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The use of room-and-pillar mining systems at deep levels of iron ore mines

Abstract. The increasing occurrence of adverse rock pressure effects with mining depth in the mines of the Kryvyi Rih basin often prevents the use of room-and-pillar systems with their effective ore extraction parameters. The objective of this study was to develop an innovative, safe, and efficient technology for mining ore deposits at the existing deep levels of iron ore mines. The study employed a system of methods to investigate the state of the rock massif, the structural parameters of the mining system, and to create a technological flowsheet for ore extraction at deep mine levels. The research established relationships showing the change in the dimensions of rooms and pillars with depth and their lifespan. It also determined the influence of rock strength on the permissible exposure parameters, as well as the optimal conditions for using high-performance self-propelled equipment to

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improve the efficiency of ore exraction. The study investigated the relationship between the productivity of a range of self-propelled equipment used in contemporary mining and the ore haulage distance within the stope block. An innovative design-and-technology scheme was proposed for stoping with sublevel stope block development. The developed technology focuses on the use of temporary I-shaped pillars, active rock pressure management, and the substantiated lifespans of the components of the sublevel room-and-pillar mining system. The practical significance of this work is the extension of the room-and-pillar mining system's application range to depths of 1,400 m and more. This is achieved by improving the quality of the extracted ore through a 10-12% increase in the room reserve while simultaneously reducing the room exposure stand-up time by one month within a mining unit

Keywords: underground mining; rock pressure; stability and lifespan of exposures; temporary crowns; haulage by self-propelled machinery; innovative technology

Introduction

Mineral deposits in the iron ore mines of the Kryvyi Rih basin (Kryvbas) are being mined at depths of 1,400 m and more. Active adverse rock pressure effects with the increasing depth of mining operations preclude the application of room-and-pillar systems with effective parameters of ore extraction. Consequently, there is a trend to abandon room-and-pillar mining and transition to sub-level caving systems, which leads to a degradation of extraction indicators and, overall, a reduction in the effectiveness of ore stoping.

A. Mazhitov & P. Volkov (2020) concluded that most companies have now depleted their prospective reserves and are inevitably turning to the sub-economic ones. Consequently, exploration is a relevant and high-priority direction for many mining enterprises. The authors demonstrated optimal methods for mining deposits that consist of multi-grade ore bodies, the majority of which are structurally complex and contain off-balance ores. The solutions presented enable an increase in the service life of the enterprise by expanding its reserves of previously sub-standard ores. The findings of the study confirmed that reserves are depleted with increasing mining depth, which necessitates the search for additional reserves and new technologies for developing deposits. However, the study did not specify any effective mining technologies for the high-quality extraction of ore reserves from mining units using room-and-pillar systems.

In V. Bondarenko *et al.* (2023), the influence of geomechanical processes in the undermined rock massif was studied. The authors examined the patterns of influence of geomechanical factors by using the finite element method to model the displacement parameters of mineable layers to justify the layout of degassing boreholes during high-speed stoping. Three computational models were developed and justified based on the shape and dimensions of the computational zone, the rock massif texture and the mechanical properties of its lithotype, the loading conditions on the model boundaries, the characteristics of the stress-strain relationship in the model elements, and the criteria for determining the boundary state. The study also established how the depth of the face location and the rock massif texture influence the rock displacement parameters. However, insufficient attention was paid to researching the temporal prediction of stability within a disturbed rock massif.

A. Smolinski *et al.* (2022) investigated the influence of leaving waste rock in the mined-out space on the geomechanical state of the surrounding rock massif. The study determined the significance and patterns of reduction in stress intensity concentrations in the main roof of the frontal bearing pressure zone and the relaxation zone with an increasing rock layer thickness to ore body thickness ratio. However, the authors did not address the issue of developing a flowsheet that considers the parameters of stoping processes and the dimensions and types of the technical equipment. A study by M. Stupnik *et al.* (2022) determined the quality of ore extraction from mining units within the mining system. The article emphasised that dilution and high losses of broken ore at great depths are a significant problem that affects the extraction of marketable products when mining iron ore deposits by underground methods. The article also analysed and summarised the causes of these high losses and dilution during extraction. A rational technology for ore mining and transportation was also developed and scientifically validated. This technology improves the grade of the mined ore by enabling a more complete extraction of the broken clean iron ore reserves. Nevertheless, the authors paid insufficient attention to the influence of the stability of underground structures on ore extraction indicators.

When mining some thick ore deposits using room-and-pillar systems, rock pressure is managed by backfilling the mined-out space. A prime example of using solidifying backfill in stopes up to 100 m high is the "Bilozerske" iron ore deposit, the "Ekspluatatsiina" underground mine. O. Lysenko *et al*. (2020) provided an analysis and interpretation of the geological information, actual mining data, and the characteristics of the main natural conditions of the deposit occurrence. These factors influence not only the feasibility and effectiveness of using solidifying backfill in mined-out rooms but also the profitability of mining rich iron ore deposits. However, the authors did not analyse other methods of managing rock pressure, such as through shrinkage stoping.

Backfilling the mined-out space can eliminate active deformation processes in the surrounding rock environment, stabilising rock pressure and avoiding its adverse effects with increasing mining depth. However, backfilling requires additional expenses (up to 25% or more of the cost of the ore mass and significant capital expenditures for creating a backfilling complex at the mine) and other additional non-production work. Therefore, managing rock pressure with backfilling is only effective when mining deposits under complex mining and geological conditions or when developing valuable deposits. Further effective mining of mineral deposits at deep mine levels requires a more detailed analysis of existing technologies and new research to improve the stability of exposures in rooms and pillars. This also involves reducing the lifespan of underground structures. This can be achieved by actively ensuring the stability of rock exposures, which makes it possible to increase dimensions of stopes. This, in turn, improves mineral extraction indicators as mining depths increase. Therefore, scientific search for and development of more effective room-and-pillar systems for mining deep reserves of rich iron ores remains highly relevant.

The research aimed to develop an innovative modern technology for mining ore deposits at deep levels of iron ore mines. This technology focuses on creating a sublevel room-and-pillar system with temporary crowns of new shapes and actively managing rock pressure in the surrounding rock massif. To achieve this, the structural elements of the system were justified, based on newly established relationships between the dimensions of rooms and pillars, their lifespan, and the implementation of modern equipment.

Literature Review

The issue of improving mining methodologies for mineral deposits was addressed in numerous publications. In particular, O. Bazaluk *et al*. (2022) proposed a new methodological approach for the comprehensive assessment of mining enterprises, based on the effectiveness of their flowsheets and their receptiveness to innovation. The study addressed the determination of the boundary parameters of these technologies and the application of criteria to assess the efficiency of mineral extraction. It was indicated that the concentration and effectiveness of ore extraction can be improved by implementing innovative technologies, optimising parameters of mining methodologies, and considering a system of mineral extraction indicators. The work is highly relevant, particularly with the deepening of mining operations. However, the authors focused on mine-wide issues rather than on the specifics of technological reserve extraction within the mine's stope blocks.

The preparation of a stope block for extraction by creating appropriate workings is a key component of room-and-pillar mining systems. D. Chepiga & O. Tkachuk (2022) investigated the stability of preparatory workings at great depths. The research found that the cross-sectional area of preparatory workings is reduced by 50% or more in the zone of influence of stoping operations, even when mining drifts are protected. Additionally, the deformation of protective structures reaches a maximum value of $\lambda = 0.8$ after they lose their stability. This results in the deformation of supports in the working and lateral rock failure. Such a production environment can lead to accidents. A functional relationship, expressed as a numerical series, was established to account for the changes in the relative deformation of protective structures during production processes in the stope block. Nevertheless, the study did not fully investigate the stability of rooms and rock exposures.

W. Elrawy *et al*. (2020) addressed similar issues, emphasising that the protection of various workings and stopes is a crucial element for rock stability and mine safety. Therefore, rock support became a dominant component in underground ore mines. The study investigated the influence of support types on the stability of existing underground workings in iron ore mines in terms of deformation, dimensions of workings, and rock massif strength. The research results demonstrated that the stability of workings significantly deteriorates with the deepening of mining operations. However, little attention was paid to the study of the stability of pillars and rooms.

The study by M. Kononenko *et al*. (2023) focused on a key process in ore stoping: determining and improving parameters of rock massif destruction by blasting in room-and-pillar mining systems. Analytical modelling was conducted to determine the parameters of the fragmentation and fracture zones that form in the rock massif around the charge cavity during ore breaking. Based on the changes in the stress-strain state of the rock massif caused by blasting, numerical modelling of the fragmentation and fracture zones was performed using the finite element method. The established radii of the intense fragmentation and fracture zones that form during blasting the rock massif vary as a power function of the explosive charge diameter, the pressure of the blast products in the charge cavity, and the rocks strength. Thus, the process of blasting room reserves was improved. However, the study did not focus on the specific drilling and blasting sequence required to ensure the parabolic shape of the room and the quality of ore fragmentation for intensified drawing and haulage. B. Lysko & T. Hutsul (2024) assessed the effectiveness of ground-based methods for observing neotectonic processes at geodynamic testing areas. The study found that geodetic methods provide the highest accuracy for detecting surface deformations, whereas geophysical methods are better suited for investigating deep structures but are less effective for monitoring slow changes. Furthermore, the authors provided only a limited discussion of the cost-effectiveness of an integrated approach and the feasibility of its implementation under technical or natural constraints.

Many researchers addressed the important and complex problem of underground mining: the study of geomechanical processes in the rock environment and the search for solutions to manage rock pressure. A. Matayev *et al.* (2024) conducted a comprehensive study of the mechanical properties of ores and rocks within a mineral deposit. They evaluated the natural stress field of the rock massif to address geomechanical challenges during the optimisation of mining operations. The study found that the hard rock massif is characterised by heterogeneous fracturing of a tectonic origin, with the number of fractures ranging from 10-15 to 15-25 per metre for different lithologies. The study identified that water saturation influences a reduction in the strength and deformability of rocks, with significant variability depending on the rock type. The research notably found a significant reduction in uniaxial compressive and tensile strength, as well as a decrease in Young's modulus. The measurements yielded a linear relationship between stress and depth. However, the study did not provide data on how mining rooms influence stress redistribution or the stability of rock exposures. Additionally, the research contains insufficient information to predict the application of room-and-pillar mining systems at deep levels.

A. Salkynov *et al.* (2023) conducted a study on deformation processes in the rock massif surrounding the stope face while mining inclined ore deposits. The authors proposed a new solution to a key scientific problem: predicting the natural and man-made geomechanical state of the rock massif. The study obtained patterns for the changes in the stress-strain state around the stope face. The results enable the development of technical solutions for modernising open stope mining systems in deposits with inclined ore bodies. However, the study did not consider the temporal development of deformation processes in the structural elements of the mining system. Furthermore, it did not investigate the influence of the ore body's dip angle and the strength coefficient of the hanging wall on the stability of exposures in rooms, depending on the stress state of the ore body.

I. Kushnerov *et al.* (2025) developed a technology for mining parallel contiguous ore bodies that involves managing geomechanical processes in the interlayer rock thickness using stable vault formations. The vault parameters were determined based on the stope face width, the interlayer rock thickness, and the ore body thickness. However, mining these ore bodies can cause significant changes in the stress-strain state of the surrounding rock massif due to over- or under-mining of the mineral reserves, which leads to hazardous conditions and a decrease in ore extraction indicators. Additionally, the successful implementation of this technology requires favourable geological conditions and the stability of the interlayer rock mass. Furthermore, a limited number of publications focused on the interrelationship between the timing of stoping processes and the regulation of dimensions of a mining system's structural elements.

Materials and Methods

The present study employed a comprehensive research methodology. An analysis of the geometric dimensions of rooms and pillars of the room-and-pillar mining system was conducted based on the operations of the "Kozatska" mine (PrJSC Kryvbaszalizrudkom) during the mining of the "Pivnichnyi" ore body (2000-2013). The study also summarised research findings on deformation processes, determined the ore mining conditions and the safety of operations at deep iron ore mine levels, and investigated the geomechanical properties of the rock and ore massif. Additionally, the relationship between the productivity of load-haul-dump machines (LHDs) (models XUL-307, ST-3,5, and TORO-400D) and the ore haulage distance was investigated.

Using a method of calculated functional characteristics that accounts for mining and geological factors, the study obtained parameters for the structural modelling of a sublevel room-and-pillar mining system for ore bodies at deep mine levels using self-propelled equipment. The calculations determined the following key parameters of the system's structural elements: room length along the strike ℓ_{cm} and along the dip b, crown thickness h_s, and the width of the inter-room pillar p. The lifespan of the underground structures was based on the productivity of the equipment used in the main technological processes within the stope block and an assessment of the room stability, taking into account the geomechanical state based on equivalent stresses. The influence of equipment productivity on the stope mining period T_k was determined by the formula:

$$T_k = Q_{cm} \cdot (P_d \cdot n_c \cdot n_s \cdot n_d)^{-1}, \text{ months}, \tag{1}$$

and the relationship between a stable, permissible parameter of the stope (e.g., its length along the strike) and the technological components of extraction, while other factors are held constant, can be expressed by the following formula:

$$[\ell_{cm}] = T_k \cdot P_d \cdot n_c \cdot n_s \cdot n_d \cdot (m \cdot b \cdot g)^{-1}, \text{ m}, \tag{2}$$

where Q_{cm} – ore reserve of one room, t; P_d – productivity of an LHD, t/shift; n_c – number of LHDs per room, units; n_s – number of LHD shifts per day, units; n_d – number of haulage days per month; ℓ_{cm} – room length along the strike, m; m – ore body thickness, m; b – room length along the dip, m; g – ore volume weight, t/m^3.

The geomechanical state of the surrounding ore massif was also evaluated using the methodology of O. Shashenko *et al.* (2021):

$$\sigma_{eq} \geqslant R_s \cdot k_{st}, \tag{3}$$

where σ_{eq} – equivalent uniaxial stress, MPa; R_s – uniaxial compressive strength of the rock, MPa; k_{st} – structural weakening coefficient.

$$\sigma_{eq} = A + B, \text{ MPa}, \tag{4}$$

where
$$A = \frac{(f_r - 1)\cdot(\sigma_1 + \sigma_3)}{2\cdot f_r}, \text{ MPa}; \tag{5}$$

$$B = \frac{\sqrt{(1-f_r)^2\cdot(\sigma_1+\sigma_2)^2 + 4\cdot f_r\cdot(\sigma_1-\sigma_3)^2}}{2\cdot f_r}, \text{ MPa}, \tag{6}$$

where f_r – brittleness coefficient; $\sigma_1, \sigma_2, \sigma_3$ – components of the principal stress tensor, MPa.

$$f_r = \frac{R_s}{R_{st}}, \tag{7}$$

where R_{st} – uniaxial tensile strength of the rock, MPa.

Based on the completed research, the structural modelling was performed to develop an optimal sublevel room-and-pillar mining system for iron ore deposits at deep mine levels.

Results

To assess the performance of the room-and-pillar mining system at the “Kozatska” mine (PrJSC Kryvbaszalizrudkom), the authors analysed the changes in structural element dimensions, reserves, and ore extraction indicators with increasing depth during the mining of the “Pivnichnyi” ore body between 2000 and 2013 (Table 1).

Table 1. *Analysis of the components of the room-and-pillar mining system*

Level (mining depth)	Mining system dimensions, m					Ore reserves, t				Losses, %	Dilution, %
	Room			Inter-room pillar width	Crown thickness	room	pillar	block	room, %		
	along strike	across strike	Height								
870-790 m	34	23	40	10	11	115,736	65,867	181,603	63.73	7.4	8.2
1,110-1,030 m	28	24	40	11	12	99,456	68,908	168,364	59.07	8.3	8.7
1,190-1,110 m	21	23	40	12	15	71,484	69,654	139,138	51.37	9.2	10.2
1,270-1,190 m	15	25	40	13	17	55,500	71,687	127,187	43.63	12.4	13.8

Source: *developed by the authors*

The data in Table 1 indicates a decrease in room reserves and a corresponding increase in pillar reserves. Specifically, the percentage of ore reserves in the rooms decreased by 47.9% as the depth of mining operations deepened by almost 500 m. This occurred because larger pillars were employed throughout the depth interval under study, which resulted in an 8.83% increase in the reserves contained within them. Furthermore, and importantly, the ore extraction indicators, namely losses and dilution, increased by 40.3% and 40.5%, respectively. This confirms that, according to the research conducted and guidelines, the dimensions of rooms decrease with increasing mining depth, while the parameters of pillars, conversely, increase. This trend resulted in the inefficient extraction of the iron ore deposits. Therefore, the study investigated the dependence of the stability of the room exposures and pillars on their lifespan. The lifespan is known to be regulated by the stope mining intensity. It depends on the applied equipment, the organisation of labour in the stope mining processes, and other factors. The established relationships between a stope’s length along the strike and its lifespan and the mining depth, while other influencing factors remain constant (with an average ore strength of $f = 8$), are shown in Figure 1.

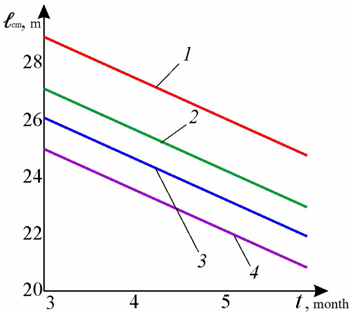

Figure 1. *The relationship between stope length along the strike ℓ_{cm} and block mining time t*

Notes: *1, 2, 3, 4 – mining depths of 900, 1,100, 1,200, 1,400 m, respectively*

Source: *based on the authors' own calculations*

Similarly, graphs showing the relationship between stope length along the dip and its mining time at various depths were constructed (Fig. 2).

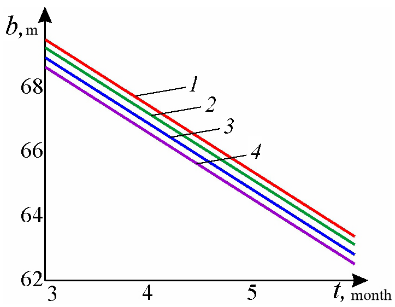

Figure 2. *The relationship between stope length along the dip b and block mining time t*

Notes: *1, 2, 3, 4 – mining depths of 1,000, 1,100, 1,200, 1,300 m, respectively*

Source: *based on the authors' own calculations*

An analysis of the graphs in Figures 1 and 2 shows that as stope mining time increases, the stope dimensions decrease linearly. For the same depth, each additional month of stable stope standup requires a dimension reduction of 1-1.5 m along the strike and 1-2 m along the dip. Thus, for example, in a 20 m thick ore body with a 25 m × 37 m stope, 10-12% of the clean ore reserve is lost in just one month of operation. In contrast to the stopes, a predictable, inverse relationship exists for the inter-level crown and inter-room pillars in the stope block. Figure 3 presents the relationship between the inter-level crown thickness and its lifespan at various mine levels.

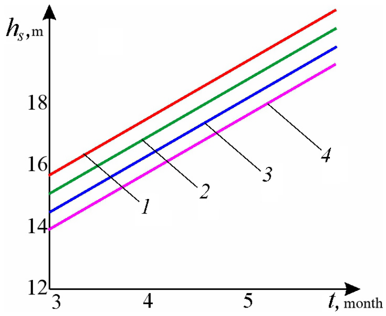

Figure 3. *The relationship between inter-level crown thickness h_s and block mining time t*

Notes: *1, 2, 3, 4 – mining depths of 1,300, 1,200, 1,100, 1,000 m, respectively*

Source: *based on the authors' own calculations*

The relationship between the inter-room pillar width, its standup time, and the mining depth of the iron ore deposit was also investigated (Fig. 4).

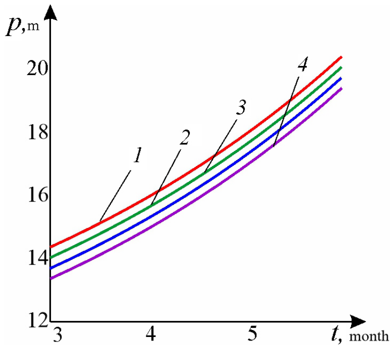

Figure 4. *The relationship between inter-room pillar width p and block mining time t*

Notes: *1, 2, 3, 4 – mining depths of 1,300, 1,200, 1,100, 1,000 m, respectively*

Source: *based on the authors' own calculations*

The research presented in Figures 3 and 4 established that for a standup time of one month, the dimensions of the structural elements of the mining system must be increased by 2 m or more, leading to a 14-15% increase in the pillar reserve. However, the ore reserve mined from these pillars yields poorer ore extraction indicators, with losses reaching up to 30-40% and dilution reaching up to 30%. It was also determined that as mining depth increases, room reserves decrease while ore reserves in pillars increase. Their absolute dimensions also depend on other mining and geological factors of the mining conditions. The stability of the mining system's structural elements is heavily dependent on the strength coefficient of the ore and rock. This coefficient is a key parameter that significantly influences pillar dimensions and, most notably, the exposure dimensions. The relationship between the room length along the strike and the rock strength coefficient is presented in Figure 5.

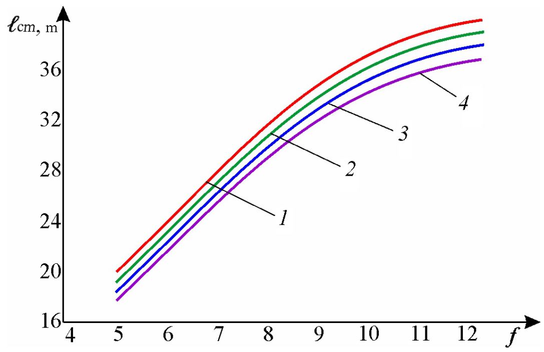

Figure 5. *The relationship between the room length along the strike ℓ_{cm} and the hanging wall rock strength f*

Notes: *1, 2, 3, 4 – mining depths of 1,000, 1,100, 1,200, 1,300 m, respectively*

Source: *the authors' own development*

The graphs show that increasing the rock massif strength by one point allows for a 2-2.5 m increase in room dimensions, which in turn improves mineral extraction indicators. Block mining processes are a crucial component of the overall mining system, and the structural elements must be designed accordingly. This is particularly relevant for the design of the receiving level bottom, which is optimised for self-propelled equipment of various sizes to minimise the standup time of underground structures. The haulage distance for the broken ore is a key parameter of the receiving level. Figure 6 presents the investigated relationship between the productivity of self-propelled equipment and the broken ore haulage distance.

