виходу летких речовин. Загальна пористість є унікальною характеристикою конкретного вугільного пласта в межах шахтного поля і лише частково визначається вмістом летких речовин. Усереднені емпіричні залежності від показника виходу летких речовин надають лише загальне уявлення про тенденції зміни пористості вугілля під час метаморфічних перетворень шахтопластів Результати дослідів дозволяють розробити пропозиції задля удосконалення нормативної бази щодо прогнозування прояву небезпечних властивостей шахтопластів при гірничих роботах. Виявлені у дослідженні факти можна використовувати у нормативних документах для прогнозу небезпечних властивостей шахтопластів, оскільки вони дозволяють розробити пропозиції та методики щодо удосконалення нормативної бази з безпечного ведення гірничих робіт. Це призведе до зниження рівня аварійності з тяжкими наслідками, виробничого травматизму на вугледобувних підприємствах

Ключові слова: вугільний пласт; небезпечні властивості; вуглефікація; охорона праці

ГІРНИЧИЙ ВІСНИК

Том 58, № 2
2024

Заснований у 1966 р.
Виходить два рази на рік

Редагування англомовних текстів:
С. Воровський

Відповідальний редактор:
С. Тіхлівець

Редагування бібліографічних списків:
С. Тіхлівець

Комп'ютерна верстка:
О. Глінченко

Підписано до друку 24.12.2024
Формат 60*84/8
Ум. друк. арк. 6,7
Наклад 100 прим.

Контактна адреса:
Криворізький Національний Університет
50027, вул. В. Матусевича, 11, м. Кривий Ріг, Україна
Тел.: +38 (056) 409-06-06
E-mail: info@mining-journal.com.ua
https://mining-journal.com.ua/uk

MINING JOURNAL
Kryvyi Rih National University

Volume 58, No. 2
2024

Founded in 1966.
Published 2 times per year.

Editing English-Language Texts:
S. Vorovsky

Managing Editor:
S. Tikhlivets

Editing Bibliographic Lists:
S. Tikhlivets

Desktop publishing:
O. Glinchenko

Signed to the print 24.12.2024
Format 60*84/8
Conventional Printed Sheet 6.7
Circulation 100 copies

Address for contacts:
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50027, 11 Vitalii Matusevich Str., Krivyi Rih, Ukraine
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