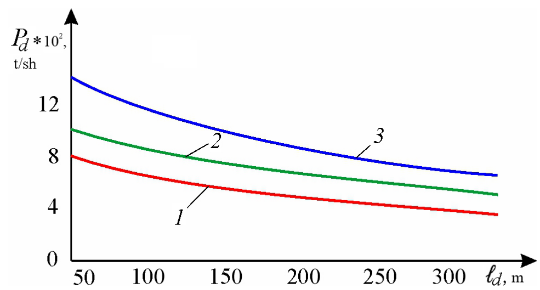

Figure 5. *The productivity of self-propelled machines P_d as a function of haulage distance ℓ_d*

Notes: *1, 2, 3 -XUL307, ST-3,5; TORO-400D, respectively*

Source: *based on the authors' own calculations*

Importantly, the productivity analysis accounted for the haulage distance to the orepass raise, a factor integral to the mining system's design. Thus, the research considered the interrelationship between the stope block's bottom design, the resulting equipment productivity, and the stable lifespan of the room, which in turn determines parameters of the stope block itself. Therefore, the design of specific LHDs directly governs the mining period of the room reserves and the dimensions of the mining unit. Figure 6 presents the relationship between the productivity of three different types of LHDs and the ore haulage distance from the loading to the unloading point. It was found that for the same haulage distances, the TORO-400D is the most productive machine. For example, at a distance of 200 m, its productivity is 1,200 t/shift, whereas the XUL307 and ST-3,5 have a productivity of 700 and 900 t/shift, respectively.

The research also found that due to their size, high-productivity haulage machines require a larger cross-section for underground workings. As shown in Figure 6, the maximum productivity of self-propelled equipment is achieved with an ore haulage distance of 50-100 m. However, the structural features of the haulage level, particularly under conditions of high rock pressure, do not always allow for such parameters. Therefore, based on this research and modern industry experience, it is recommended that for room-and-pillar mining of thick ore bodies at significant depths (1,300-1,400 m), the XUL307 and ST-3,5 machines should be used for ore haulage at distances of 100-200 m. Thus, based on the research conducted, it was established that the optimal application of self-propelled equipment requires an integrated consideration of anticipated rock stability, costs for haulage workings of the necessary cross section, and the productivity, geometric parameters, and defined lifespan of the stope block. The selection of a particular LHD is the dominant factor in this optimisation.

Based on the authors' research (Figs. 1-6) and the application of a methodology for assessing the safe condition of room-and-pillar mining system elements (using formulas 1-7), an innovative technology for mining iron ore bodies at deep levels was developed. The core of this technology is a proposed sequence for extracting stope block reserves and a new structural design of the mining system. It determines the room and pillar parameters by correlating the intensity of the room reserve extraction and the subsequent pillar reserve extraction. The structural dimensions determined by the authors ensure the stability of exposures of rooms and temporary sublevel pillars. The authors named the technology "Temporary I-shaped Pillars (Crowns)". The flowsheet for this technology is presented in Figure 7.

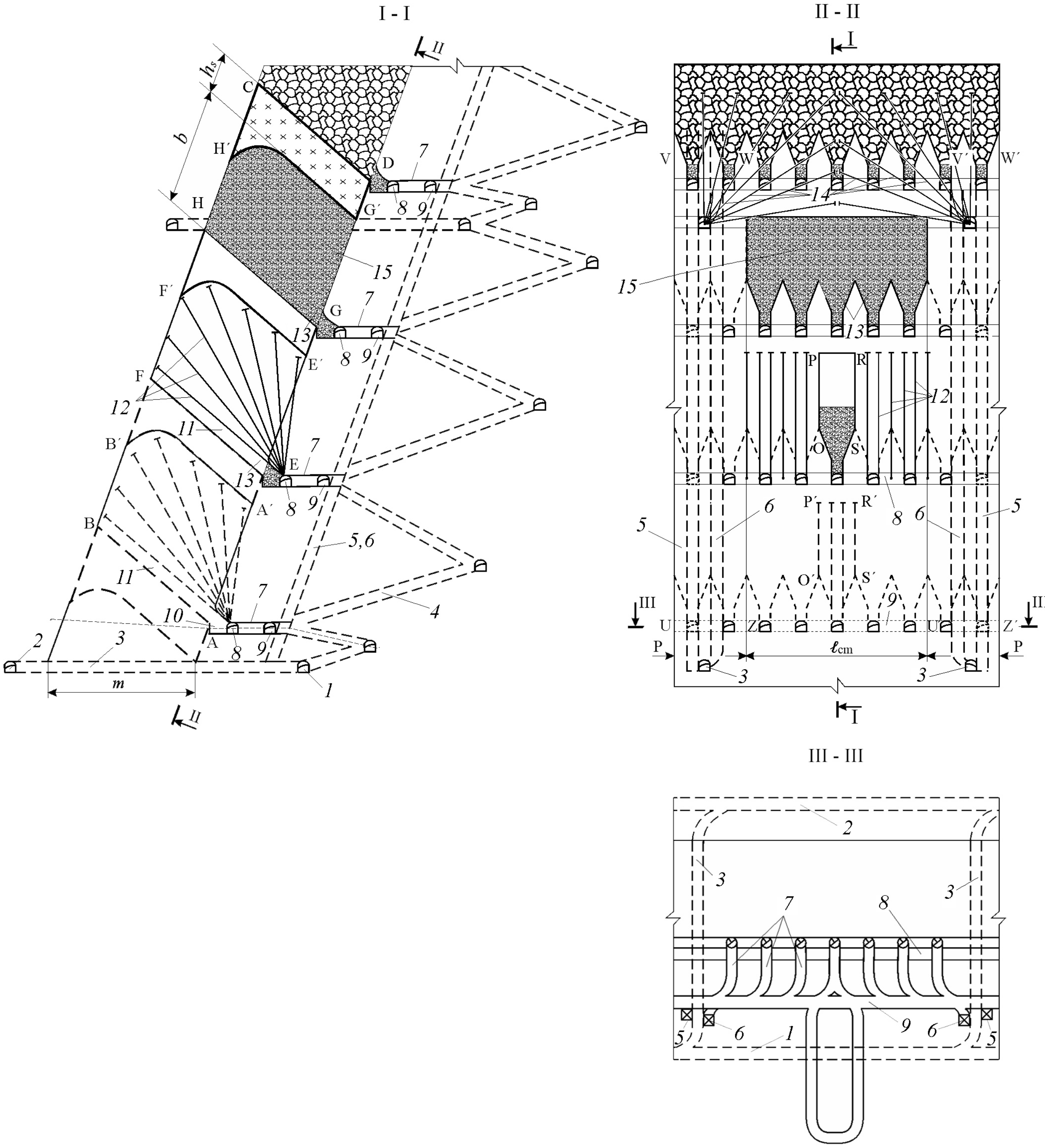

Figure 7. *Sublevel room-and-pillar system for mining steep iron ore deposits*

Notes: *I-I – across-strike projection with ore mass shrunk in the upper sublevel room, drilled ore reserves in the lower sublevels, and I-shaped pillars (crowns); II-II – along-strike projection with sublevels, stopes, and inter-room pillars; III-III – horizontal projection*

Source: *developed by the authors*

A steep iron ore deposit is developed using vertical shafts and inclined runaways as mining progresses. This study considers ore extraction at deep mine levels, where each level is subsequently divided into sublevels. Projection I-I is an across-strike cross-section of the ore body with a thickness *m*, and illustrates the elements of a sublevel room-and-pillar mining system. Within this projection, ABCD represents the level reserves, ABB′A′, EFF′E′, and GHH′G′ are the sublevel stopes, A′B′FE and E′F′HG are the sublevel crowns, and G′H′CD is the inter-level crown. The upper room contains the shrunken ore, the middle room is drilled with longholes, and the lower room shows the designed longhole pattern. Projection II-II, a section along the strike, illustrates the sublevels, stopes with length ℓ_{cm}, and inter-room pillars UVWZ with dimension *p*. Also shown are the boreholes for caving the inter-level crown, the vertical compensation slot OPRS on the middle sublevel, and the contours of drawpoints, drawbells, and other workings. Finally, horizontal projection III-III shows the mineable and preparatory workings.

According to the flowsheet, the sublevel room reserves are mined sequentially down-dip, with the ore mass shrunk in these rooms. The inter-room pillars left along the strike, the I-shaped crowns in the cross-strike projection, and the shrunken ore are all used to support the surrounding rock. To reduce the standup time of the exposures and extract high-quality ore, an intensive simultaneous ore drawing is performed from the sublevel rooms. The reserves of the two lower sublevel crowns are then broken and drawn. Finally, with a time delay, the remaining reserves of the inter-room pillars and the inter-level crown are broken, followed by a mass drawing of the broken ore. The mining operations in the mining unit are performed as follows. The stope block is divided along the strike into stopes, inter-room pillars, and an inter-level crown, with their geometric dimensions determined based on the research (Figs. 1-6). The structural elements of the proposed sublevel room-and-pillar system are governed by the stability of the ore body and surrounding rock. It was found that a shorter production cycle within the stope block allows for an increase in stope dimensions and a reduction in pillar dimensions, which in turn improves ore extraction indicators and overall mining efficiency. Therefore, the mining system is designed to use high-performance self-propelled equipment (Fig. 6).

In addition, temporary support crowns with a I-shaped cross-section and an increased area are formed in the hanging wall between the sublevels. Their purpose is to reliably support the exposures of the hanging wall and the caved overlying rock (Fig. 7, Projection I-I). Importantly, the dimensions and shape of these temporary crowns are governed by the lifespan of the stope in the sublevel while the inter-level crown's dimensions are governed by the mining block's lifespan. The stope block reserves are prepared using haulage drifts *1* and *2* (in the footwall and hanging wall, respectively), access crosscuts *3*, and inclined runaways *4*. The block also contains manway raises *5* and orepasses *6* (Fig. 7). Furthermore, sublevel haulage crosscuts *7*, drill drifts *8*, and sublevel haulage drifts *9* are driven. These workings are connected to the inclined runaways *4* to facilitate the movement of equipment and materials.

The blasting of the ore massif within the stope begins with the formation of a cut slot and the vertical compensation space OPRS at the centre of the stope. To achieve this, an inclined cut raise *11* is created from the drawpoint *10* along the upper contour of the crown (Fig. 7, Projection I-I). Within the stope (e.g., EFF′E′), the ore massif is then blasted using charges in inclined longholes, first to the width of the cut raise and then to the diameter of the drawbell, thereby creating the vertical compensation space OPRS. After this, from the working *8*, the stope massif is drilled with vertical longhole rings *12*, which are then charged with explosives. Part of the longholes in the stope's roof are under-charged in the contact zone of the crown with the hanging wall (Fig. 7, Projection I-I). A stable, I-shaped crown and a more stable vault-like shape for the stope are created in accordance with the blueprint for drilling, charging, and caving the massif with rings of longholes. Subsequently, vertical layers of the ore massif cave into the created compensation space (Fig. 7, Projection II-II). The drawbells *13* from the drawpoints *10* are opened as the ore mass is blasted, partially using the final sections of the blastholes *12*. After blasting, a volume of ore equivalent to the loosening factor is drawn, while the main portion is shrunk to support the exposures in the stopes and reduce the standup time of the open stope space. Once the stope reserves are caved, the ore drawing and haulage process is conducted using high-performance self-propelled equipment via workings *13*, *10*, *7*, *9*, and *6* (Fig. 7). During this process, the surfaces of the stopes and pillars are exposed. Their standup time is governed by the equipment's productivity and can be determined using formula (1).

Using the ratio of rock strength to the stresses within the rock massif, the safety factor of the mining system's structural elements can also be determined. This includes their standup time and the critical exposure of the rock, all calculated using formulas (3-7). The stoping parameters are also linked to the type of LHDs used and their productivity, which in turn depends on the haulage distance. As shown in Figure 7 (Projection III-III), this relationship is considered when determining the stable, long-term parameters of the mining unit. The mining equipment choice must account for the mining depth, rheological processes, and the active stresses within the massif.

Based on the geomechanical processes in the rock massif surrounding the ore body and the stability of the mining system's structural elements, various options exist for extracting the balance reserves. Each sequence or variant for mining the sublevel reserves has its own advantages and disadvantages, necessitating further research on the stability of the system's elements, ore extraction and quality, and the integration of all production operations. This paper proposes the following flowsheet for stope mining the reserves in a block. After the room reserves are mined, the sublevel crowns A′B′FE and E′F′HG are mined first, while retaining the inter-level crown G′H′CD. This sequence allows for the removal of the ore from these crowns with minimal loss and dilution. The crown reserves are drilled using longholes *14* from preparatory workings located within the inter-room pillars UVWZ. Finally, mass drawing and haulage of the caved ore are performed. Thus, the primary goal of this research was achieved: to study and justify the use of a safe and efficient room-and-pillar mining system for extracting ore at deep mine levels.

Discussion

The adverse effects of high rock pressure at deep levels of Kryvbas mines are prompting a shift from room-and-pillar systems to sublevel caving methods, despite the latter having worse ore extraction indicators. While room-and-pillar mining provides higher-quality ore extraction from stope blocks, the stability of open rectangular rooms decreases with depth. This necessitates a reduction in stope reserve size and an increase in pillar dimensions, which in turn leads to poor extraction. This is corroborated by an analysis of the mine's operational data (Table 1). Overall, this reduces the efficiency of mineral extraction and the saleability of the final product, a particularly crucial consideration in a market-driven economy. This is evidenced by the research of S. Pysmennyi *et al*. (2020), which focuses on enhancing the ore extraction rate in the mining of rich iron ores by altering the stope shape and substantiating its parameters under conditions of rock pressure. The authors of that study proposed a parabolic-shaped stope with geometric parameters that directly depend on the deposit's characteristics, mining depth, and the direction of the principal stresses. The formation of stable, parabolic stopes using an I-shaped crown and enhancing its stability with shrunken ore is also proposed in the technology developed by the authors. This approach increases the extracted reserves of clean, undiluted ore by up to 12%.

Research by S. Pysmennyi *et al*. (2020) found that the ore extraction rate can be improved by employing larger compensation rooms and by establishing their stable parameters under rock pressure. Using the ANSYS software package, it was determined that forming a parabolic-shaped compensation room can significantly reduce stress concentration around the stope block. The compensation room's geometric dimensions are dependent on the deposit's parameters, mining depth, and the direction of the principal stresses. However, the ore volume from the compensation room reserve is a relatively low proportion (18-25%, depending on the loosening factor) compared to the ore reserves in the other components of the stope block. This means that the method does not, in itself, ensure the potentially achievable high-quality ore extraction.

It is crucial for this work to determine and assess the stability and durability of the exposures of rooms and pillars, and to correlate these factors with the mining intensity in the mining unit. The study established novel relationships showing how the stable geometry and standup time of the mining system's structural elements change with mining depth during stope operations. These relationships exhibit trends and patterns with increasing depth that are consistent with the findings of the similar research by O.V. Kalinichenko (2020) on steep deposits. Using the finite element method to study the geomechanical deformation of the rock mass surrounding underground workings, O.V. Kalinichenko (2020) found that the stability of rock exposures decreases with the increasing mining depth. This stability is primarily dependent on the rock strength, the standup time of a structural element, and its geometric dimensions. Values of the stress around underground cavities and the geometric parameters of the room-and-pillar system's elements depend on the mining depth, the physical properties of the rock, and length of the ore body along the strike. The results of the study corroborate the measurements presented in the current work and the relationships showing that the changes in the room span and pillar dimensions follow similar patterns.

The condition of the undermined ore massif and the room exposures was assessed using the method of calculated functional characteristics, a mandatory procedure for designing iron ore deposit development. The method of analysing the stability of underground structures was also employed. Similarly, O. Shashenko *et al*. (2020) evaluated the state of underground workings by studying the stress-strain properties of rock samples and comparing them to the stress state of the surrounding rock massif to determine the strength limit at the exposure points, as stipulated by accepted methodology. Therefore, the assessment of the rock massif condition performed by the authors of this work is valid and applicable to the conditions under consideration, as the research findings corroborate the results of the cited work.

A. Kosenko (2021) established that optimising the use of self-propelled equipment requires an integrated consideration of several factors. These factors include the equipment's productivity, the potential stability of the block bottom rock, the required cross-section of the haulage workings, and the stope block's reserves and geometric parameters with a defined lifespan.

The dominant factor in this process is the selection of specific self-propelled equipment for ore drawing and haulage, a finding that is corroborated by the research. The researcher used physical modelling to establish the relationships between the quality and quantity of ore extraction, the intensity of ore drawing, and the physical and mechanical properties of the ore. These relationships allowed for the justification of rational parameters for the structural elements of the ore drawing and haulage flowsheet. Similarly, the authors of this work justified the rational design of the block bottom, the haulage technology, and the equipment used, which ensured a reduction in the standup time of the room exposures.

Based on the conducted research, a novel design and flowsheet was developed for mining ore deposits using a sublevel room-and-pillar system at deep levels in iron ore mines. This scheme incorporates temporary I-shaped crowns, manages rock pressure using shrinked ore, and accounts for the lifespan of the mining system's components. By mitigating peak stresses and preventing active irreversible deformations in the ore body, this system's design, tailored for thick ore bodies, ensures the stability of its elements at significant depths. Similarly, A. Kosenko *et al*. (2023) established that the key factor affecting the selection of stable structural elements for stope panels is the stress-strain state of the host rocks. This state is determined by mining depth, the thickness and dip angle of the ore body, the shape and dimensions of the displacement zones, and the sequence and intensity of mining the reserves from both compensation rooms and stopes. The research established the maximum possible stable parameters for room exposures during ore blasting. It also provided relationships for the equivalent width of stope panel deflection and the equivalent horizontal and vertical stable exposures. The established relationships allow for the selection of the most effective mining flowsheets for rich iron ore deposits based on ore extraction indicators. This confirms the validity and soundness of the technical and technological solutions made by the authors during the research and development of an effective room-and-pillar system for mining rich iron ore reserves at deep mine levels.

Conclusions

Based on the practice of mining iron ore deposits using room-and-pillar systems, a trend was established: the stope reserve decreases with mining depth, while the pillar dimensions in the mining units increase. Calculations showed that a deepening of mining operations by 500 m results in a decrease of stope ore reserves by almost 48%. At the same time, reserves in the inter-room pillars increase to 8.83% due to the larger geometric dimensions stipulated in the mining projects. This change in parameters leads to a significant increase in ore extraction losses and dilution, by 40.3% and 40.5%, respectively.

Using the method of calculated functional characteristics, the study was conducted on how the geometry of exposures of stopes and pillars in_stope blocks changes with mining depth. Based on the established relationships, it was found that when the standup time extends by a month, the dimensions of inter-room pillars and inter-level crowns must be increased by 2 m or more, which in turn leads to a 14-15% increase in the ore reserves within these structures. Therefore, extraction of the balance reserves from these pillars becomes more difficult, with losses potentially reaching 30-40% and dilution up to 30%. It was noted that the stability of the system's structural elements significantly depends on the rock strength coefficient and their lifespan. The study also established novel relationships between the dimensions of exposures in stopes and the rock strength coefficient, which demonstrate that a 1-point increase in the rock massif strength allows stope dimensions to be increased by 2-2.5 m, thereby improving mineral extraction indicators.

To boost productivity in the stope block and consequently reduce the standup time of the stope exposures, the research was conducted on the use of self-propelled LHDs. The study found that the TORO-400D is the most productive LHD for a haulage distance of 200 m, showing a productivity of 1,200 t/shift. In comparison, the similarly designed but smaller XUL307 and ST-3,5 machines achieved 700 and 900 t/shift, respectively, under the same conditions. The research also established that more productive LHDs are structurally larger and therefore require bigger haulage workings. Under the given conditions, with the surrounding rock strength of 5-6 points, it is impossible to ensure a stable working cross-section that allows for the movement and manoeuvring of self-propelled equipment. The graphs also show that the maximum productivity of these machines is achieved when hauling ore for a distance of 50-100 m. However, the structural characteristics of the haulage level, particularly due to rock pressure, do not always permit these optimal parameters. Thus, based on the research performed, it is recommended to use the XUL307 and ST-3,5 for ore haulage when mining thick deposits using room-and-pillar systems at depths of 1,300-1,400 m or more. Thus, based on the research conducted, it was established that the optimal application of self-propelled equipment requires an integrated consideration of anticipated rock stability, costs for the haulage workings of the necessary cross section, and the productivity, geometric parameters, and defined lifespan of the stope block.

Based on their research, the authors of this work developed a novel, safe, and efficient design and flow-sheet for mining ore deposits using a sublevel room-and-pillar system at deep horizons in iron ore mines. The proposed technology extends the application range of this method to depths of 1,400 m and more. It ensures stable parameters for rooms and pillars by accounting for their lifespan, which improves the quality of the extracted ore by increasing the room reserve by 10-12% while reducing the standup time of the room exposures by one month. Further research will focus on improving the technology and mining parameters by investigating new relationships between the system's elements, taking into account geomechanical processes in the surrounding rock massif and the dimensions of modern equipment.

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Conflict of Interest

None.

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Застосування камерних систем розробки покладів на глибоких горизонтах залізорудних шахт

Анотація. Активний розвиток негативних проявів гірського тиску з глибиною гірничих робіт на шахтах Криворізького басейну часто унеможливлює застосування камерних систем розробки з їх ефективними параметрами по вилученню рудної маси. Метою досліджень були пошук та розробка інноваційної безпечної й ефективної технології відпрацювання рудних покладів на досягнутих глибоких горизонтах залізорудних шахт. Використана система методів та прийомів досліджень стану гірського масиву, конструктивних параметрів системи розробки та створення технологічної схеми видобутку руд на глибоких горизонтах шахтових полів. Дослідженнями встановлено закономірності зміни розмірів камер і целиків із глибиною та часом їх експлуатації, виявлено вплив міцності порід на допустимі параметри оголень, а також визначено оптимальні умови застосування високопродуктивної самохідної техніки для підвищення ефективності вилучення рудної маси. Досліджена залежність продуктивності ряду самохідних машин, які використовуються в сучасному гірничому виробництві, від довжини доставки рудної маси в очисному блоці. Запропоновано нову конструктивно-технологічну схему очисного виймання руд при підповерховій підготовці очисного блоку. Технологія, яка розроблена, орієнтована на застосування тимчасових стелин одиницеподібної форми, активне керування гірським тиском та обґрунтованими термінами існування складових підповерхово-камерної системи розробки. Практична значимість роботи – розширення області застосування камерних систем розробки до глибин 1 400 м і більше та підвищення якості вилученої рудної маси збільшенням камерного запасу на 10-12 % при зниженні терміну стояння оголень в камерах на 1 місяць у виїмковій одиниці

Ключові слова: підземна розробка; гірський тиск; стійкість і існування оголень; тимчасові стелини; доставка самохідною технікою; інноваційна технологія

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Geometrical features of crack network formation on rock surfaces during cooling

Abstract. This study aimed to determine the most probable geometric shape of cracking cells based on the principle of minimising the energy required to cause failure in the surface layer of rocks. The research methodology was based on analysing the classical isoperimetric problem. This states that, among shapes with the same perimeter, the circle has the largest area, while among polygons, the regular *n*-gon has the largest area. The energetically most favourable configuration of the crack system was substantiated, taking into account the physical conditions governing crack formation. The theoretical propositions were then compared with experimental data and the results of previous thermomechanical rock failure studies. It was found that cooling heated surfaces predominantly results in a polygonal crack structure with hexagonal cells forming. It was demonstrated that the hexagon is the most optimal geometrical figure, in that it allows for dense packing on a plane without the formation of additional voids or stresses, and at the same time provides the minimum perimeter for a given area. The size of the cracking cells was found to be determined by a combination of factors, the most important of which were the physical and mechanical properties of the rock, the magnitude of the temperature gradient and the cooling regime. The characteristic cell size decreases as the temperature difference between heating and cooling increases. The broad

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spectrum of structural dimensions formed, ranging from fractions of a millimetre to several metres, was confirmed. The practical significance of these results lies in their potential application in predicting fracture parameters and controlling rock failure processes during mineral deposit development, and in designing technologies involving thermal effects on rock masses

Keywords: thermal cyclic loading; isoperimetric problem; regular tessellation; honeycomb structure; thermal cyclic failure

Introduction

The successful execution of contemporary geotechnological operations is contingent on a capacity to regulate the development of fractures within rock formations. This applies to the development of geothermal systems and enhanced oil recovery and mineral extraction, as well as to ensuring the stability of mine workings and underground structures. It is particularly interesting to look at thermal cyclic loading processes that follow a "heating-cooling" sequence. This is because these processes cause significant temperature differences in the surface layers of rocks. This leads to the development of tensile stresses and the formation of ordered polygonal systems of surface cracks. The geometrical characteristics of these systems directly influence the subsequent failure of rock, its permeability, the intensity of defect development and the energy required for mechanical comminution. The formation of polygonal crack structures is governed by regularities. This makes it both a fundamental scientific problem in fracture mechanics and an important applied task. Solving it will contribute to the development of more efficient technologies. These technologies are for the thermal treatment of rock masses.

The review by L.N. Wong & Z. Liu (2025) provides a summary of the current state of research, systematically presenting the results of numerous experimental and numerical studies of thermal shock in rocks, and analysing its effects on changes to the structure, mechanical properties and durability of rock masses. The authors showed that thermal failure is determined by the complex interplay of temperature regimes, heating and cooling rates, mineral composition, texture, initial fracturing and boundary conditions. However, they also concluded that there is currently no universal mechanical model capable of explaining the regularities of thermal rock failure under different loading conditions. The authors placed particular emphasis on the need to develop new theoretical approaches. These approaches should account for the spatial organisation of crack systems. They should also account for the characteristics of the actual rock structure.

T. Chen *et al.* (2022) made a significant advance in the study of polygonal crack geometry by numerically reproducing the process of crack formation on rock surfaces during cooling. The authors demonstrated that the type of boundary conditions dictates the nature of crack formation, while the thickness of the surface layer and structural heterogeneity regulate the average size, regularity, and morphology of the polygonal cells formed. Building on these findings, X. Hu *et al.* (2022) have significantly advanced the understanding of the mechanisms underlying crack propagation through the use of modern numerical methods. They demonstrated that crack propagation paths in granite are governed by mineral structural heterogeneity, the mechanical properties of individual grains, and the nature of intergranular contacts. Conversely, Q. Li *et al.* (2021) revealed that thermal damage evolves via the gradual accumulation of microcracks that form a spatially connected macroscopic failure system as thermal loading increases. Overall, the findings of these studies confirm that the final configuration of the crack network is the result of a complex interaction between the microstructural characteristics of the rock and the evolution of localised damage.

The effect of repeated thermal loading on the development of crack structures has been a particular focus of researchers. For example, D. Zhu *et al.* (2023) investigated how repeated heating and cooling cycles affect the tensile strength of granite. They experimentally demonstrated that as the number of thermal cycles increases, the density of microcracks and the degree of internal damage to the rock gradually increase, resulting in a corresponding reduction in tensile resistance. Additionally, they demonstrated that the failure pattern shifts from the formation of isolated defects to the development of an interconnected crack network, which ultimately results in a loss of load-bearing capacity. R.A. Haque *et al.* (2023) conducted a study that examined the evolution of polygonal crack systems in clay materials during repeated wetting and drying cycles. Based on experimental observations and statistical analysis, the authors concluded that the crack network gradually restructures geometrically over successive cycles, with short, unstable segments disappearing and polygons acquiring a more regular shape. The authors of the study concluded that the self-organisation of the polygonal network is the result of the system's tendency to move towards a more energetically favourable state.

T. Chen *et al.* (2026) investigated the regularities that govern the formation of polygonal cracks in multilayered rocks under cooling-induced shrinkage, using a three-dimensional thermomechanical model. The authors determined that the geometry of weak interlayers has a substantial impact on the density of the crack network, the dimensions of the polygonal blocks, and the redistribution of thermal stresses. Their findings confirm that the morphology of the polygonal structure is determined by both the temperature regime and the structural heterogeneity of the rock. The development of rock thermomechanics and geomechanics in Ukraine was given a sound scientific basis by fundamental studies carried out by Ukrainian researchers, which occupy an important place in the development of this field.

Ukrainian researchers D.L. Vasyliev *et al.* (2020) made a significant contribution to the investigation of the mechanisms governing the destruction of the surface layers of geomaterials under thermal shock, describing in detail the nature of rock-surface failure during rapid cooling. They demonstrated that critical tensile stress development causes degradation of the near-surface zone. However, the geometrical principles governing the regular packing of resulting crack contours require further analytical substantiation. A.F. Bulat *et al.*'s (2022) monographic study provides comprehensive substantiation for the application of nonlinear dynamic systems theory and fractal analysis to problems involving the destruction of geomaterials. They showed that the geometrical parameters and scale invariants of crack systems directly reflect the kinetics of energy dissipation within a loaded rock mass. The post-peak stability of rocks subjected to local external effects was investigated by S. Skipochka *et al.* (2025). The authors showed that failure development is determined by stress redistribution and the accumulation of potential energy within the rock mass. Mathematical modelling was also shown to make it possible to predict the loss of system stability. The findings demonstrate the efficacy of employing an energy-based method for analysing crack formation processes.

Analysis of the current research literature indicates that most studies focus on the experimental investigation of thermal damage to rocks and the assessment of changes to their physical and mechanical properties. Other areas of focus include modelling microcrack initiation and development and analysing the effects of temperature regimes, material heterogeneity and boundary conditions on the nature of failure. Significant progress has been made in reproducing crack propagation processes through numerical modelling, as well as in identifying the regularities that govern the evolution of polygonal networks. At the same time, the studies analysed give virtually no consideration to the fundamental geometrical principles. These principles underpin the self-organisation of polygonal crack systems. The studies also do not substantiate the reasons for the statistical predominance of hexagonal cells. They do not propose an analytical criterion either. This criterion would be capable of explaining the selection of their characteristic dimensions. These dimensions depend on the physical and mechanical properties of rocks. They also depend on the parameters of thermal loading. The application of the isoperimetric approach as a theoretical basis for describing the formation of polygonal structures during the rapid cooling of rocks remains largely unexplored. This study aimed to determine the most probable geometric shape of cracking cells by analysing the classical isoperimetric problem and the principle of minimising the energy required to fail the surface layer of rocks. It also aimed to derive analytical relationships for estimating the characteristic dimensions of resulting hexagonal structures depending on thermal cyclic loading conditions.

Materials and Methods

This theoretical and analytical study aimed to establish the regularities governing the formation of surface crack systems in rocks subjected to thermal cyclic loading. The study focused on the formation process of surface crack systems in rocks under thermal cyclic loading. The study examined the geometrical regularities that govern the formation of a polygonal surface crack structure, as well as the impact of the structural characteristics of rocks and thermal shock parameters on the shape and dimensions of cracking cells.

To achieve this, a combination of theoretical and analytical research methods was employed. These included the theoretical substantiation of the optimal geometrical form of a polygonal crack system. This was based on an analysis of the isoperimetric problem. Another was the determination of the geometrical cell shape. This was the one that ensures minimum energy expenditure during crack system formation. Then there was the analysis of the conditions for regular tessellation of a plane by regular polygons. Another was the generalisation of published experimental data. This was on the formation of polygonal crack systems in rocks. It was under different thermal cyclic loading regimes. Another was the assessment of the effects of rock structural heterogeneity. This was on thermal shock parameters. It was also on the shape and characteristic dimensions of polygonal cells. Finally, there was the comparison of the regularities governing polygonal structure formation in rocks. This was with analogous processes in other natural and biological systems.

When a rock that has been heated is cooled at its surface, multiaxial tensile thermal stresses arise within the surface layer. Once these stresses reach a critical level, the surface layer fails, forming a crack system that divides it into individual cells. These cells are predominantly regular or nearly regular polygons. Therefore, establishing the regularities governing the formation of their geometrical shape constitutes a distinct scientific problem. The following assumptions were made when analysing the formation of the polygonal crack system: fragmentation occurs along the path requiring the least energy; cracks generally propagate along straight lines; elastic fracture occurs, with plastic deformation being absent or insignificant; and the cells are packed as densely as possible over the surface, without empty spaces between them.

The energy required to form a single destruction cell will be considered minimal when, for a given cell area S, its perimeter is minimal. The essence of the classical isoperimetric problem, the focus of this study, can be summarised as follows: it is necessary to determine the figure with the largest area among all possible figures having the same perimeter. In other terms, given a set of geometrical configurations with an equal external contour length, the configuration providing the maximum area must be identified. This problem is of fundamental importance in geometric optimisation and has practical applications in analysing the regularities that govern the spatial distribution of cracks. In the present context, analysing the isoperimetric problem explains why a hexagonal, or honeycomb, crack structure predominantly forms as it is the most efficient configuration in terms of minimising surface energy and ensuring a uniform stress distribution. This explanation is in line with the geometrical crack patterns that are produced when materials fail due to heat and that have been observed in both natural conditions and in experimental studies.

The fundamental principles of energy minimisation that underlie the self-organisation of crack structures are based on the classical isoperimetric problem. As early as the works of the ancient Greek mathematician Zenodorus in around 200 BC, it was demonstrated that the circle has the largest area of any plane figure with a given perimeter (Heath, 1921). Nevertheless, even though this proposition may seem obvious, its mathematical proof is not simple. It was not until the eighteenth century that L. Euler (1744) proved the isoperimetric property of the circle using the calculus of variations and provided a geometric justification for the problem. In the present study, the isoperimetric approach was employed to substantiate the most probable geometry of a polygonal crack system formed during the thermal cracking of rock surfaces. The classical isoperimetric inequality was the basis of the solution to the isoperimetric problem. This inequality establishes a relationship between the length L of a closed curve, or polygon, and the area S of the surface enclosed by it. The isoperimetric inequality states that:

$$4\pi S \leqslant L^2. \qquad (1)$$

This inequality becomes an equality if and only if the curve is a circle. This relationship was used as a theoretical criterion. It was used for evaluating the most energetically favourable shape of polygonal cells. It reflects the fundamental principle that, for a given area, the circle has the smallest perimeter. Since forming each crack requires additional energy, the most favourable shape for a polygonal cell is the one that minimises the total crack length. For quantitative comparisons of regular polygons, the isoperimetric quotient Q was used:

$$Q = \frac{4\pi S}{L^2}, \qquad (2)$$

where S – is the area of the polygon; L – its perimeter. The isoperimetric quotient was used as the main criterion for comparing regular polygons quantitatively, according to how closely they approximate a circle (which corresponds to the maximum value of $Q = 1$. The greater the coefficient, the smaller the perimeter of a figure with the same area, and consequently the lower the potential energy expenditure required to form the polygonal crack system. For a regular n-gon, the isoperimetric quotient was determined using the following relationship:

$$Q_n = \frac{\pi}{n \cdot tg\frac{\pi}{n}}. \qquad (3)$$

This formula was used to calculate the isoperimetric quotients of regular polygons with between three and ten sides. These values were then used in a comparative analysis of different geometric shapes, considering minimum perimeter length and the possibility of regular tessellation of a plane. The analysis also took into account the classical isoperimetric theorems, which state that among all n-gons with the same perimeter, the regular n-gon has the largest area and that, among n-gons inscribed in a given circle, the regular n-gon has the maximum area and perimeter. These propositions were used to provide a theoretical basis for the optimal geometry of polygonal cells. To estimate the thermal stresses arising in the surface layer of a rock under thermal shock and first-kind boundary conditions, the classical thermoelasticity equation was used:

$$\sigma_* = \frac{\beta \cdot E \cdot (T_i - T_c)}{1-\mu}, \quad (4)$$

where β – is the coefficient of linear thermal expansion of the rock; E – Young's modulus; T_i – is the initial rock temperature; T_c – is the temperature of the cooling medium; μ – is Poisson's ratio. Formula (4) was used to calculate the magnitude of the thermal stresses that arise in the surface layer of the rock during rapid cooling. The following relationship was used to estimate the characteristic size of the polygonal cells under specified cooling condition:

$$g = \frac{0.45 \cdot K^2 \cdot \sigma_c^2}{\pi^2 \cdot \sigma_*^2 \cdot \sigma_t^2}, \quad (5)$$

where K – is the cohesion modulus of the rock; σ_c – is the compressive strength; σ_t – the tensile strength. This formula (5) was used to analyse the impact of the physical and mechanical properties of rocks, as well as thermal cyclic loading regimes, on the size of the characteristic cells within the polygonal crack system. To verify the proposed theoretical model, a comparative analysis was conducted. This analysis was of published experimental studies. These studies concerned the formation of polygonal crack systems. These systems were formed under different thermal cyclic loading regimes. Laboratory experiments and field observations investigating the formation of polygonal structures over a broad range of scales, from fractions of a millimetre to several metres, were analysed. Additionally, the effect of the structural heterogeneity of rocks on the geometry of the polygonal crack system was analysed, as well as the effect of the temperature difference between heating and cooling on the characteristic dimensions of the polygonal cells.

In the final stage of the study, a comparative analysis was carried out of the patterns governing the formation of polygonal structures in rocks, in relation to similar processes in other natural and biological systems. This made it possible to assess the universality of the principle of energy minimisation as a general mechanism for the formation of cellular structures of various physical natures. The proposed model is based on the assumption of homogeneity and isotropy of the material within the study area, as well as on the sufficient uniformity of the temperature field in the zone where surface cracks form. At the same time, the model does not take into account natural fracturing, mineralogical heterogeneity, anisotropy of the physical and mechanical properties of rocks, moisture content, residual stresses, or local inhomogeneities in the temperature field. Consequently, it describes the general geometric patterns of polygonal fracture system formation and can be used as a theoretical basis for the further development of models of thermal rock failure.

Results

The theoretical analysis first determined which polygonal cell geometry is most energetically favourable when a surface crack system is formed. The underlying premise is that forming each new crack creates fracture surfaces, which requires energy. Therefore, all other conditions being equal, the most probable cell configuration should provide the minimum total boundary length for a given area. Analysis of experimental observations indicates that such cells predominantly take the form of regular or nearly regular polygons. The most probable geometric shape of these cells was determined by quantitatively analysing the relevant relationship. To quantify this relationship, the isoperimetric quotients Q of regular polygons with between three and ten sides were analysed using formula (3). The calculation results are presented in Table 1.

Table 1. *Isoperimetric quotients for different polygons*

Number of polygon sides, *n*	3	4	5	6	7	8	9	10
Q	0.61	0.78	0.86	0.90	0.95	0.96	0.97	0.98

Source: *calculated by the authors based on their own computations*

The isoperimetric quotient of regular polygons approaches unity as the number of sides increases, as a comparative analysis showed. Of the figures considered, the regular decagon has the highest value, with an isoperimetric quotient of around 0.98. This indicates the most favourable ratio of area to contour length, meaning that the specific energy expenditure required to form the polygon boundaries is lowest. From the standpoint of fracture mechanics, this relationship has important physical implications. The same area with a smaller perimeter will result in a shorter total length of newly formed crack surfaces. This means less energy is needed to form them. Thus, the isoperimetric quotient can be considered a geometrical indicator of the potential energy efficiency of a polygonal structure.

At the same time, the results of the calculations indicate that the maximum value of the isoperimetric coefficient does not, in itself, determine the geometry of a polygonal fracture system. Although polygons with a large number of sides are closer in shape to a circle and exhibit better isoperimetric properties, most of them are unable to regularly fill a plane without creating gaps or overlaps. Under these conditions, minimising the perimeter cannot be the sole criterion for the self-organisation of the system. Consequently, the results of the first stage of the study show that determining the most probable geometry of polygonal cells requires simultaneous consideration of two independent requirements: maximum approximation of the shape to the isoperimetric optimum and the possibility of regular tessellation of the plane. It is precisely the analysis of the combined effect of these criteria that enables the determination of the geometry that is realised during the thermal fracturing of rock.

The results of the isoperimetric analysis showed that the geometric efficiency of a regular polygon increases consistently with the number of its sides. However, this relationship alone cannot explain the formation of polygonal cracks in rocks during thermal failure. Another fundamental condition, derived from the physical nature of the process, must also be considered. A polygonal crack system develops as a continuous network that divides the surface layer of a rock into separate fragments without producing voids or overlaps, unlike an isolated geometrical figure. Therefore, the geometry of an individual cell must allow the entire plane to be regularly tiled, since only such a configuration is compatible with the continuous propagation of cracks within the surface layer. A comparative analysis of regular polygons revealed that only three geometric figures satisfy the condition of regular tessellation: the equilateral triangle, the square and the regular hexagon (Fig. 1). Furthermore, when a system of elastic circles is arranged on a plane and compressed, the circles transform specifically into hexagons (Fig. 2).

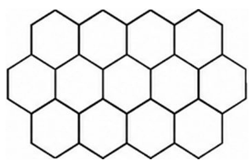

Figure 1. *Dense packing of hexagons on a flat surface*
Source: *compiled by the authors*

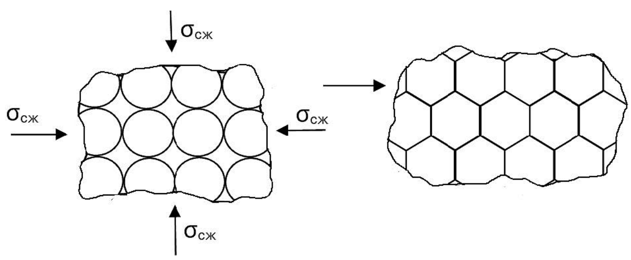

Figure 2. *Transformation of elastic circle s into hexagons under compression*
Source: *compiled by the authors*

Practical observations suggest that the resulting crack structure closely resembles a honeycomb pattern, meaning it is predominantly hexagonal. Both during intensive cooling and during temperature-induced polymorphic transformations of quartz, this relationship is observed. Heating the low-temperature modification of β-quartz to 573°C transforms it into the high-temperature modification, α-quartz. This transformation is diffusionless and occurs without breaking the principal interatomic bonds, accounting for its virtually instantaneous nature. Subsequent cooling below 573°C normally causes α-quartz to transform back into β-quartz, accompanied by volumetric changes in the crystal lattice and the development of internal stresses.

It has been established that when quartz that has been heated above 573°C is rapidly cooled, a specific system of inversion cracks forms within its structure. The geometry of this system is predominantly honeycomb, or hexagonal, and it can be detected using microscopic methods. Honeycomb cracks produced by cooling quartz rapidly from above the inversion range to below the inversion temperature are diagnostic $\alpha \rightarrow \beta$ of quartz phase transformations. These transition cracks only form under intensive cooling, such as with water, and are absent during slow cooling, such as in air. The degree of quartz cracking under these conditions is very high. In the experiments, a crack network with a characteristic size of 0.15 × (0.2 ÷ 0.4) mm was obtained. A comparison of the three possible tessellation patterns revealed significant differences in their geometrical efficiency. The isoperimetric quotient of an equilateral triangle is approximately 0.605; that of a square is 0.785; and that of a regular hexagon is 0.907. Therefore, among all regular polygons capable of tiling a plane in a regular manner, the hexagon provides the minimum total boundary length for the same cell area.

The formation of cracks is accompanied by an energy cost associated with the creation of new surfaces; therefore, the system seeks to minimise their total length. Given a regular tessellation of the plane, this problem boils down to finding a geometric compromise. If only the minimisation of the perimeter is considered, the optimal shape is a circle, which cannot tightly fill the plane. If only the tessellation condition is considered, the possible shapes are a triangle, a square and a hexagon. The simultaneous combination of these two independent criteria leads to a single analytical solution – a regular hexagon, which provides the smallest perimeter for a given cell area. This geometric principle forms the basis for the self-organisation of real fractured structures in rock formations.

The crack system evolves towards a hexagonal configuration in stages. During the initial stage of thermal shock, an isotropic field of biaxial tensile stresses forms on the surface of the rock. Due to the mineralogical heterogeneity of the material and the random distribution of local stress concentrators, individual cracks form independently of each other. Further propagation of the defects transforms the local stress state of the surface. Each newly formed crack produces a surrounding relaxation zone. This is also known as an unloading zone. The interaction between these zones via adjacent mechanical stress fields transforms the random crack formation process into a self-organising regime. As energy is dissipated, the number of possible network configurations becomes limited: polygons with a small number of sides (triangles) have an excessively high specific boundary length, which is energetically unfavourable, whilst polygons with $n > 6$ do not provide a continuous tessellation of the plane. As a result, the system stabilises at an optimal compromise solution – a regular hexagon. The structural and thermal heterogeneity of real rocks causes local deviations of individual cells from the ideal geometry, resulting in the formation of adjacent pentagonal and heptagonal contours; however, the overall tendency towards the formation of a honeycomb topology remains dominant.

Laboratory experiments involving the rapid cooling of granite, basalt and other brittle rock surfaces demonstrate the formation of such polygonal networks. The cells formed are predominantly pentagonal, hexagonal and heptagonal in shape, with a clear statistical predominance of hexagonal elements. Under natural conditions, this geometric mechanism manifests itself in the formation of columnar structures during the cooling of crystallised lava. A honeycomb system of cracks forms on its surface, with hexagonal blocks ranging in size from a few centimetres to 1.5 m, penetrating into the massif to a depth of up to 30 m. The mechanisms governing the development of such structures at great depths depend significantly on high geostatic pressure. The planetary and universal nature of this phenomenon is confirmed by the discovery of similar hexagonal cooling formations on the surface of Mars. Thus, a comparison of theoretical propositions with empirical and field data reveals their qualitative consistency. This confirms the adequacy of the proposed isoperimetric model for predicting the topology of thermal cracking in geomaterials.

Nevertheless, it should be noted that the verification conducted is qualitative in nature. The proposed model describes the fundamental geometrical regularities governing the formation of a polygonal network. However, quantitative prediction of the proportions of polygons of different shapes requires consideration of material heterogeneity, crack-development kinetics, the three-dimensional stress state, and other factors beyond the scope of the present study. The linear dimensions of polygonal cells are determined by the balance between the accumulation of elastic energy in the near-surface layer and its dissipation during failure, unlike their shape. Analysis of the developed model and formula (5) shows that the scale of the resulting network changes systematically under the influence of thermomechanical parameters. Tensile stresses are accelerated by an increase in the intensity of thermal loading, the elastic modulus, or the coefficient of linear thermal expansion. Consequently, the critical state is reached at a shorter distance between adjacent defects, resulting in a denser network with smaller individual cells. The tensile strength of the rock has the opposite effect. A higher concentration of thermal stresses is required to initiate failure when tensile strength increases. This leads to larger polygons being formed, with the spacing between cracks increasing.

The analytical relationships established provide a physical basis for the known experimental data for granites and basalts, where accelerated cooling is always accompanied by a refinement of the fracture structure. Thus, during thermal fracture, the geometric topology of the network is governed by the principles of energy optimisation, whilst its scale factor is a function of the properties of the geomaterial and the thermal loading conditions. Combining the isoperimetric criterion with the condition of regular tessellation of the plane analytically proves that a regular hexagon is the only energetically optimal configuration that ensures minimal energy expenditure for the formation of fracture surfaces. The transition from chaotic crack initiation to an ordered hexagonal network results from the self-organisation of the system through the interaction of local stress relaxation zones. The heterogeneity of the geomaterial's properties determines the statistical nature of the model, which is expressed in the dominance of hexagonal cells alongside the presence of defective pentagonal and heptagonal contours. A fundamental distinction between the factors governing crack formation has been established: the topology of the network is governed by geometric principles of perimeter minimisation, whilst its linear scale is a function of the thermomechanical parameters of the medium and the intensity of the heat flow.

Discussion

The results obtained allow to explain the predominantly hexagonal shape of the polygonal crack system in terms of minimising fracture energy and geometrically optimising the surface. Unlike traditional approaches, which focus on strength criteria and the mechanisms responsible for initiating thermal cracks, the proposed isoperimetric model explains the geometric nature of the resulting defect system. Recent mathematical studies, particularly the review by J. Li & S. Pan (2025), support the fundamental significance of the selected isoperimetric approach, as they demonstrated the universal applicability of isoperimetric inequalities in different types of spaces. Their proposition that the isoperimetric inequality is a key instrument for optimising geometrical forms appears well founded. However, unlike this general theoretical approach, the present study is restricted to tessellation problems, specifically the dense tiling of the Euclidean plane. This is critical for explaining the formation of a hexagonal crack network within a rock mass.

The results obtained are consistent with those of W. Nie *et al.* (2023), who used numerical modelling to demonstrate the formation of an extensive system of thermal cracks in rocks. While the authors of that study analysed the kinetics and mechanisms of crack development, this research focuses on explaining why hexagonal cell geometry predominates specifically during thermal cracking. These findings are also consistent with those of Q. Lu *et al.* (2023), who investigated thermal damage in rocks and shales under thermal shock conditions. They confirmed the intensive development of cracks and changes in rock mass permeability as a function of temperature gradients. The proposed approach reveals the topological characteristics of the resulting polygonal structure, unlike their studies, which focused on the quantitative assessment of accumulated damage.

The study by T. Wang *et al.* (2026) is interesting because it draws parallels with the present research. This earlier study analysed the influence of surface defects on crack initiation during soil desiccation. The authors support the proposition in this study that local stress concentrators on the surface trigger the formation of regular structures. Their conclusion that defects play a decisive role in crack initiation seems entirely justified. However, in contrast to their strategy, which centred on observing changes in soil deformation, this study aims to provide a detailed explanation of the shift from a random arrangement of defects to a hexagonal pattern in solid rocks. This transformation is driven by the principle of reducing isoperimetric energy. The results of this study are consistent with the observations of Y. Akiba *et al.* (2021a; 2021b), who used field measurements of columnar joints and solidified lava to identify universal statistical patterns in the geometry of polygonal cracks. Unlike their predominantly statistical and descriptive studies, the isoperimetric model proposed here provides a physical and geometrical explanation for the predominance of hexagonal cells.

Important confirmation of the hierarchical nature of the established model is provided by the results of C.-S. Tang & T. Wang (2026), who demonstrated that the architecture of crack networks is governed by a recursive stress-field feedback mechanism. They demonstrated that over 80% of secondary microcracks originate at the midpoint of a parent crack, and that mutual attraction occurs when the distance between them decreases to approximately two to four times their width, resulting in the formation of nodal junctions. This process leads to a shift from chaotic cracking to ordered polygonal structures. Unlike the objects investigated by C.-S. Tang & T. Wang (2026), in which this process develops gradually during soil desiccation, similar hexagonal cell topologies form in brittle rocks under conditions of intensive thermal shock. The characteristic hexagonal network pattern is therefore a universal outcome of geometrical self-organisation. This is governed by the isoperimetric principle of fracture-energy minimisation. This is irrespective of the nature and rate of the external influence.

In the context of energy optimisation principles governing cracking, the proposed isoperimetric approach closely aligns with recent specialist studies on damage evolution in rocks subjected to thermal effects. The evolution of rock damage during rapid cooling has been extensively examined by L. Dong *et al.* (2024), and the results of this contemporary experimental data confirm it. The authors examined the temperature dependence of the physical and mechanical properties of hot, dry rocks when subjected to a sudden reduction in temperature. They demonstrated through experimentation that a high cooling rate is a critical trigger for the widespread initiation of macrocracks and the rapid degradation of the rock mass. Their approach is different. It records the loss of strength. This is unlike the present study. It explains how this avalanche-like evolution of damage geometrically self-organises in space. This is done so as to minimise energy expenditure.

This degradation inevitably involves a complex transformation of the system's energy balance, which was analysed in depth by W. Shen *et al.* (2026). Their study considered energy evolution in granite. This was under cyclic loading combined with thermal shock and seawater cooling. The authors convincingly demonstrated that crack formation is the principal mechanism through which accumulated thermoelastic energy is dissipated in rocks. While the study by W. Shen *et al.* (2026) shows that a lot of energy is spent creating new surfaces, the isoperimetric approach proposed here explains why this dissipation is optimum through the formation of a hexagonal network.

Similar processes can be clearly represented in terms of their kinematics and spatial development using modern numerical modelling methods, as demonstrated in the study by L. Su *et al.* (2026). The authors used the discrete element method (DEM) to visualise the propagation of cracks and dynamic damage in granite that was directly subjected to high-temperature thermal shock. The model they developed shows how microcracks initially develop chaotically, gradually merging into larger structures as they are influenced by temperature variations. While DEM modelling shows the progressive course of failure over time, the analytical geometrical model in this study identifies the ideal topological outcome of this process: formation of a hexagonal cell, as this is the most energy-efficient geometric shape.

Analytical degradation models, such as that developed by Y. Li *et al.* (2026), also reflect the theoretical basis of these processes. This study proposed a comprehensive mathematical model of damage evolution in granite subjected to extreme high-temperature thermal shock. The researchers' primary focus was on quantitatively assessing the deterioration of the material's mechanical properties and changes in its structural integrity. This study builds on their work by translating quantitative damage indicators into the qualitative domain of topology, demonstrating that the final macrocrack configuration is strictly governed by the macroscopic isoperimetric principle.

In the context of geometrical optimisation, the study by Q. Ma *et al.* (2023), which directly applies the concept of planar tessellation, merits particular attention. The authors applied a two-scale tessellation approach within the discrete element method. This was to analyse the thermal failure of granite under different temperature conditions. However, in their study, polygonal subdivision was primarily used as a mathematical tool, or mesh, to accurately model a continuum numerically. In contrast, in the present study, tessellation is not treated as an artificial approximation tool, but rather as a fundamental physical and geometrical mechanism that explains the natural formation of regular polygons.

The geometry of cracking described in this study is in line with the key review by L. Wong & Z. Liu (2025), which identified thermal shock as a major cause of damage to underground structures. While that review documents the formation of polygonal structures as a typical consequence of energy dissipation, the present study provides a mathematical demonstration of why this self-organisation tends towards a regular hexagon under planar tessellation conditions. When analysing the geometrical parameters of crack networks, the recently published dataset by A. Asadian *et al.* (2026) should also be considered. This contains labelled geometrical characteristics for hundreds of shrinkage-crack networks. The authors recorded the predominance of polygonal structures. These had mainly triangular, quadrilateral, and hexagonal cell geometries. A. Asadian *et al.*'s (2026) conclusion that the formation of polygonal structures is statistically characteristic of failure processes appears well founded. However, in contrast to their method, which merely documented geometric parameters without elucidating the underlying physical mechanism, this study delves into the origin of these structures. Thus, the data of A. Asadian *et al.* (2026) provide an empirical basis for observation. This study explains why the hexagonal form becomes dominant during intensive cracking. This addresses a gap in the theoretical understanding of the mechanism responsible for the formation of such structures.

The methods developed by the authors for thermal cyclic weakening and volumetric treatment of strong rock masses, which are protected by Ukrainian Utility Model Patents No. 154853 (2023) and Ukrainiфan Utility Model Patent No. 161823 (2026), represent a practical development of the theoretical propositions obtained in this study. Unlike the present study, these patents primarily focus on the technological implementation of artificial fracture generation and substantiating thermal treatment regimes. By contrast, the present work reveals the underlying geometrical nature of the crack system formed when the patented methods are implemented. The proposed isoperimetric approach extends the existing understanding of thermomechanical rock failure and is of considerable importance for optimising geotechnologies, the effectiveness of which depends directly on the controlled management of rock mass permeability.

Conclusions

The mechanism governing the formation of a polygonal cooling-crack network has been theoretically substantiated. This was based on the isoperimetric approach and dense planar tessellation. It has been established that, of the shapes capable of regularly tiling a surface, the regular hexagon provides the greatest isoperimetric efficiency. The predominance of hexagonal geometry has been shown to result from minimising the total crack perimeter, which corresponds to the lowest energy expenditure required for failure. The statistical predominance of hexagonal polygonal cells has been shown to be a natural consequence of the geometrical self-organisation of the crack system. This system forms during the thermal failure of rocks.

The proposed model explains how individual pentagonal and heptagonal cells can form next to hexagons in the real world. This is associated with heterogeneity in mineral composition, local variations in stress levels and the natural anisotropy of rocks. The characteristic size of polygonal cells has been shown to be determined by the intensity of thermal loading and the physical and mechanical properties of the rock. As the temperature difference between the heated rock and the cooling medium increases, the density of cracks rises and the average size of the polygonal cells decreases systematically. The theoretical conclusions are in line with the experimental observations, which confirm the formation of a honeycomb-like polygonal structure with characteristic cell sizes ranging from fractions of a millimetre to several metres, depending on the thermal exposure conditions.

The proposed model's practical significance lies in its potential use for predicting the morphology of polygonal crack systems during thermal failure of rocks in thermal drilling, thermal treatment, and the stimulation of geothermal-reservoir permeability. It can also be used to interpret natural polygonal structures of different origins. Future research should extend the model to account for the anisotropy of the physical and mechanical properties of rocks, the heterogeneity of their mineral composition, the three-dimensional development of crack networks and integrate the analytical approach with modern numerical modelling methods. This would enable to progress from qualitative descriptions to quantitative predictions of the parameters of polygonal structures.

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Conflict of Interest

None.

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Геометричні особливості формування сітки тріщин на поверхні гірських порід при охолодженні

Анотація. Метою роботи було встановлення найімовірнішої геометричної форми комірок розтріскування на основі принципу мінімізації енергетичних витрат при руйнуванні поверхневого шару гірських порід. Методологічну основу дослідження становили аналіз класичної ізопериметричної задачі, згідно з якою серед фігур з однаковим периметром максимальна площа має коло, а серед багатокутників – правильний *n*-кутник. З урахуванням фізичних умов формування тріщин виконано обґрунтування найбільш енергетично вигідної конфігурації системи тріщин. Теоретичні положення зіставлено з експериментальними даними та результатами раніше проведених досліджень у галузі термомеханічного руйнування гірських порід. У результаті встановлено, що при охолодженні нагрітих поверхонь формується переважно полігональна структура тріщин з комірками шестикутної форми. Показано, що шестикутник є оптимальною геометричною фігурою, що забезпечує мінімальний периметр при заданій площі та можливість щільного пакування на площині без утворення додаткових порожнин або напруг. Встановлено, що розмір комірок розтріскування визначається сукупністю факторів, серед яких ключовими є фізико-механічні властивості породи, величина температурного градієнта та режим охолодження. При збільшенні різниці температур між нагріванням та охолодженням відбувається зменшення характерного розміру комірок. Підтверджено широкий діапазон розмірів структур, що формуються – від часток міліметра до метрів. Практичне значення результатів полягає у можливості їх використання для прогнозування параметрів тріщинуватості та управління процесами руйнування гірських порід при розробці родовищ, а також при проектуванні технологій термічного впливу на масив

Ключові слова: термоциклічне навантаження; ізопериметрична задача; регулярна теселяція; стільникова структура; термоциклічне руйнування

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Nature-based technologies for the utilisation of technogenically disturbed lands in mining regions

Abstract. The intensive development of the mining industry in the Kryvyi Rih basin has led to the formation of significant areas of technogenically disturbed land (quarries, rock dumps, tailings storage facilities), characterised by complex engineering-geological and geo-ecological conditions and limited suitability for traditional agricultural use. The aim of the study was to analyse the current state of technogenically disturbed land in the Kryvyi Rih mining region and to justify the feasibility of applying nature-based technologies during its revitalisation through the installation of wind turbines. The methodological basis of the study comprised methods of systems analysis, a review of scientific publications, a geo-ecological assessment of technogenically disturbed areas, a comparative analysis of the engineering-geological characteristics of mining sites, and an analysis of natural and technological factors influencing the feasibility of their reuse. The findings identified the specific features of the current mining and environmental conditions of the Kryvyi Rih basin and determined the integrated potential of waste dumps, exhausted open pits, and tailings storage facilities for the safe installation of wind turbines. A detailed analysis of the engineering-geological characteristics confirmed the high potential for using spoil heaps as an alternative means of developing disturbed landscapes. Furthermore, a geo-ecological assessment demonstrated that the considerable height of rock spoil heaps allows for the effective optimisation of the interaction between wind turbines and air flows. Basic principles for the nature-based restoration of disturbed landscapes have been formulated, which envisage synergy between technical-biological reclamation and the infrastructure development of renewable energy without the appropriation of new natural land areas.

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The practical value of the study lies in the scientific justification for the reuse of land disturbed by human activity without further removal of natural areas from economic use, which contributes to improving the efficiency of land resource use, reducing the anthropogenic impact on the environment, and implementing the principles of sustainable development in mining regions

Keywords: reclamation; revitalisation; waste dumps; wind turbines; Kryvyi Rih basin

Introduction

The current stage of global industrial development requires a fundamental rethinking of approaches to sustainable land use. Prolonged mineral extraction by both surface and underground mining methods has resulted in the large-scale degradation of natural ecosystems, the formation of deep open pits, and the accumulation of extensive waste rock dumps. Restoring such areas to an environmentally safe and economically productive condition has become a major challenge for many industrialised countries, as conventional land reclamation techniques often require substantial financial investment and do not always ensure the long-term ecological stability of restored landscapes. Between 2020 and 2025, international practice has demonstrated a clear transition from the traditional reclamation model, focused primarily on the technical restoration of disturbed land, towards the broader concept of post-mining land use. This approach emphasises the long-term planning of functional land use for technogenically disturbed areas in mining regions, taking into account environmental, economic, and social considerations. As highlighted by C. Pagouni *et al*. (2024), K. Karalidis *et al*. (2024), and S. Worden *et al*. (2024), the principal criteria for determining future land use include ecosystem resilience, economic viability, societal value, and consistency with regional development strategies.

One of the most dynamic areas of research during this period is the implementation of Nature-based Solutions (NbS) in the restoration of degraded areas. According to the methodology of the International Union for Conservation of Nature (IUCN), nature-based solutions are measures aimed at the conservation, restoration and sustainable management of natural or modified ecosystems, which simultaneously deliver environmental, social and economic benefits. According to the findings of M. Cardinali *et al*. (2021), the further development of this concept is reflected in the European Commission's practical recommendations on assessing the effectiveness of nature-based solutions as a tool for implementing climate policy and sustainable land management. In this study, nature-based technologies are considered as the practical implementation of the principles of Nature-based Solutions for technogenically disturbed land in mining regions, involving the integration of engineering solutions with natural ecosystem self-recovery processes to form ecologically sustainable nature-technology systems.

Experience from countries such as Germany, the USA, Peru, Poland and Ukraine shows that one of the most promising avenues for the reuse of technogenically disturbed land is the development of renewable energy, as confirmed by the works of K. Kaczmarczyk *et al*. (2023), O.O. Medvedieva *et al*. (2024), and M.A. Cotrina-Teatino *et al*. (2025). Locating solar and wind power stations on the sites of former quarries, waste rock dumps and other mining facilities minimises the use of natural land, contributes to the decarbonisation of the economy and enhances the economic efficiency of revitalisation programmes. At the same time, the study by J.M. Kiesecker *et al*. (2024) emphasised the importance of identifying areas with a low level of environmental conflict for the deployment of wind and solar power generation facilities within the context of the pan-European energy transition. Similarly, S. Worden *et al*. (2024) argued that decisions regarding the future utilisation of technogenically disturbed land should be based on a comprehensive assessment of geotechnical, environmental, spatial, and socio-economic factors.

In Ukraine, the issue of utilising land disturbed by human activity is becoming particularly pressing due to the significant areas of land affected by both surface and underground mining. Traditional approaches have mainly focused on the regulatory and legal framework for land reclamation, improving land-use planning, the protection of land resources, and the application of strategic environmental assessment tools in the field of subsoil use. However, only a few researchers in Ukraine, notably O.S. Kovrov *et al*. (2023) and O.O. Medvedieva *et al*. (2024), have directly addressed issues relating to a comprehensive approach to the utilisation of technogenically disturbed land, its revitalisation and technical-biological reclamation. However, research combining these processes with the systematic integration of nature-based solutions principles and the direct siting of renewable energy facilities on spoil heaps currently requires further development and scientific justification. Given the level of anthropogenic impact, this aspect is of paramount importance for the Kryvyi Rih iron ore basin, one of Europe's largest mining complexes. More than a century of intensive iron ore extraction has resulted in extensive areas of technogenically disturbed land, including open pits, waste rock dumps, tailings storage facilities, and zones of ground deformation. At the same time, the morphometric characteristics, spatial distribution, and wind potential of waste rock dumps create favourable conditions for combining ecological restoration with the development of renewable energy.

Despite significant progress in scientific research into the utilisation of technogenically disturbed land, the scientific and methodological foundations for integrating nature-based technologies, land reclamation, revitalisation and the siting of wind power installations into a unified management system for anthropogenically disturbed areas remain underdeveloped. This necessitates the development of a comprehensive approach to the use of these lands, adapted to the natural, climatic and technogenic conditions of Ukraine. The aim of the study was to justify nature-based technologies for the utilisation of technogenically disturbed land in mining regions based on the principles of Nature-based Solutions, and to determine the prospects for the use of wind turbines as a component of their revitalisation. To achieve this aim, the following objectives were undertaken: to analyse the experience of European Union countries (in particular Poland and Germany) regarding post-mining land use; to investigate the spatial condition of technogenic disturbed areas in the Kryvyi Rih iron ore basin; to summarise the principles of nature-based restoration of degraded landscapes and to assess the engineering-geological prerequisites for using waste rock dumps to accommodate wind energy facilities.

Materials and Methods

This analytical and predictive study was based on a comprehensive geo-ecological assessment and spatial modelling of the potential for renewable energy on degraded landscapes. The regional case study focused on technogenically disturbed land at the largest mining enterprises in the Kryvyi Rih iron ore basin, which was formed as a result of prolonged (over 140 years) intensive open-cast and underground mining and the processing of iron ore. The criteria for selecting specific study sites were: the scale of anthropogenic disturbance, the duration of the disturbed state, the elevation and geometric parameters of the disturbed areas, as well as the presence of developed industrial infrastructure and the absence of current competition from agriculture or forestry.

The research materials comprised scientific publications, regulatory and legal documents in the field of land protection, as well as summarised geo-ecological and statistical reports from mining enterprises in the Kryvyi Rih iron ore basin for the period 2021-2025. In particular, the analysis utilised environmental impact assessment reports and post-project monitoring materials, which are publicly available on the official websites of industrial enterprises in the city of Kryvyi Rih, the Kryvyi Rih District State Administration, and on the web portal of the Ministry of Economy, Environment and Agriculture of Ukraine (n.d.). The criteria for selecting scientific sources for the analysis were: relevance to the topics of post-mining land use and Nature-based Solutions; indexing in scientometric databases (Scopus, Web of Science); geographical coverage (EU countries, the USA, Latin America); and publications no more than five years old. A general description of the sites studied within the mining concessions of Kryvyi Rih basin enterprises is presented in Table 1.

Table 1. *Sites of technogenically disturbed land at mining enterprises in the Kryvyi Rih basin*

Enterprise	Principal features	Number of features	Total area, ha
Sukha Balka Mine	Subsidence zones and waste rock dumps, disturbed land, "Dubrova Gully", and waterlogged area	6	250.2
Southern Mining and Processing Plant	Sections of the "Shymanivskyi" and "Pravoberezhnyi" waste dumps	1	68.7
Central Mining and Processing Plant	Open pits and waste dumps	3	126.5
Northern Mining and Processing Plant	Open pits, truck-operated waste dumps, and disturbed land areas	4	209.0
Ingulets Mining and Processing Plant	Waste Dumps No. 1 and No. 3	2	259.5
ArcelorMittal Kryvyi Rih	Truck-Operated Waste Dump No. 3	1	54.0
Total			967.9

Source: *compiled by the authors based on an analysis of the enterprises' geo-ecological and statistical data (Sukha Balka, n.d.; Southern Mining and Processing Plant, n.d.; Central Mining and Processing Plant, n.d.; Ingulets Mining and Processing Plant, n.d.; ArcelorMittal Kryvyi Rih, n.d.)*

The study was carried out in several consecutive stages. The first stage involved an analysis of current scientific approaches to the reuse of technogenically disturbed land, the revitalisation of post-mining areas and the implementation of nature-based technologies, as outlined in the works of M. Hendrychova *et al.* (2020), C. Pagouni *et al.* (2024), and S. Worden *et al.* (2024). A system of fundamental reclamation and energy principles was developed by integrating three key components, namely the theoretical basis drawn from the literature, from which the conceptual foundations of ecological balance and the engineering and energy compatibility of sites were derived, the requirements of Ukraine's regulatory and legal documents, in particular the Land Code and the Subsurface Code, which defined the boundaries of legal certainty and the mandatory stages of mining reclamation; and the actual regional geo-ecological characteristics of the Kryvyi Rih basin, including the physical and mechanical properties of the spoil heaps, the topographic potential of waste dumps and the parameters of the local wind climate, which set the actual technical constraints. The choice of these specific principles is dictated by the need to simultaneously address environmental objectives regarding landscape stabilisation and engineering requirements for ensuring efficient power generation.

These principles were incorporated into the conceptual model as fixed spatial filter criteria, against which each analysed waste dump was systematically assessed for compliance with the specified requirements; this made it possible to identify specific sites suitable for revitalisation and to use them as the basis for developing the final conceptual model. In the second stage, a geo-ecological characterisation of the technogenically disturbed lands of the Kryvyi Rih basin was carried out, taking into account their morphological features, types of disturbance, engineering-geological condition and current use. Particular attention was devoted to waste rock dumps, which were identified as the most promising locations for the deployment of wind energy systems owing to their considerable elevation, favourable conditions for wind flow enhancement, open terrain, and the absence of conflicts with agricultural land use. The third stage comprised a comparative assessment of the natural, technogenic, and engineering-geological factors determining the potential for the reuse of different categories of technogenically disturbed land.

The methodological basis of the study was provided by methods of systems analysis, which were applied to consider technogenically disturbed lands as complex natural-technical systems; the method of comparative analysis was used to compare different types of disturbed areas in terms of their suitability for revitalisation. The comparison criteria were as follows: the geometric parameters of the landmasses (plateau area and elevation), the degree of geotechnical stability of slopes and the riverbed, the intensity of hazardous geodynamic processes, the level of flooding and characteristics of the hydrogeological regime, proximity to existing energy infrastructure hubs of industrial enterprises, as well as the degree of surface erosion vulnerability. A geo-ecological assessment method was employed to determine the ecological status and potential for the reuse of the studied areas. Structural-functional analysis was used to establish the interrelationships between the processes of reclamation, revitalisation, and renewable energy development. In addition, the method of generalisation was applied to systematise contemporary scientific approaches to the utilisation of technogenically disturbed land, as presented in the works of C. Pagouni *et al.* (2024) and S. Worden *et al.* (2024).

The conceptual basis of the study was the adaptation of the principles of Nature-based Solutions to the conditions of technogenically disturbed land in mining regions (Cardinali *et al.*, 2021; Rendle *et al.*, 2023). When assessing the prospects for land use, the following factors were taken into account: ecological balance, adaptability to anthropogenically altered landscapes, compatibility with land reclamation and energy generation, the potential for integrated land use, safety in terms of geotechnical and hydrogeological conditions, and the energy feasibility of siting wind turbines (Guan *et al.*, 2022; Xiao *et al.*, 2022; Aska *et al.*, 2024). The limitations of this study included its focus exclusively on the specific characteristics of iron ore enterprises in the Kryvyi Rih basin, which have high waste rock dumps, without taking into account the characteristics of degraded landscapes in coal-mining regions. Furthermore, the spatial analysis was limited by the available open-access data from environmental impact assessment reports and post-project monitoring materials from the enterprises, as the imposition of martial law made it impossible to carry out a full range of detailed field engineering, geodetic and aerial surveying work directly at the sites.

Results and Discussion

Assessment of the potential of post-mining areas and the development of a model for their reclamation and energy-based revitalisation

The analysis of technogenically disturbed land in the Kryvyi Rih Iron Ore Basin demonstrated that the most promising sites for the installation of wind energy systems are waste rock dumps and exhausted open pits, which are characterised by extensive areas, well-developed landforms, and the absence of competition from other forms of land use. However, the effectiveness of their utilisation depends not only on natural conditions but also on compliance with a comprehensive set of environmental, engineering, and spatial requirements (Rahmonov *et al.*, 2022; Medvedieva *et al.*, 2024).

To provide a detailed assessment of site suitability, the proposed evaluation criteria were applied to the mining enterprises listed in Table 1. In particular, Truck-Operated Waste Dump No. 3 of ArcelorMittal Kryvyi Rih (54.0 ha) and Waste Dumps No. 1 and No. 3 of the Ingulets Mining and Processing Plant (total area 259.5 ha) were identified as potentially suitable locations for the safe deployment of vertical-axis wind turbines. The principal selection criteria included the geotechnical maturity of the waste dump masses (active dumping having ceased more than 15 years ago, allowing adequate foundation stabilisation), the extensive plateau areas available to ensure safe spacing between turbines, and elevations exceeding 40 m, which provide favourable conditions for the natural acceleration of near-surface wind flows. In contrast, the subsidence zones and waterlogged areas of the Sukha Balka Mine, despite their considerable area (250.2 ha), exhibit limited environmental and engineering potential owing to the risks of unpredictable geodynamic movements and flooding, making the construction of heavy engineering structures unsuitable. Based on a synthesis of contemporary approaches to post-mining land use, a system of principles for the nature-based utilisation of technogenically disturbed land for the deployment of wind energy systems was developed (Table 2). Unlike existing approaches, the proposed framework integrates the requirements of environmental safety, land reclamation, geotechnical reliability, and renewable energy development into a unified concept for the management of post-mining landscapes (Kovrov *et al.*, 2022; Medvedieva *et al.*, 2026).

Table 2. *Principles of nature-based utilisation of technogenically disturbed land for the deployment of wind energy systems*

Principle	Main content	Practical significance
Environmental sustainability	Minimising environmental impact, noise pollution and disruption to bird migration	Preservation of natural ecosystems and biodiversity
Adaptability to man-made landscapes	Utilising existing waste dumps, quarries and man-made elevations without significantly altering the terrain	Reduction in the volume of earthworks and improvement in energy efficiency
Compatibility with land reclamation and energy generation	Combining wind turbine construction with technical and biological restoration measures	Comprehensive land restoration
Closed-loop technological cycle	Maximising the use of existing infrastructure and recycled materials	Reduction in the consumption of natural resources
Integrated land use	Combining wind energy with other environmentally compatible activities	Creation of multifunctional post-mining landscapes
Geotechnical and hydrogeological safety	Taking into account the stability of waste dumps, and the risks of subsidence, landslides and flooding	Ensuring the long-term operational reliability of wind turbines
Energy efficiency	Using sites with sufficient wind potential and the capacity for off-grid operation	Improving the efficiency of electricity generation

Source: *compiled by the authors based on the results of the study*

The results obtained indicate that individual principles cannot be applied in isolation. For example, utilising the natural elevations of rock dumps significantly increases the efficiency of wind turbines due to the natural acceleration of air masses; however, without taking into account the geotechnical stability of the slopes and the dynamic load on the rock mass, there is a high risk of accidents occurring. Similarly, the integration of wind turbines with land reclamation measures not only ensures the production of renewable energy but also contributes to the restoration of ecosystem functions in disturbed areas. In this context, studies by M. Resak *et al.* (2022) and K. Kaczmarczyk *et al.* (2023) confirm that combining energy development with the ecological management of post-mining landscapes makes it possible to minimise cumulative anthropogenic pressure. At the same time, as K. Wang *et al.* (2025) rightly point out, it is precisely a comprehensive approach to the restoration of biogeocenoses within the impact zone of energy facilities that is the key factor in ensuring the long-term stability of reclaimed land.

The proposed system of principles significantly expands traditional approaches to the reclamation of disturbed land, shifting them from the realm of passive environmental conservation to that of active technological and energy-based regeneration. Traditional engineering solutions, which dominate current practice, are usually limited to two approaches: a technical one, involving the grading of spoil heaps and covering them with protective layers; and a biological one, aimed at applying a fertile soil layer and phytoremediation to prevent dust and erosion. At the same time, spoil heaps and quarries are viewed purely as sites of accumulated environmental damage, requiring long-term financial and technical expenditure to maintain their stability. The proposed approach broadens this paradigm in several fundamental respects, most notably by transforming such sites from environmental liabilities into valuable resources. Rather than isolating disturbed land, it advocates its valorisation through the integration of an energy-generating function directly into the structure of the post-mining landscape. Under this concept, the technogenic landform – particularly the plateaus of elevated waste rock dumps – performs a beneficial engineering function by naturally accelerating near-surface wind flows, thereby improving the efficiency of wind energy generation.

At the same time, synergy between reclamation and power generation is achieved, whereas the conventional approach often regards industrial construction on reclaimed land as a source of additional burden. In the developed system, the principles of geotechnical safety and reclamation-energy compatibility are integrated in an interrelated manner: biological reclamation, achieved by anchoring surfaces with grass roots, stabilises the top layer of the spoil heap, significantly reducing abrasive wear on the moving parts of vertical-axis wind turbines caused by dust, whilst energy generation covers the operational costs of monitoring the condition of the waste dump mass. Another important aspect of the proposed approach is the differentiation of disturbed land according to the type of technogenic landform. Unlike existing regulatory approaches, which generally prescribe uniform management strategies for disturbed land, the proposed framework enables flexible site classification. As illustrated by the enterprises presented in Table 1, it provides a practical tool for excluding inherently hazardous areas, such as the subsidence zones of the Sukha Balka Mine, while identifying geotechnically mature plateaus, including Truck-Operated Waste Dump No. 3 of ArcelorMittal Kryvyi Rih and the waste dumps of the Ingulets Mining and Processing Plant, as sites suitable for technological development. Thus, whilst traditional approaches aim to restore the landscape to a notional "original", often low-productivity state, the author's system of principles creates a forward-looking model of revitalisation. It demonstrates that the ecological restoration of mining regions can take place not in spite of, but due to, the deployment within their territory of innovative industrial infrastructure – decentralised "green" energy based on vertical-axis installations.

The nature-based use of post-mining sites for the development of wind energy

The results of the analysis indicate that the effective utilisation of technogenically disturbed land cannot be limited to the simple selection of suitable sites for the installation of wind energy systems. Achieving maximum environmental and economic efficiency is possible only through the comprehensive integration of land reclamation, revitalisation, and renewable energy development into a unified management framework for post-mining landscapes. In this context, the studies of K. Karalidis *et al.* (2024) and S. Amirshenava & M. Osanloo (2022) convincingly demonstrate that the isolated planning of individual reclamation measures reduces the overall restoration potential of industrial regions.

The synthesis of the identified principles enabled the development of a conceptual model for the nature-based utilisation of technogenically disturbed land, illustrating the interrelationships between natural restoration processes, engineering interventions, and the anticipated outcomes of their implementation. The distinctive feature of applying this model within the Kryvyi Rih Iron Ore Basin is that the theoretical principles presented in Table 2 are translated into a clearly defined technological framework, in which each component of the model (Table 3) represents a specific stage in the landscape restoration lifecycle. The transition from general environmental and engineering principles to a practical implementation model is achieved through a system of spatial filters linking the physical characteristics of individual waste dumps, such as the strength properties of the waste rock and the elevation of the plateau, with the operational parameters of vertical-axis wind turbines. Through this approach, the model evolves beyond a declarative set of objectives into a dynamic planning tool, whereby the geotechnical stabilisation of waste dump surfaces during the reclamation stage directly establishes a safe engineering platform for the subsequent installation of wind energy infrastructure while simultaneously facilitating the restoration of biogeocoenoses during the revitalisation phase.

Table 3. *Conceptual model for the nature-based utilisation of technogenically disturbed land*

Component	Natural component	Engineering component	Expected outcome
Land reclamation	Restoration of vegetation	Site planning	Land stabilisation
Revitalisation	Restoration of ecosystem functions	New functional use	Enhancing ecological value
Wind energy	Utilisation of wind energy potential	Installation of wind turbines	Renewable energy production
Nature-based Solutions	Integration of natural processes	Minimisation of human intervention	Sustainable land use

Source: *compiled by the authors*

The interrelationship between the components of the conceptual model presented is characterised by sequential determinism, whereby the successful implementation of each preceding stage is a mandatory engineering and environmental prerequisite for the deployment of the next. The logic behind the transition from the theoretical principles set out in Table 2 to the practical architecture of the model lies in the transformation of general requirements into interrelated technological stages. In particular, the principles of geotechnical safety and adaptation to technogenically transformed landscapes are directly translated into the land reclamation component. This component ensures the initial stabilisation of the disturbed massif through engineering planning and the creation of stable slope profiles, thereby minimising landslide processes.

The subsequent transition from reclamation to revitalisation implements the principles of ecological balance and reclamation-energy compatibility. At this stage, the engineered surface becomes a substrate for the implementation of nature-based solutions, which trigger the natural self-recovery of biogeocenoses and the formation of stable vegetation cover. An important innovative feature of the model is that the plant community formed during the revitalisation stage serves a protective function for the third component – wind power generation – as dense vegetation drastically reduces the level of dust in the air at ground level. This minimises abrasive wear on the moving parts and blades of vertical-axis wind turbines, significantly extending their service life and enhancing the project's overall energy efficiency.

The specific application of the developed model to the conditions of the Kryvyi Rih iron ore basin is determined by the region's unique geological, technogenic and aerodynamic parameters. Unlike conventional coal spoil heaps or sand quarries, the large waste rock dumps of the Kryvbas region consist mainly of hard rock and are characterised by considerable height, often exceeding 40-80 metres, as well as large areas of flat plateaus. This geometry of the man-made relief massif creates the effect of artificial orographic acceleration of surface wind flows, transforming the tops of the spoil heaps into areas with high wind energy potential.

At the same time, the substantial dynamic loading generated by heavy mining equipment during waste rock deposition, together with the prolonged period required for the natural consolidation of waste rock masses, necessitates strict compliance with minimum stabilisation periods before engineering development can commence. The proposed model therefore assumes that wind energy infrastructure based on vertical-axis wind turbines may be deployed only on geotechnically mature sites, where active slope adjustment and foundation settlement processes have ceased for at least 15 years. The flexibility and multifunctionality of the proposed model enable it to address two critical challenges facing the Kryvyi Rih region simultaneously: the shortage of decentralised electricity generation capacity required to meet peak industrial energy demand and the need for large-scale ecological restoration of degraded landscapes without withdrawing valuable productive land from agricultural use.

According to the data in Table 3, the proposed conceptual model is based on the sequential integration of natural and engineering solutions. In the initial stages, reclamation ensures the initial stabilisation of areas disturbed by human activity and creates the basic conditions for their subsequent safe use. In this context, studies by O. Rahmonov *et al*. (2022) and M. Tibbett (2024) confirm that high-quality technical preparation of the substrate is a fundamental basis for any post-mining landscape development scenarios. The next step in the revitalisation phase involves restoring lost ecosystem functions and establishing a new functional purpose for the areas. The subsequent integrative stage involves the direct implementation of wind energy facilities, which allows for the harmonious combination of long-term ecological restoration with the generation of renewable energy. Combining these processes within a single framework of nature-based solutions framework facilitates the comprehensive utilisation of technogenically disturbed land in accordance with the principles of sustainable development, minimises additional anthropogenic pressure, and substantially improves the efficiency of land resource utilisation. Thus, whilst Table 2 sets out in detail the fundamental principles that must be taken into account during decision-making, Table 3 clearly demonstrates the mechanism for their practical implementation, ensuring a clear logical transition from theoretical principles to the authors' proposed concept of nature-based utilisation of technogenically disturbed land.

The analysis carried out has shown that the use of vertical-axis wind turbines on technogenically disturbed land in the Kryvyi Rih mining region offers a number of significant advantages compared with the traditional use of such areas. Unlike the development of natural land, the installation of wind turbines on waste rock dumps enables the industrial reuse of degraded areas without any additional withdrawal of valuable land from the natural or agricultural land reserve. Furthermore, the design features of vertical-axis turbines allow for the effective utilisation of the complex aerodynamic conditions found in technogenic landscapes, which are characteristic of waste rock dumps and other elevated landforms. The previously cited work of M. Tibbett (2024) clearly demonstrates that vertical-axis wind turbines exhibit substantially greater tolerance to turbulent airflow and rapidly changing wind directions generated by the distinctive orography of waste rock dumps than conventional horizontal-axis turbines. The results of the comprehensive assessment of the principal environmental benefits associated with the deployment of vertical-axis wind turbines are presented in Table 4.

Table 4. *Environmental benefits of deploying vertical-axis wind turbines on technogenically disturbed land*

Assessment aspect	Description of the effect	Practical significance
Sustainable land use	Reuse of mine spoil without encroaching on natural areas	Preservation of natural ecosystems and agricultural land
Reduction of greenhouse gas emissions	Electricity generation without burning fossil fuels	Reducing the carbon footprint of mining enterprises
Impact on birdlife	Lower risk of bird strikes with the rotor compared to horizontal-axis wind turbines	Improving environmental safety
Noise impact	Lower noise and vibration levels	Reducing the impact on the population and the environment
Adaptation to wind patterns	Operation in turbulent and variable airflows without the need to align with the wind direction	Improved utilisation of technogenic landforms
Geo-ecological stabilisation	Combining wind turbine installation with land reclamation measures	Improving the stability of waste rock dumps
Formation of a post-mining landscape	Transforming degraded areas into production and environmental complexes	Implementing the principles of sustainable development

Source: *compiled and summarised by the authors based on research of D. Harrison-Atlas et al. (2022) and O. Medvedieva et al. (2024)*

According to the data presented in Table 4, the greatest environmental benefit is achieved through the synergy of two complementary processes: the revitalisation of technogenically disturbed land and the generation of renewable energy. This makes it possible to simultaneously reduce the area of degraded land that remains unused and minimise the environmental impact associated with electricity generation from conventional sources. Of particular significance for the conditions of the Kryvyi Rih basin is the ability of vertical-axis wind turbines to operate in turbulent airflows, which are characteristic of waste rock dumps. Unlike horizontal-axis turbines, they do not require constant reorientation to follow the wind direction, which ensures more stable operation in conditions of complex man-made terrain. Furthermore, their design features help to reduce noise pollution, the risk of bird strikes against the blades, and potential hazards in the event of structural failure.

The results obtained are conceptually consistent with current international research into the use of post-mining areas, which regards renewable energy facilities as one of the most effective avenues for their revitalisation. At the same time, the proposed approach expands on existing concepts by integrating the processes of land reclamation, geo-ecological stabilisation and renewable energy production into a single system for the nature-based utilisation of technogenically disturbed land. Under such conditions, wind turbines not only fulfil an energy-generation function but also become an integral part of the comprehensive transformation of degraded areas into multifunctional post-mining landscapes, in line with the principles of Nature-based Solutions and contemporary approaches to the sustainable development of mining regions, as previously outlined by researchers M. Cardinali *et al.* (2021), Q. Bo *et al.* (2024), as well as experts from the International Energy Agency (2023).

To strengthen the scientific discussion and validate the proposed model, a broader range of contemporary international studies was incorporated into the analysis. In particular, in the context of the integrated selection of post-mining land-use options, researchers S. Amirshenava & M. Osanloo (2022) emphasise the critical importance of applying strategic matrix planning, which helps to avoid haphazard land development. The model proposed in the present study advances this concept by introducing explicit spatial filtering criteria specifically adapted to waste rock massifs. The global environmental consequences of mining activities have likewise been highlighted by B. Aska *et al.* (2024), who argue that the accumulation of mining waste threatens biodiversity and that its reuse for infrastructure development should therefore be regarded as an environmental priority.

An analysis of global bibliometric data conducted by M.A. Cotrina-Teatino *et al.* (2025) clearly demonstrates a rapid rise in interest in the implementation of renewable energy sources specifically within mining operations. However, whilst most international authors focus on conventional horizontal-axis wind turbines or photovoltaic power stations, the present study demonstrates the advantages of vertical-axis wind turbines specifically for disturbed terrain. Researchers Y. Guan *et al.* (2022) demonstrate that the success of land reclamation depends on the phased restoration of vegetation cover. In the proposed model, vegetation serves not only to stabilise waste dumps but also to protect the kinematic components of vertical-axis wind turbines from abrasive dust, highlighting the technological interdependence of the different restoration stages.

The importance of assessing the spatial dynamics of wind energy deployment is confirmed by the work of D. Harrison-Atlas *et al.* (2022), which highlights the variability in land use during the long-term operation of turbines. Furthermore, whilst investigating the integration of nature-based solutions within the renewable energy sector, E.J. Rendle *et al.* (2023) proposed a three-step algorithm for aligning ecological zones with wind farms, which closely corresponds to the sequence adopted in the present study: "reclamation – revitalisation – wind energy". A further argument in favour of using vertical turbines specifically is provided by the findings of P. Robinson *et al.* (2022), whose aerodynamic tests confirmed their superior efficiency under conditions of oblique and turbulent wind, which is artificially generated by the geometry of the waste dump slopes.

Particular attention should be paid to the specific nature of the operation of facilities under the legal regime of martial law in Ukraine. As noted by O. Medvedieva *et al.* (2026), the operation of the Kryvyi Rih basin mining and processing complexes under these conditions requires the rapid introduction of decentralised energy supply sources to enhance the resilience of industrial hubs, the installation of local wind energy systems on waste rock dumps represents not only an nature-based solution but also a strategically important measure for energy security. Thus, the present study demonstrates that the integration of wind energy infrastructure based on vertical-axis turbines into the degraded landscapes of mining regions facilitates a transition from the passive conservation of disturbed land areas to their active, nature-based restoration. The proposed conceptual model, based on the sequential implementation of the stages of geotechnical stabilisation, biological revitalisation and energy generation, enables the transformation of accumulated environmental damage into a spatial and technological resource. The practical implementation of this approach in the Kryvyi Rih iron ore basin creates the conditions for the formation of sustainable, multifunctional post-mining landscapes, which is fully in line with the principles of Nature-based Solutions and ensures the environmental and energy decentralisation of the region without the additional encroachment on natural land.

Conclusions

The results of this study substantiate the feasibility of using technogenically disturbed land in mining regions as a promising spatial resource for the development of renewable energy based on the principles of Nature-based Solutions. It has been established that the integration of nature-based technologies, land reclamation, revitalisation and wind energy provides a comprehensive approach to the reuse of post-mining areas and meets modern requirements for sustainable development and the circular economy. An analysis of technogenically disturbed land in the Kryvyi Rih iron ore basin has revealed that its total area within the boundaries of the enterprises under study is 967.9 ha. Waste rock dumps and disused quarries have been identified as the most promising sites for the installation of wind turbines, as they are characterised by their considerable size, established topography, the presence of transport infrastructure and the absence of competition from traditional land use.

A system of principles for the nature-based technologies for the utilisation of technogenically disturbed lands has been summarised, taking into account ecological balance, adaptability to anthropogenically transformed landscapes, reclamation-energy compatibility, geotechnical safety and the energy feasibility of land use. Based on these, a conceptual model has been developed that integrates the processes of reclamation, revitalisation and the siting of wind turbines into a unified management system for post-mining landscapes. It has been demonstrated that the use of vertical-axis wind turbines on technogenically disturbed land facilitates the reuse of degraded areas without the additional appropriation of natural land, reduces the anthropogenic impact on the environment, cuts greenhouse gas emissions and improves the efficiency of land use. The design characteristics of such turbines enable reliable operation under the complex wind conditions associated with technogenic landforms while enhancing the environmental safety of their operation. Prospects for further research relate to the development of a multi-criteria assessment methodology for evaluating the suitability of technogenic disturbed land for the siting of wind power plants, utilising geoinformation technologies, remote sensing and mathematical modelling of wind potential. Another important area is the assessment of the technical and economic efficiency of the proposed solutions and their environmental impact throughout the full life cycle of energy facilities.

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Природоузгоджені технології використання техногенно порушених земель гірничодобувних регіонів

Анотація. Інтенсивний розвиток гірничодобувної промисловості Криворізького басейну призвів до формування значних площ техногенно порушених земель (кар'єрів, скельних відвалів, хвостосховищ) які характеризуються складними інженерно-геологічними й геоекологічними умовами та обмеженою придатністю до традиційного господарського використання. Метою дослідження був аналіз сучасного стану техногенно порушених земель Криворізького гірничодобувного регіону та обґрунтування можливості застосування природоузгоджених технологій під час їх ревіталізації шляхом розміщення вітроенергетичних установок. Методологічну основу роботи становили методи системного аналізу, узагальнення наукових публікацій, геоекологічної оцінки техногенно порушених територій, порівняльного аналізу інженерно-геологічних характеристик гірничих об'єктів, а також аналізу природних і техногенних чинників, що впливають на можливість їх повторного використання. У результаті дослідження встановлено специфіку сучасних гірничо-екологічних умов Кривбасу та визначено інтегральний потенціал використання відвалів, відпрацьованих кар'єрів і хвостосховищ для безпечного позиціонування вітрогенераторів. Доведено, що ревіталізація відвалів дозволяє ефективно використовувати їхню висоту для оптимізації вітрового потоку. Детальний аналіз інженерно-геологічних характеристик підтвердив високу перспективність використання відвальних масивів для альтернативного освоєння порушених ландшафтів. При цьому геоекологічна оцінка довела, що значна висота породних відвалів дозволяє ефективно оптимізувати параметри взаємодії вітроенергетичних установок із повітряними потоками. Сформульовано базові принципи природоузгодженого відновлення порушених ландшафтів, які передбачають синергію техніко-біологічної рекультивації та інфраструктурного розвитку відновлюваної енергетики без вилучення нових природних угідь. Практична цінність дослідження полягає у науковому обґрунтуванні повторного використання техногенно порушених земель без додаткового вилучення природних територій із господарського обігу, що сприяє підвищенню ефективності використання земельних ресурсів, зниженню антропогенного навантаження на довкілля та реалізації принципів сталого розвитку гірничодобувних регіонів

Ключові слова: рекультивація; ревіталізація; відвали; вітроенергетичні установки; Кривбас

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Assessment of safety of CO_2 storage in depleted oil and gas reservoirs

Abstract. Research relevance is determined by the need for safe geological storage of carbon dioxide as part of the implementation of carbon capture, transport and storage (CCS/CCUS) technologies. Study aimed to assess safety of CO_2 storage in depleted oil and gas reservoirs and to justify the feasibility of use of the natural pulsed Earth electromagnetic field (NPEMFE) method for real-time monitoring of reservoir pressure and the identification of potential fluid migration pathways. The research methodology was based on an analysis of the results of experimental geophysical studies conducted at the Dolynskyi oilfield research site in the western region of Ukraine, as well as on the application of spatial correlation analysis to establish relationships between NPEMFE parameters and reservoir pressure. Depleted hydrocarbon fields were considered as promising sites for long-term CO_2 sequestration due to their significant storage capacity, proven leak-tightness and existing production infrastructure. The study established a regular relationship between reservoir pressure and NPEMFE parameters. An inverse relationship was identified, whereby an increase in reservoir pressure is accompanied by a decrease in the intensity of the NPEMFE, whilst a decrease in reservoir pressure increases electromagnetic activity. Study demonstrated that changes in the intensity of the NPEMFE are associated with stress redistribution processes within the rock mass. The anisotropic nature of the spatial distribution of NPEMFE anomalies has been

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established, reflecting the directions of fluid flow and zones of increased permeability. Correlation analysis has confirmed the existence of a relationship between changes in the natural electric field and formation pressure. A conceptual approach has been developed for organisation of a geophysical monitoring system for CO_2 geological storage sites, based on regular observations of NPEMFE parameters, which can be used for early detection of potential hydrocarbon migration pathways and storage integrity breaches. The practical value of the results obtained is determined by their potential use by specialists in the oil and gas industry, geoecology and geophysical monitoring to monitor the condition of underground CO_2 storage sites, assess the risks of leaks and improve the environmental and technological safety of geological carbon storage

Keywords: geological CO_2 storage; depleted gas fields; formation pressure; the Earth's natural pulsed electromagnetic field; monitoring; storage site safety; fluid migration

Introduction

Global climate change and the need to achieve carbon neutrality targets cause rapid development of technologies for the capture, transport, utilisation and geological storage of carbon dioxide (CCUS). Geological storage of CO_2 is regarded as one of the most effective tools for reduction of anthropogenic greenhouse gas emissions and is a key component of decarbonisation strategies for the energy and industrial sectors in the European Union, the USA, Canada, China and other countries. Among the potential sites for geological storage, depleted oil and gas fields are of particular interest. Their advantages include the proven natural impermeability of the reservoirs, significant volumes of available pore space, well-developed well and transport infrastructure, as well as many years of experience in geological research and operation. According to existing estimates, the global potential for CO_2 storage in depleted oil and gas reservoirs amounts to hundreds of billions of tonnes, which exceeds annual global emissions.

One of the key factors in the successful implementation of geological storage projects is ensuring their safety. The main risks remain potential CO_2 leaks due to breaches in the integrity of the caprock, the activation of tectonic faults, the degradation of cement stone and well casings, and the formation of man-made fluid migration pathways. It is therefore necessary to establish effective monitoring systems capable of promptly tracking changes information pressure, the stress-strain state of the rock mass, and the development of potentially hazardous filtration zones. Traditional monitoring methods, based on the use of observation wells, repeat seismic surveys, and gravimetric and geodetic observations, are characterised by high costs and limited timeliness in obtaining information. In this regard, the search for alternative methods to monitor the state of the geological environment is substantial. The increase in global greenhouse gas emissions and the need to achieve climate neutrality are driving the active development of carbon capture, utilisation and storage (CCS/CCUS) technologies. One of the most promising areas for the implementation of these technologies is considered to be the geological storage of carbon dioxide in depleted oil and gas fields, which are characterised by significant storage capacity, the presence of natural isolating barriers and well-developed production infrastructure.

A comprehensive analysis of existing state of geological CO_2 storage in depleted hydrocarbon reservoirs is presented in the papers by B. Wei *et al.* (2023) and K.K. Nsiama *et al.* (2024). Authors noted that such sites are among the most well-prepared for the implementation of CCS technologies, as their geological structure, permeability and storage capacity, and the impermeability of the cap rocks have been studied in detail during many years of operation. At the same time, the effectiveness of long-term storage is determined by a combination of geological, geomechanical, hydrodynamic and technological factors. The prospects for use of existing underground gas storage facilities for the storage of CO_2 and hydrogen have been investigated by Y. Demchuk *et al.* (2025). The authors assessed the geological and petrophysical characteristics of Ukrainian underground gas storage facilities and established that a significant proportion of these sites offer favourable conditions for the implementation of geological carbon storage technologies. This creates the conditions for the development of a national CCS infrastructure and Ukraine's integration into European decarbonisation programmes. A substantial area of research is the use of CO_2 to improve oil recovery whilst ensuring its long-term sequestration in the reservoir. X. Zhou *et al.* (2024) summarised the results of existing research into CO_2-EOR technologies and demonstrated that, under optimal conditions, a significant proportion of the injected carbon dioxide may remain in the reservoir after the field has been depleted. Study also emphasised the need to address phase transitions, the interaction of CO_2 with formation fluids, and changes in the reservoir properties of the rocks.

A significant number of scientific papers have been devoted to the issues of long-term safety in the geological storage of carbon dioxide. According to the findings of A. Ahmed *et al.* (2025), the success of CCS projects depends to a large extent on integrity of the storage site over decades or even centuries. To achieve this, a comprehensive risk assessment must be conducted covering geological, geomechanical, economic and environmental aspects of the facility's operation. One of the most critical elements of a geological storage system is the wells. Research by V. Nguyen *et al.* (2023) has shown that prolonged contact between CO_2 and the metallic components of casing strings and the cement matrix can cause corrosion, cement degradation and the formation of potential leakage pathways. In this regard, monitoring the technical condition of wells at all stages of CCS project implementation is substantial. Monitoring systems minimise potential risks. According to M. Fawad & N.H. Mondol (2021), modern monitoring of geological CO_2 storage is based on the integrated use of geophysical, geochemical and hydrodynamic monitoring methods. Similar conclusions are presented in the work by W. Tang *et al.* (2025), which provides an overview of existing monitoring technologies and numerical modelling of carbon dioxide dispersion processes in the geological environment.

Study by V. Fedoriv *et al.* (2019) examined application of integrated interpretation of geophysical surveys to determine the petrophysical characteristics of reservoir rocks, in particular their clay content, porosity and structural features. Study demonstrated that the use of a combination of geophysical parameters improves the reliability of rock property estimates, which is substantial for prediction of storage and filtration characteristics of reservoirs. The approaches developed can be used in assessment of safety of geological CO_2 storage in depleted oil and gas reservoirs, as the accurate determination of the properties of reservoir rocks and cap rocks is essential for prediction CO_2 migration, assessment of integrity of the storage site and selection of an effective monitoring system. E.D. Kuzmenko *et al.* (2020) investigated the application of the NPEMFE method for prediction of deformation processes in rock masses. A correlation was established between electromagnetic anomalies and zones of instability in the rock mass, confirming potential for NPEMFE to monitor the safety of CO_2 storage in depleted oil and gas reservoirs.

Thus, an analysis of existing scientific publications indicates significant progress in the development of CO_2 geological storage technologies and methods for ensuring their safety. At the same time, issues relating to the operational monitoring of changes in reservoir pressure and the early detection of potential CO_2 migration pathways based on geophysical observations remain under-researched. Of particular relevance is the development of monitoring methods capable of ensuring continuous monitoring of the geological environment during the operation of storage facilities. The study aimed to assess the safety of CO_2 storage in depleted oil and gas reservoirs and to justify the feasibility of using the Earth's natural pulsed electromagnetic field to monitor reservoir pressure in real time and identify potential fluid migration pathways.

Materials and Methods

The test site is situated and operates within the Dolyna oilfield (wells No. 1-Smolianska, No. 61-Pivnichna Dolyna, No. 152-Pivnichna Dolyna, No. 81-Vygoda Vytvytsia, No. 64-Dolyna) and was established based on legacy oil wells following a special permit for subsoil use granted to the university by the State Service of Geology and Subsoil of Ukraine. To investigate the patterns of formation pressure variations within the Dolyna oilfield (well No. 152 "Pivnichna Dolyna"), the method of the Earth's natural pulsed electromagnetic field was employed. The natural Earth electromagnetic field method is one of the modern geoelectric techniques, which has become increasingly widespread for a wide range of geological and geophysical problems. Its principle is based on the detection of electromagnetic pulses generated by dielectric minerals under stress and strain. The Earth's natural pulsed electromagnetic field is understood to be the aggregate of electrical discharges that occur within the Earth's interior, particularly within rock masses. As rocks consist of heterogeneous mineral components containing impurities, pore spaces, charged dislocations and other structural defects, their internal structure is excited under the influence of external energy sources. This causes a disturbance of the equilibrium state and the accumulation of excess energy, which can be released in the form of electromagnetic pulses.

The main processes responsible for the generation of such pulses are the excitation of the crystal lattice in a field of alternating mechanical stresses, the intensive filtration of fluids through pores and capillaries, the relaxation of the excited medium, the formation of a double electric layer, and plasma formation processes. The combination of these physical phenomena causes Earth's natural pulsed electromagnetic field under various conditions of stress in rock formations. The study was conducted within the area surrounding Well No. 152 "Pivnichna Dolyna". The NPEMFE method was performed based on a radio-wave stress-strain indicator (RWSSI) and has the following characteristics (Table 1).

Table 1. Technical specifications of the RWSSI device

Parameter name	RWSSI
1. Number of registration channels	3(X,Y,Z)
2. Frequency range	2-50 kHz
3. Low-pass and high-pass filter	Discrete settings 2 kHz
4. Connecting external antennas	3 with a pre-amplifier, up to 10 metres
5. Measurement modes	Automatic, semi-automatic, manual
6. Measurement duration	1 s, 2 s, 10 s, 1 min
7. Pulse count scale	00000-131071
8. Scale for measurement of average pulse amplitude	0000-4095
9. Number of measurements at a single point	1-15
10. Time reference for measurements in semi-automatic and automatic modes	Present
11. Interface for connection of a removable memory module to a computer	Present
12. Power supply for the RWSSI indicator	12 V, 2.2 A rechargeable battery
13. Overall dimensions of registration unit	335×260×95 mm
14. Weight of registration unit	4.2 kg

Source: *compiled by the authors*

The RWSSI operated in the frequency range from 2 to 50 kHz and allowed the low-pass and high-pass filters to be adjusted in 2 kHz steps, which was used to isolate relevant signal and reduce the impact of external electromagnetic interference. The instrument supported the connection of three external antennas with pre-amplifiers and cable lengths of up to 10 m, providing flexibility for field measurements. Three operating modes were provided – automatic, semi-automatic and manual – adapting measurement process to specific research conditions. The recording duration could be 1 s, 2 s, 10 s or 1 min, depending on the tasks at hand and the required level of detail in the observations. The measurement range for the number of pulses was from 0 to 131,071, and for the average amplitude – from 0 to 4,095 conventional units. Furthermore, the instrument allowed for between 1 and 15 repeated measurements at a single observation point, which improves accuracy of the results and reduce random errors.

The procedure involved synchronising the two instruments before measurement (via a cable and by configuring same time), selecting the signal gain to ensure field differentiation and the correct detection of anomalies, as well as setting the frequency range to 2-50 kHz (or a narrower range, but not less than 5 kHz) with pulses recorded as an integral characteristic. In addition, a pulse accumulation mode was set (1-15 measurements of varying durations), which reduced random errors and can be used to calculate number of pulses per second. The frequency range of 2-50 kHz can be used to receive signals from the first few tens of metres up to a thousand metres, which is necessary for the set task.

The measurement time step is also set, which determines the intervals at which the signal is recorded simultaneously, covering the observation step and the movement between points. The X, Y, Z orientations of the antennas are set (X – north-south, Y – west-east, Z – vertical) is conducting, with the directions for both instruments aligned; the instruments are divided into variation and field units (the variation unit is set up in a homogeneous zone to negate external influences); and data is recorded for subsequent reading and processing using specialised software. The requirements for the NPEMFE observation grid are similar to the general requirements for geophysical profiling (electrical, magnetometric, gravimetric) in either profile or planar configurations. The layout of the profile lines within the study area is as follows: main lines – north-south and west-east; additional lines – north-west-south-east and north-east-south-west. This profile layout enables objective data to be obtained around the study area. The observation interval along the profiles for the NPEMFE is 10 metres. The observation scheme is shown in Figure 1.

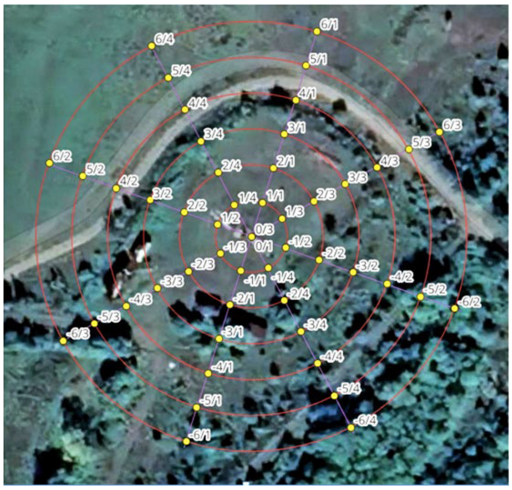


Figure 1. *Layout of observation profiles using the NPEMFE method at Well 152 "Pivnichna Dolyna"*

Source: *compiled by the authors*

The combination of mutually perpendicular and diagonal profiles ensures a more comprehensive detection of anomalous zones, regardless of their orientation, reduces probability of omitting local heterogeneities, and enhances the objectivity of the interpretation of results. This observation scheme is particularly effective during investigation of zones of faults, fracturing and other structural features of the geological environment. The observation spacing along the profiles was 10 m, which provides sufficient spatial resolution for detailed mapping of geoelectric heterogeneities and the identification of local anomalies in the Earth's natural pulsed electromagnetic field. The selected density of the observation network was optimal for detailed geophysical investigations, ensuring reliable information on the stress-strain state of the rocks within the study area.

Results and Discussion

Geological and man-made risks associated with CO_2 storage in depleted oil and gas reservoirs

The effectiveness of geological carbon dioxide storage is determined not only by the reservoir's capacity, but also by the geological system's ability to ensure the long-term integrity of the storage site (Benson & Cole, 2008; Bachu, 2015). When CO_2 is injected into a formation, this causes a change in formation pressure, a redistribution of stresses within the rock mass and a change in the filtration regime. If permissible pressure limits are exceeded, new fractures may form or existing ones may be activated, the integrity of the cap rock may be compromised, and fluid migration pathways may develop. The main potential pathways for CO_2 leakage are tectonic faults, naturally fractured zones, man-made disturbances in the near-wellbore zone of the formation, and abandoned wells (Bai *et al*., 2016). Therefore, one of the key tasks of the monitoring system is the timely detection of zones of increased permeability and the monitoring of changes in formation pressure during the operation of the storage facility. Modern monitoring systems for geological CO_2 storage are based on the integrated use of seismic, geochemical, geodetic and geophysical methods. However, most of these systems are characterised by high costs and the discrete nature of the data collected. In this regard, a promising approach is the use of passive geophysical methods, in particular the Earth's natural pulsed electromagnetic field (EPEMF), which can be used to continuously monitor changes in the geological environment. The Natural Earth Pulse Electromagnetic Field (NEPEMF) method is an effective geophysical monitoring tool that can identify areas with elevated stress-strain states in rock formations and track changes in their physical and mechanical properties. The results obtained do not provide direct information on the technical condition of the underground repository; however, can be used for an indirect assessment of the geodynamic processes that may affect its geometric integrity and safe operation.

In particular, the NPEMFE method can be used to identify or indirectly assess the following potential risks:

- activation of faults and tectonic disruptions, which may form permeable channels for the vertical migration of gas;
- development of fractured zones in overlying strata, which reduces their insulating capacity;
- change in stress-strain state of rock mass associated with an increase in formation pressure during CO_2 injection;
- formation and development of local electromagnetic anomalies, which may indicate increased activity in deformation zones or filtration processes.

Assessment of the safety of geological CO_2 storage in depleted oil and gas reservoirs emphasises control of reservoir pressure and its impact on the stress-strain state of the reservoir and overlying rocks. During CO_2 injection, the increase in reservoir pressure may impose additional mechanical loads on the rock mass, whilst its redistribution may alter the stability conditions of existing geological structures (Rutqvist, 2012). If these changes exceed the rocks' adaptive capacity, tectonic faults may be activated, existing fractures may open, or new microfractures may form. Such processes are accompanied by the generation of electromagnetic pulses, which can be recorded using the natural pulsed Earth electromagnetic field (PEMEF) method. Thus, changes in the parameters of the natural electromagnetic field can be used as an indicator of the development of deformation processes associated with changes in formation pressure during CO_2 storage.

The formation of zones of fracturing or increased permeability is one of the key risk factors for the long-term safety of CO_2 storage, as such areas may create potential pathways for the migration of carbon dioxide outsode the target formation. Fractures and weakened zones within the rock mass are characterised by elevated concentrations of mechanical stresses and may act as channels for more intense filtration of formation fluids. Under these conditions, physical processes are activated, accompanied by the generation of electromagnetic pulses, as a result of which local anomalies in the NPEMFE may be recorded above such areas. Analysis of the spatial distribution, intensity and configuration of these anomalies can identify potentially weakened zones, assess their orientation and determine areas requiring further geophysical, geomechanical or engineering-geological investigations. It is worth noting that results of the NPEMFE are interpretative and do not constitute direct evidence of a breach in the integrity of the geological repository or of CO_2 leaking outside the reservoir. To draw reliable conclusions regarding storage safety, a comprehensive analysis of the NPEMFE results must be conducted in conjunction with geological, geomechanical, hydrodynamic and industrial geophysical data, as well as information on CO_2 injection regimes, changes in formation pressure and the operational parameters of the storage facility.

The relationship between formation pressure and the intensity of NPEMFE

The results of experimental studies at the Dolinsky oilfield research site indicate a regular relationship between formation pressure and the parameters of the Earth's natural pulsed electromagnetic field. The experiment involved measuring the Earth's natural pulsed electromagnetic field under three specified operating conditions: 1) formation pressure of 72; 2) formation pressure is falling; 3) formation pressure is reduced and equal to zero. The distribution of the pulsed field corresponding to the specified formation pressure levels is shown in Figure 2. The borehole for all conditions was located at the centre of the site at the intersection of four profiles defined at the surface, with a distance of 10 metres between points along the profiles. At an initial stable maximum pressure of 72 atm, the distribution of the NPEMFE intensity is not isometric but is elongated into a band-shaped anomaly (a), which corresponds to a decrease in field intensity. As the pressure decreases (drops), the anomaly of reduced intensity extends from the north to the south-east (b), and subsequently the reduction in intensity extends to the eastern and southern parts of the study area. In other words, a pronounced anisotropy of formation pressure has been observed. An explanation for the observed distribution of the anomaly at this stage should be sought in the correlation between changes in formation pressure and the intensity of natural radiation. In particular, the direction of oil inflow varies over time, as demonstrated in Figure 2. The natural pulsed electromagnetic field measured at the earth's surface is variable in nature and depends on the formation pressure at the wellbore. At the same time, its isotropic nature is confirmed.

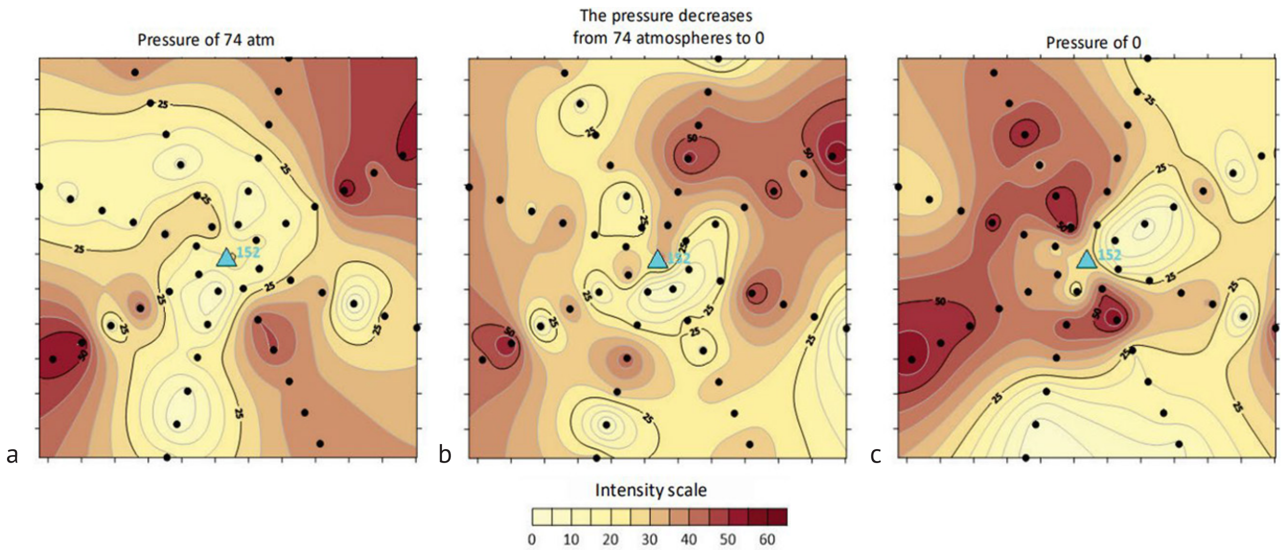


Figure 2. *Variation in the intensity of NPEMFE radiation at different formation pressures in Well No. 152, "Pivnichna Dolyna"*

Notes: *a) pressure is stable at 74 atm; b) pressure decrease from 74 to 0 atm; c) pressure is 0 atm*

Source: *compiled by the authors*

The observations showed that, at maximum formation pressure values in the well, the lowest values of NPEMFE intensity were observed. As the pressure decreases, the intensity of electromagnetic radiation gradually increases. The established relationship is of an inverse nature and reflects the response of the geological environment to changes in the stress-strain state and filtration processes within the formation. Physically, this pattern is determined by changes in the flow conditions of formation fluids within the porous medium. An increase in formation pressure contributes to the stabilisation of the hydrodynamic regime and a reduction in local deformations of the pore space. When the pressure decreases, processes such as stress redistribution, the opening of microcracks and local changes in the direction of filtration flows are activated, accompanied by the generation of additional electromagnetic pulses (Fig. 3).

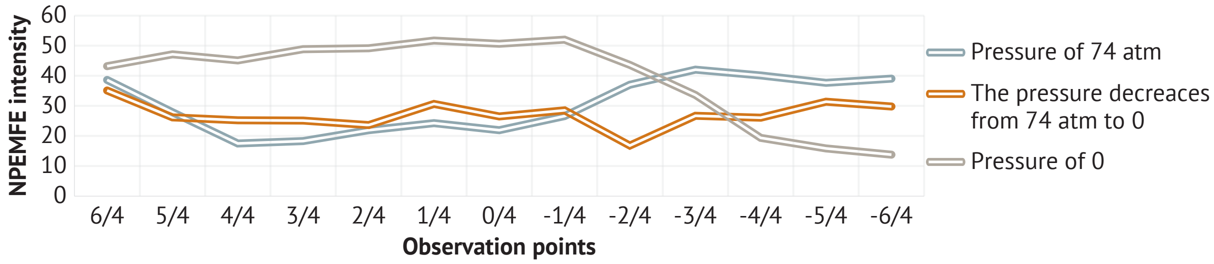


Figure 3. *Graphs depicting intensity of electromagnetic field radiation at different formation pressures*
Notes: *formation pressure 72 atm; formation pressure decreases from 74 to 0; formation pressure is reduced and equals zero*
Source: *compiled by the authors*

For CO_2 geological storage projects, this is substantial, as introduces use of NPEMFE parameters as an indicator of changes in formation pressure without the need to drill additional monitoring wells.

Identification of areas of increased permeability and potential CO_2 migration pathways

The observed anisotropy in the distribution of electromagnetic anomalies is of particular interest for assessing the safety of storage facilities. When formation pressure changes, the anomalous zones of the NPEMFE form an elongated shape and exhibit a defined orientation in specific directions (Fig. 4).

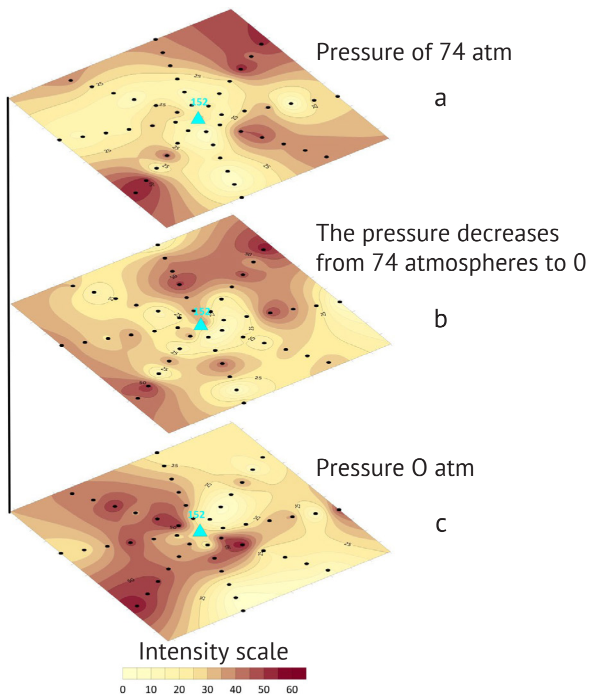


Figure 4. *Distribution of the pulsed electromagnetic field according to the specified formation pressure levels*
Notes: *a) formation pressure of 72 atm; b) formation pressure decreases from 74 to 0; c) formation pressure is reduced and equals zero*
Source: *compiled by the authors*

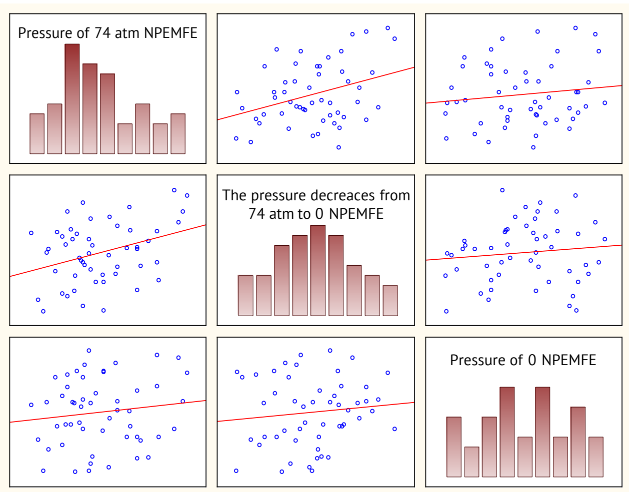
Spatial organisation of the electromagnetic field indicates the existence of zones of increased permeability, which are controlled by fracture systems or local tectonic disturbances. These areas may act as natural channels for fluid migration during CO_2 injection. Analysis of the NPEMFE distribution maps shows that the directions in which the anomalies develop change in tandem with changes in formation pressure. This indicates the presence of active filtration processes and confirms the method's high sensitivity to changes in the formation's hydrodynamic regime. For CO_2 geological storage sites, the identification of such zones is substantial, as it can be used for localisation of potentially hazardous areas even before the start of commercial injection or during the early stages of storage operation.

The most relevant factors for interpretation are the differences in intensity, extent, shape and spatial location of the NPEMFE anomalies. Comparison of individual parts of the figure can be used to assess how the distribution of electromagnetic pulses changes under different reservoir operating conditions. Appearance of new anomalous zones, displacement of existing anomalies, and changes in their size or intensity should be emphasised. If the anomalies retain their position but change in amplitude, this may indicate a redistribution of stresses within existing geological structures. If, however, their spatial position or configuration changes, this may be a sign of the activation of new deformation zones or a change in filtration conditions. Changes in formation pressure during CO_2 injection into depleted oil and gas reservoirs are accompanied by a transformation of the stress-strain state of the reservoir and surrounding rocks, which may affect the characteristics of the Earth's natural pulsed electromagnetic field. An increase in reservoir pressure during CO_2 storage can lead to the concentration of mechanical stresses in localised areas of the geological environment, particularly near zones of faults, fractures and rock heterogeneities. Such changes may manifest as an increase in intensity, an expansion in area or a change in the spatial position of individual NPEMFE anomalies.

When the storage facility's operating conditions change – in particular, when formation pressure decreases, or pressure redistribution occurs as a result of fluid migration – further changes occur in the stress state of the rock mass. This may form new local electromagnetic anomalies or changes in the configuration of existing ones. Analysis of the dynamics of the spatial distribution of NPEMFE can be used to assess geological environment's response to changes in CO_2 storage conditions and identify areas of potential geomechanical instability. Thus, spatio-temporal changes in NPEMFE parameters can be used as an additional indicator of processes associated with stress redistribution within the formation during CO_2 storage. However, the method fails at direct determination of formation pressure or confirmation of CO_2 migration; therefore, the results obtained must be analysed in conjunction with hydrodynamic modelling, well logging, seismic monitoring and other methods of storage site monitoring (Ajayi *et al.*, 2019; Massarweh & Abushaikha, 2024).

Anisotropy is manifested in the uneven distribution of electromagnetic anomalies in different directions. On NPEMFE maps, this is reflected in the fact that anomalous areas have an elongated shape, a predominant orientation, or varying intensity along different profiles. Such features may be associated with the direction of tectonic faults, the system of natural fracturing, the layering of rocks, or the orientation of principal mechanical stresses. The detection of anisotropy can form conclusions regarding presence of structural heterogeneity in the geological environment and determine predominant directions of deformation processes. Under natural conditions, the filtration of liquids and gases predominantly occurs not uniformly, but along fractures, faults and other weakened structural elements characterised by increased permeability. These elements are often linear or elongated in nature, which is why NPEMFE anomalies form a similar shape. If elongated anomalies extend over a considerable distance and are consistent with known geological structures or the results of other geophysical surveys, they can be interpreted as potential zones of increased permeability or the predominant directions of formation fluid flow. However, such an interpretation must be corroborated by a suite of independent data, as the NPEMFE method is indirect and does not independently determine the presence of flow pathways.

Further confirmation of the relationship between formation pressure and geodynamic processes was obtained through a correlation analysis of NPEMFE data at different formation pressures. The correlation coefficients obtained demonstrate consistency in the spatial structures of the anomalies under different well operating conditions (Fig. 5). The greatest changes in the structure of the correlation functions are observed during periods of active change in formation pressure, confirming the sensitivity of electromagnetic methods to stress redistribution processes within the rock mass.



	NPEMFE (Pressure 74 atm)	NPEMFE (Pressure decreases from 74 to 0 atm)	NPEMFE (Pressure 0 atm)
NPEMFE (Pressure 74 atm)	1.000	**0.348**	0.131
NPEMFE (Pressure decreases from 74 to 0 atm)	**0.348**	1.000	0.113
NPEMFE (Pressure 0 atm)	0.131	0.113	1.000

Figure 5. *Pairwise correlation matrix*

Notes: *values marked in red are statistically significant at $p < 0.05000$*

Source: *compiled by the authors*

Figure 5 shows the correlation coefficients between the spatial distributions of the Earth's natural pulsed electromagnetic field (NPEMFE), obtained under three formation pressure regimes: at a pressure of 74 atm, during its decrease from 74 to 0 atm, and after it has fully decreased to 0 atm. Values of 1.000 are shown on the main diagonal, as each dataset is fully correlated with itself. The highest correlation coefficient between different regimes is observed between the state at a formation pressure of 74 atm and the process of its reduction to 0 atm (r = 0.348). This indicates a moderate similarity in the spatial distribution of NPEMFE anomalies, which is to be expected, as some structural features and stress concentration zones are still preserved during the process of reservoir depressurisation.

By contrast, the correlation between the distributions obtained at a pressure of 74 atm and after the pressure had been fully reduced to 0 atm is only 0.131. Similarly, the correlation coefficient between the gradual pressure reduction regime and the final state at 0 atm is 0.113. Such low values indicate a significant change in the spatial structure of the electromagnetic field following the completion of the reservoir depressurisation process. The results obtained demonstrate that a change in formation pressure is accompanied by a noticeable reorganisation of the spatial distribution of NPEMFE anomalies. The greatest similarity is observed between the initial state and the transient regime, whilst after zero formation pressure is reached, the nature of the electromagnetic pulse distribution differs significantly from the previous states. This may be associated with a redistribution of the stress-strain state of the rock, a change in the activity of existing fracture zones, and the weakening or emergence of new sources of electromagnetic pulse generation. It should be noted that the correlation coefficients presented characterise only the degree of statistical similarity between the NPEMFE maps. They fail to establish causes of the changes and must be analysed in conjunction with geological, geomechanical and industrial geophysical data. The identified patterns can be used to predict the directions of propagation of the injected CO_2 front and to assess the risks of it extending outside design boundaries of the storage site.

A methodology for monitoring the safety of geological CO_2 storage based on NPEMFE

Based on the results, a methodological approach to monitoring the safety of geological CO_2 storage using the NPEMFE has been proposed. In the first stage, a baseline map of the natural electromagnetic field is generated prior to the start of CO_2 injection. Subsequently, during operation, regular observations are conducted along a network of profiles located above the reservoir and within the predicted fluid migration zones. Comparison of existing data with baseline can be used for rapid detection of: changes in formation pressure; activation of fractured zones; emergence of new filtration channels; directions of movement of the CO_2 front; potential areas where the storage facility may leak. In the event of local anomalies detected by the NPEMFE, the relevant areas may be further investigated using seismic, geochemical or borehole methods. Thus, NPEMFE can be used to create an early warning system for potential leaks from geological storage sites and significantly enhances the safety of long-term carbon dioxide storage in depleted oil and gas reservoirs.

The proposed methodological approach is based on research findings which have shown that the spatial distribution of NPEMFE varies depending on the formation pressure regime. Analysis of the NPEMFE maps and correlation relationships demonstrated that a significant restructuring of the electromagnetic anomaly pattern occurs during the transition from a pressure of 74 atm to 0 atm. The low correlation coefficients between the states at 74 atm and 0 atm (r = 0.131), as well as between the process of reservoir depressurisation and the final state (r = 0.113), indicate the method's high sensitivity to changes in the stress-strain state of rocks. This confirms the suitability of using NPEMFE as one of the tools for geophysical monitoring of underground and geological CO_2 storage sites.

NPEMFE baseline map depicts the natural state of the geological environment before the onset of anthropogenic influence. It serves as the reference against which all subsequent changes in the electromagnetic field are assessed. Without such a map, it is impossible to determine whether the detected anomalies are the result of CO_2 injection or whether they existed previously as natural features of the geological structure. Furthermore, the baseline map can be used to identify background anomalies associated with faults, zones of natural fracturing and lithological heterogeneities.

Existing measurements must be conducted following the same observation scheme, using identical profiles, measurement intervals, recording parameters and data processing conditions. The comparison should include an analysis of the spatial location of anomalies, their intensity, extent, configuration and orientation. It is also advisable to use statistical indicators, in particular correlation coefficients, difference maps and other methods of spatial analysis, which can be used for a quantitative assessment of the degree of deviation from the baseline. The emergence of new local anomalies, a significant increase or decrease in the intensity of already known anomalous zones, or a change in their geometric dimensions, orientation or spatial location may provide grounds for conducting further investigations. Anomalies that recur systematically over several observation cycles, or that spatially coincide with known tectonic faults, boreholes or other potentially hazardous areas, should be emphasised. Such changes do not constitute direct evidence of a breach in the storage facility's integrity; however, they may indicate a change in the stress-strain state of the rock and require verification using other methods.

The NPEMFE method is best used as part of a comprehensive monitoring system. NPEMFE data can be correlated with the results of 3D seismic surveys or repeat seismic surveys to refine the location of faults and zones of disturbance. Geochemical studies of soil gases or groundwater can accompany verification of whether electromagnetic anomalies by the migration of CO_2 or other fluids. Well-based methods (monitoring of formation pressure and temperature, well logging and geophysical surveys) provide information on the condition of the reservoir directly within the wellbore. Consistent results from several independent methods significantly improve reliability of the interpretation (White, 2009; Michael *et al*., 2010).

The integrated use of NPEMFE alongside traditional methods provides a more comprehensive picture of the state of the geological environment. In contrast to borehole measurements, which characterise individual points, NPEMFE can be used for areal mapping of the study area and rapid detection of local changes in the stress-strain state. The method is non-invasive, relatively quick to conduct and can be applied repeatedly without interfering with the operation of the storage facility. Its main advantage lies in the early detection of areas where changes in the geomechanical state are occurring, after which these specific areas can be investigated in detail using more expensive or localised methods. Thus, NPEMFE should be regarded as a tool for initial screening and spatial monitoring, rather than as a standalone method for confirming leaks or breaches in the integrity of a geological repository.

Comparison of the results obtained with data from existing studies

B. Wei *et al*. (2023) investigated the prospects for using depleted oil and gas fields for the long-term storage of carbon dioxide. Study found that the safe operation of such facilities is determined not only by the geological characteristics of the reservoir, but also by the ability to continuously monitor CO_2 migration processes and changes in reservoir pressure (Albertz *et al*., 2023). This conclusion is fully consistent with the results of presented study, as the identified relationship between formation pressure and NPEMFE parameters can be used as an additional tool for such monitoring. Similar conclusions were reached by K.K. Nsiama *et al*. (2024), who conducted a comprehensive analysis of modern technologies for the geological storage of CO_2 in depleted hydrocarbon reservoirs. The researchers noted that one of the key factors for long-term safety is the ability of monitoring systems to detect changes in the physical state of the reservoir in a timely manner. The results obtained in presented study confirm the validity of this approach and demonstrate the potential for use of geophysical parameters as indicators of changes in the geological environment.

Y. Demchuk *et al*. (2025) investigated geological and petrophysical characteristics of Ukrainian underground gas storage facilities concerning their suitability for storage of hydrogen and CO_2. The authors found that most of the sites studied have sufficient capacity and favourable geological conditions for the implementation of CCS projects. Presented study correlates with these conclusions; however, the assessment of storage site suitability must necessarily be accompanied by the development of systems for the continuous monitoring of the reservoir's geomechanical state. This aspect is insufficiently addressed in study of mentioned authors. A. Ahmed *et al*. (2025) is noteworthy for interpretation of the results obtained. It addressed integrity and safety of underground CO_2 storage sites. The researchers concluded that the main risks remain breaches in the integrity of the caprock and wells, which can form gas migration pathways. The results obtained in this study do not contradict these conclusions. On the contrary, the ability to record changes in the stress state of the rock mass using the NPEMFE method could serve as an additional tool for the early detection of potentially hazardous zones.

X. Zhou *et al*. (2024) analysed the effectiveness of CO_2-EOR technologies and the behaviour of carbon dioxide in oil reservoirs. The authors found that changes in reservoir pressure significantly influence CO_2 migration processes, the degree to which it is retained in the reservoir, and the ultimate effectiveness of sequestration. These results are consistent with presented observations, as reservoir pressure is one of the main factors determining changes in the parameters of the NPEMFE model.

M.S. Shah *et al*. (2026) examined geological and technical aspects of the safe storage of CO_2 in depleted oil and gas reservoirs. Study emphasised significance of comprehensive monitoring of the condition of storage sites, control of formation pressure, assessment of cap rock integrity and identification of potential CO_2 migration pathways. The findings confirm the suitability of the NPEMFE method as an additional geophysical tool for assessing changes in the stress-strain state of rocks during CO_2 injection. When combined with seismic, well logging and geochemical methods, NPEMFE can improve effectiveness of the monitoring system and ensure early detection of potentially hazardous areas where storage integrity is compromised.

P.A. Eigbe *et al*. (2023) examined the prospects for using depleted oil and gas fields for the geological storage of CO_2, emphasising the need to assess reservoir capacity, cap rock integrity, injection parameters and the geomechanical stability of the system. Study noted that the safe storage of CO_2 requires comprehensive monitoring of changes within the reservoir, as the increase in pressure during injection may affect the stress-strain state of the rocks and the activation of permeability zones. The findings confirm benefits of the NPEMFE method as an additional tool for monitoring the geomechanical state of the reservoir, as it can detect changes associated with stress redistribution and the development of fracturing. When used in conjunction with seismic, well logging and geochemical methods, NPEMFE can improve the reliability of safety assessments for the long-term storage of CO_2 in depleted hydrocarbon reservoirs. J.-P. Deflandre *et al.* (2011) investigated the modelling of CO_2 injection processes at the In Salah industrial site (Algeria), emphasising the relationship between CO_2 flow, changes in reservoir pressure and the geomechanical response of the reservoir. The authors demonstrate that a reliable assessment of the storage site's behaviour requires a combination of hydrodynamic modelling, geomechanical calculations and monitoring results, in particular satellite observations of surface deformation. The results obtained confirm that pressure changes during injection can cause a redistribution of stresses in the rock and manifest as deformation anomalies. This approach is relevant for assessment of safety of CO_2 storage in depleted oil and gas reservoirs and justifies the use of NPEMFE as an additional method for monitoring changes in the stress-strain state of the rock mass.

This approach is supported by W. Tang *et al.* (2025), who conducted a review of current geophysical monitoring technologies for geological CO_2 storage. Study noted the great potential of electromagnetic methods due to their sensitivity to changes in rock fluid saturation and alterations in the medium's electrophysical properties. The current results confirm this conclusion and demonstrate that electromagnetic parameters can also reflect changes in the stress-strain state of the reservoir. The proposed approach involves creation of a baseline map of the distribution of NPEMFE parameters before the start of CO_2 injection, which characterises the natural state of the geological environment and serves as a reference for subsequent comparisons. During subsequent stages of storage operation, periodic measurements are conducted on a network of observation profiles located above the reservoir and within zones of potential fluid migration. Comparison of existing data with the baseline state can identify changes in the geodynamic state of the rock mass and processes associated with storage operation. In particular, analysis of the spatio-temporal variations in NPEMFE parameters can assess changes in formation pressure, identify the activation of zones of increased fracturing, record the formation of potential filtration channels, and determine the directions of possible propagation of the injected carbon dioxide front. Furthermore, local anomalies in the electromagnetic field may indicate the presence of areas with an increased risk of leakage from the geological storage facility.

Should anomalous zones be detected, the monitoring results can be used to plan further detailed investigations using seismic, geochemical or borehole monitoring methods. This approach enables multi-level verification of the data obtained and enhances the reliability of assessments of the geological environment. The results obtained demonstrate that the use of the NPEMFE method has the potential to create an early-warning system for detection of hazardous changes within geological CO_2 storage sites. The advantages of the proposed approach include the ability to rapidly obtain information on changes in the stress-strain state of rock masses, the relatively low cost of fieldwork, and the possibility of integration with other monitoring methods. This defines NPEMFE as a promising tool for improvement of safety of long-term geological storage of carbon dioxide in depleted oil and gas fields. Analysis of results of this study in the context of scientific publications, it is possible to state no contradiction of existing interpretaion of the mechanisms governing the operation of CO_2 geological storage sites. On the contrary, the data obtained expand current approaches to monitoring underground reservoirs using the Earth's natural pulsed electromagnetic field as an indicator of changes in formation pressure and the stress-strain state of rocks. However, further research is required at other underground gas storage facilities and potential geological carbon dioxide storage sites to definitively confirm the identified patterns. This can be used for an assessment of the universality of the proposed approach and determine the limits of its practical application in CCS monitoring systems.

Conclusions

An analysis of existing scientific research has shown that depleted oil and gas fields are promising sites for the long-term geological storage of carbon dioxide due to their significant pore volume, proven natural impermeability and the presence of a well-developed production infrastructure. At the same time, it has been established that the main risk factors during the implementation of CO_2 geological storage projects remain breaches in the integrity of the cap rocks, the activation of tectonic faults, well degradation and the formation of man-made fluid migration pathways. The research established the existence of a regular relationship between changes in formation pressure and the parameters of the Earth's natural NPEMFE. A consistent inverse relationship has been identified: an increase in formation pressure is accompanied by a decrease in the intensity of the Earth's natural NPEMFE, whilst a decrease in formation pressure increases electromagnetic radiation. This pattern is determined by changes in the stress-strain state of the rocks and the intensification of filtration processes in the geological environment. An investigation of the spatial distribution of the NPEMFE anomalies revealed their pronounced anisotropy and dependence on the formation pressure regime. It has been established that elongated anomalous zones reflect the directions of fracture development and the movement of formation fluids, which defines them as indicators of zones of increased permeability and potential migration pathways for carbon dioxide. The results of the spatial correlation analysis confirmed the existence of a genetic correlation between the Earth's atural electric field and its natural pulsed electromagnetic field. It was established that changes in the structure of the correlation functions are most manifested during the redistribution of formation pressure and reflect changes in the stress-permeability state of the geological environment.

Based on the results obtained, the feasibility of use of NPEMFE method as a tool for real-time monitoring of the safety of geological CO_2 storage was demonstrated. It has been demonstrated that the method can be used for remote monitoring of changes in formation pressure, the identification of active filtration zones, the localisation of potential leakage pathways, and the assessment of the condition of the geological environment without the need to drill additional observation wells. A conceptual approach is proposed for establishment of a system of continuous geophysical monitoring of CO_2 storage sites based on regular NPEMFE observations. Implementing this approach can be used for early detection of reservoir integrity breaches, the prediction of carbon dioxide migration pathways, and an improvement in the environmental and operational safety of geological storage. The results obtained indicate the potential for further research aimed at quantitatively establishing the relationships between NPEMFE parameters, formation pressure, rock permeability and the volumes of injected CO_2. Development in this area lays the scientific foundations for the design of automated monitoring systems and risk-based management of geological carbon dioxide storage sites.

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Conflict of Interest

None.

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Оцінка безпеки зберігання CO_2 у виснажених нафтових та газових пластах

Анотація. Актуальність дослідження зумовлена необхідністю безпечного геологічного зберігання вуглекислого газу в межах реалізації технологій уловлювання, транспортування та зберігання вуглецю (CCS/CCUS). Метою дослідження була оцінка безпеки зберігання CO_2 у виснажених нафтових та газових пластах і обґрунтування можливості використання методу природного імпульсного електромагнітного поля Землі (ПІЕМПЗ) для оперативного контролю пластового тиску та виявлення потенційних каналів міграції флюїдів. Методологія дослідження базувалася на аналізі результатів експериментальних геофізичних досліджень, виконаних на науковому полігоні Долинського нафтопромислового району західного регіону України, а також на застосуванні просторово-кореляційного аналізу для встановлення взаємозв’язків між параметрами ПІЕМПЗ та пластовим тиском. Виснажені родовища вуглеводнів розглядалися як перспективні об’єкти для довготривалої ізоляції CO_2 завдяки значній ємності, підтвердженій герметичності та наявній виробничій інфраструктурі. У результаті дослідження встановлено закономірний зв’язок між пластовим тиском і параметрами ПІЕМПЗ. Виявлено інверсійний характер залежності, за якого підвищення пластового тиску супроводжується зменшенням інтенсивності ПІЕМПЗ, тоді як його зниження призводить до зростання електромагнітної активності. Показано, що зміни інтенсивності ПІЕМПЗ пов’язані з процесами перерозподілу напружень у породному масиві. Встановлено анізотропний характер просторового розподілу аномалій ПІЕМПЗ, який відображає напрямки руху флюїдів і зони підвищеної проникності. Кореляційний аналіз підтвердив наявність взаємозв’язку між змінами природного електричного поля та пластовим тиском. Розроблено концептуальний підхід до організації системи геофізичного моніторингу об’єктів геологічного зберігання CO_2 на основі регулярних спостережень параметрів ПІЕМПЗ, що забезпечує раннє виявлення потенційних каналів міграції вуглеводнів та порушень герметичності сховища. Практична цінність отриманих результатів полягає у можливості їх використання фахівцями нафтогазової галузі, геоекології та геофізичного моніторингу для контролю стану підземних сховищ CO_2, оцінювання ризиків витоків і підвищення рівня екологічної та технологічної безпеки геологічного зберігання вуглецю

Ключові слова: геологічне зберігання CO_2; виснажені газові родовища; пластовий тиск; природне імпульсне електромагнітне поле Землі; моніторинг; безпека сховищ; міграція флюїдів

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Innovative use of UAVs and photogrammetry for automation of mining surveying in open-pit mining

Abstract. The study aimed to evaluate the potential of unmanned aerial vehicle (UAV)-based photogrammetry for automating spatial monitoring in open-pit mining. The methodology included comparative field experiments conducted in June-September 2024 at granite quarries. UAV flights were performed at altitudes of 60, 80 and 120 metres using sensors with a resolution of 20 Mpix and 45 Mpix to analyse the impact of flight altitude and sensor characteristics on spatial accuracy. The results showed a direct dependence of the accuracy of digital terrain models on flight altitude and sensor characteristics. With an increase in altitude to 120 metres, the errors increased to 6.1 cm (planimetric) and 10.3 cm (altimetric). The camera with higher resolution demonstrated consistently higher accuracy at all altitude levels, which was confirmed by statistical analysis ($p < 0.05$). In addition, the critical role of the density of the ground control point network was established: reducing their number from 18 to 6 caused an increase in the plan error from 3.4 cm to 8.9 cm, and the elevation error from 4.8 cm to 11.5 cm, with significant local deformations of the models at the periphery. When comparing three software platforms for automated calculation of rock mass volumes, the smallest error was recorded in 3D Survey (1.6% of the reference laser scan), while Trimble Business Centre demonstrated the highest performance (1.5 hours of processing versus 2.6 hours in 3D Survey). Statistically significant differences ($p = 0.033$) indicate the importance of a well-informed choice of software in accordance with priorities of accuracy or speed. The practical significance of the study is determined by the possibility of implementing the results obtained by mining companies, surveying services and engineering and geodetic departments to improve the accuracy, productivity and safety of monitoring while minimising human and technical resources

Keywords: spatial monitoring; planned errors; point cloud density; photogrammetry; autonomous aerial vehicle; geodetic instruments; digital model

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Introduction

The development of open-pit mining is accompanied by a constant complication of production processes, which requires the introduction of the latest technologies for monitoring the spatial parameters of quarries. In conditions of intensive depletion of deposits, growth in the volume of mining activities and the actualisation of occupational safety issues, there is a need to increase the accuracy of mine surveying while reducing time and resource costs. Traditional methods of engineering and geodetic measurements, although they remain the basis of technical control, often do not provide the necessary efficiency in the conditions of rapidly changing geometry of open mining workings. In this context, innovative remote sensing technologies, in particular photogrammetry using unmanned aerial vehicles (UAVs), are becoming relevant as a tool for high-precision and rapid spatial analysis. At the same time, despite the rapid development of this field, several scientific and applied issues remain related to the standardisation of methods, accuracy assessment, processing optimisation, and justification of the number of control points to ensure reliable results.

The key problem with using UAVs in surveying is the variability of accuracy, which is determined by flight altitude, sensor type, and the density of Global Navigation Satellite System (GNSS) control points. In many cases, the lack of regulated approaches to flight parameters leads to ambiguous results and complicates the integration of technology into production processes. Y. Zabolotna *et al.* (2025) analysed the impact of survey altitude on the accuracy of digital terrain models in coal mines, finding a significant deterioration in metric characteristics when the UAV was raised above 100 m. However, their study did not consider the peculiarities of high-altitude or complex-structured quarries, where relief changes are sharply pronounced locally.

A substantial feature of the use of UAVs in the extraction of solid minerals is their adaptability to various types of photogrammetric equipment. The results of a study by D. Polishchyk *et al.* (2024) indicated a significant reduction in error when using a sensor with higher resolution (24 Mpix versus 12 Mpix). At the same time, the impact of data volume on processing time and resource intensity, which is critical in production conditions, was not analysed. The accuracy of calculating the volumes of extracted rock is also substantial, as errors in this aspect can lead to financial losses. At the same time, V. Kotenko & M. Kunytska (2023) raised the issue of the accuracy of volume calculations based on models obtained from UAVs but were limited to analysis of only one software product. Their results were inapplicable for a comparative assessment of different software environments, which limits the ability of companies to choose the optimal software.

Another substantial issue is the optimal number of control points required to ensure high model accuracy. N. Bar *et al.* (2020) investigated the impact of different numbers of GNSS points on the results of orthotransformation of photogrammetric images. They established a critical threshold of 10 points, below which accuracy decreases significantly. However, their work did not address changes in accuracy depending on the type of sensor and terrain conditions. Another aspect is the comparison of photogrammetry with alternative technologies, such as terrestrial laser scanning (TLS). According to S. Tsachouridis *et al.* (2025), parallel surveying using terrestrial laser scanning and UAVs showed greater detail in the former method. At the same time, their study did not consider the economic feasibility of using each technology in industrial conditions, nor did it evaluate the effectiveness of a hybrid approach.

The issue of data processing efficiency in different software environments is also of scientific interest. K. Chand *et al.* (2024) evaluated the performance of three programmes for building digital terrain models, noting that differences in processing speed reached 50%. However, the study did not compare these parameters with the accuracy of the results, which prevents a comprehensive assessment of software efficiency. In the context of the industrial integration of UAV technologies into the mining industry, their practical testing in real conditions is relevant. At the same time, S. Mikrut (2024) conducted field experiments at an iron ore quarry, proving the possibility of regular spatial monitoring using UAVs. However, the study did not include a systematic assessment of the statistical significance of the results, which limits their application as a regulatory framework. The problem of standardising the methodology for processing photogrammetric data remains insufficiently studied. An analysis of different approaches to model validation using GNSS and TLS was presented in a study by R. Battulwar *et al.* (2020), but it did not address the influence of control point density on the results, which reduces the applicability of their recommendations for dynamic quarries.

Thus, the research is driven by the need to develop an optimised photogrammetric monitoring methodology that incorporates the impact of key shooting parameters, sensor type, number of control points, and software environment on the accuracy and efficiency of mine surveying. The main goal of the study was to determine the technical possibilities of using UAVs for automated spatial monitoring in open-pit mining. The research tasks included analysing the impact of flight altitude and sensor resolution on model accuracy, assessing the role of control points in ensuring metric reliability, and comparing three software platforms in terms of accuracy and processing speed.

Materials and Methods

The research was conducted between June and September 2024 at open-pit mines near the town of Khoroshiv in the Zhytomyr region of Ukraine, which specialises in the extraction of granite and decorative stone. Field work was conducted in cooperation with the production department of Limited Liability Company "KLM Granresurs", which conduct open-pit mining of minerals in the region. The choice of the research site was determined by the presence of active mining workings and a variety of geological structures, which create favourable conditions for testing new methods of mine surveying. The climatic conditions of the study area are temperate continental, with an average air temperature of +19.5°C in the summer months and an average precipitation of about 78 mm per month. The geological structure is represented by massifs of crystalline rocks of the Archaean and Proterozoic ages, which ensure the stability of control points and reduce the influence of vegetation cover on the accuracy of aerial photography.

Field work included a series of experimental flights using DJI Phantom 4 RTK (China) and DJI Matrice 300 RTK (China) UAVs with Zenmuse P1 cameras to compare the effectiveness of sensors with different resolutions (20 Mpix and 45 Mpix, respectively). To determine the optimal flight altitude, missions were performed at levels of 60, 80 and 120 m with 80% frontal and 70% lateral image overlap. The collected data was processed using 3D Survey (Netherlands) and Pix4Dmapper 4.9 (Switzerland) software, which was used for a comparison of the accuracy of digital terrain models and orthophotomaps created using different photogrammetry algorithms (SfM, MVS). In addition, the capabilities of automated analysis of rock mass volumes were tested in the Trimble Business Centre 5.9 software suite (USA). Three key parameters were used to evaluate the effectiveness of the rock mass volume calculation software: calculated volume (m^3), absolute deviation from the reference model built using laser scanning data (Leica ScanStation P40, accuracy 2 mm), and total processing time (hours), which was used for an objective comparison of the accuracy and performance of the selected platforms.

Ground measurements of control points were performed using a Trimble R10 GNSS receiver (USA) in RTK mode. A total of 18 control points were laid out, distributed evenly across the study areas, with an average distance of 80 m between them. Additionally, the influence of the number of control points on the accuracy of the constructed models was investigated: three series of processing were performed with a full set of points, with a 50% reduction in their number, and with a minimum required set of 6 points. This made it possible to determine the dependence of the error on the density of the control network. To verify the models, comparative measurements were also conducted using a Leica ScanStation P40 (Switzerland) terrestrial laser scanner, which provided reference three-dimensional models with an accuracy of up to 2 mm. A comparison of digital terrain models obtained from UAVs and TLS was used for a quantitative assessment of the error of deviations in planned coordinates and height. Statistical data processing included three main stages: analysis of the accuracy of digital models depending on flight altitude and control point density, comparison of the time required to update mining and graphic documentation using traditional and automated methods, and assessment of the error in calculating the volume of rock masses using different software packages. The calculations were performed in IBM SPSS Statistics 29 (USA). The analysis used analysis of variance (ANOVA) for multiple comparisons, the Wilcoxon test for paired samples, and the Kruskal-Wallis test for independent groups, with a significance level of $p < 0.05$.

To provide a contextual comparison of the effectiveness of traditional surveying technologies and modern UAV-based solutions, an analytical summary of the technical characteristics of both approaches was additionally conducted. The comparative table was compiled based on a combination of data from literary sources and the results of field tests, in particular regarding the duration of data collection, the required number of operators, the accuracy of coordinates, and access requirements to the facility. This approach systematised the key parameters of mine surveying and highlighted the technological advantages of UAV solutions in the context of open-pit mining. In addition to a quantitative analysis of errors, the study also provided practical recommendations on the minimum number of control points required to ensure the necessary accuracy. Scenarios were considered that correspond to the conditions of indicative mapping, standard surveying control and high-precision modelling for boundary calculations, incorporating resource constraints and requirements for the reliability of results.

Results

In mine surveying for open-pit mining, there is a steady trend towards the introduction of UAVs as an alternative or supplement to traditional geodetic measurement methods (Cao *et al.*, 2022). Classic instruments such as total stations, levelling instruments and GNSS receivers provide high accuracy but are characterised by limited data collection speed, significant labour intensity and dependence on complex terrain conditions. At the same time, photogrammetry technologies implemented through UAVs can be used to photograph large areas in a limited time with minimal personnel involvement. The main advantages of photogrammetric methods are the high frequency of spatial information updates, the possibility of automated processing, and reduced monitoring costs (Lu *et al.*, 2021). However, the accuracy of the results largely depends on the survey parameters, sensor type, lighting conditions, and processing software. Table 1 summarises the key technical characteristics and differences between traditional geodetic methods and modern UAV solutions in the context of open developments.

Table 1. *Comparison of traditional and UAV photogrammetric methods of mine surveying monitoring*

Parameter	Classic surveying methods	UAV with photogrammetry
Equipment type	Total station, GNSS, level	DJI Phantom 4 RTK, Matrice 300 RTK
Coverage area per session	Up to 1 ha	Up to 50 ha
Time for data collection	4-8 hours/plot	20-40 minutes/plot
Amount of operators	2-3	1-2
Accuracy of planned coordinates	±1-2 cm	±3-5 cm
Accuracy by height	±1 cm	±5-10 cm
Equipment cost	15,000-25,000 USD	30,000-55,000 USD
Update frequency	1-2 times per month	Weekly or more often
Direct access requirement	Yes	No
Weather condition impact	Moderate	High

Source: *compiled by the authors based on L. Canh et al. (2020), J. Lu et al. (2021), R. Preston (2021), D. Cao et al. (2022), D. Zhou et al. (2022)*

A comparative technical analysis demonstrated the evolution of approaches to spatial monitoring in mine surveying, from labour-intensive classical instrumental methods to highly efficient automated systems based on UAVs. This transformation was made possible by the simultaneous development of three key technological components: high-precision sensors, image processing algorithms (SfM/MVS) and geospatial referencing systems. All these components determine the overall efficiency and accuracy of digital terrain modelling, which is critical for the safe and rational organisation of open-pit mining (Zhou *et al.*, 2022). The sensor part of modern UAVs includes cameras with a resolution of 12 to 61 megapixels. Two popular kits were used in this study: the DJI Phantom 4 RTK with a 20 Mpx camera and the DJI Matrice 300 RTK with a 45 Mpx Zenmuse P1 camera. During flights at altitudes of 60, 80 and 120 m, a ground sample distance (GSD) in the range of 0.7 to 2.5 cm/pixel was achieved, providing detail even when shooting vertical quarry benches. High image overlap values (80% frontal and 70% lateral) reduced the area of "dead zones" by more than 65% compared to the minimum acceptable overlap (60×40%), which, in turn, increased the point cloud density to over 100 points/m^2 and ensured the stability of spatial reconstruction even in complex terrain areas. As a result, more than 100 points/m^2 were obtained in a dense cloud, which is 10-20 times higher than the density available when using conventional GNSS surveying. However, it is worth noting that these algorithms are sensitive to shadow areas, excessive reflection from wet surfaces, and vegetation, which complicates the reconstruction of objects in the summer.

Another critical component is the coordinate reference system. The use of the RTK module ensured a geolocation error of 1.5-2 cm for individual images without involving a complete network of ground control points. However, optimal results were achieved with a combined approach using GNSS control points and RTK photogrammetry. All constructed models were transformed into the UCS-2000 coordinate system, incorporating the parameters of the Gauss-Krüger projection, which was used to integrate the models into the QGIS geoinformation environment for further processing. Thus, the technical prerequisites for the successful implementation of UAVs in mine surveying are based on a combination of high-quality sensors, optimised image processing algorithms and accurate georeferencing methods. Compliance with these conditions ensures not only high accuracy of digital models (up to 3.2 cm in plan and 5.1 cm in height when shooting from 60 m with a 45 Mpx camera), but also a significant reduction in time and resource costs: the duration of field work is reduced from 4-8 hours to 20-40 minutes per 10-12 ha plot, and the number of personnel involved is reduced from 2-3 to 1-2 operators.

In the process of analysis of the influence of flight altitude and sensor resolution on the accuracy of digital terrain models in field research, six different photo shooting configurations were used with two types of sensors: 20 Mpix (DJI Phantom 4 RTK) and 45 Mpix (Zenmuse P1 on DJI Matrice 300 RTK). The photography was conducted from three altitude levels: 60 m, 80 m and 120 m. All missions adhered to the same overlap parameters of 80% frontal and 70% lateral, and the data were processed in Pix4Dmapper using the same recursive optimisation parameters. As shown in Table 2, lower flight altitudes provided better detail (lower GSD values) and, accordingly, higher accuracy of both planned position and altitude.

Table 2. *Accuracy of digital terrain models depending on flight altitude and sensor type*

Flight height (m)	Sensor type	GSD (cm/pixels)	Average planned error (cm)	Average maximum error (cm)	p (planned error)	p (maximum error)
60	20 Mpix	1.2	4.5	7.8	0.031	0.028
60	45 Mpix	0.8	3.2	5.1	0.031	0.028
80	20 Mpix	1.8	6.7	10.2	0.017	0.013
80	45 Mpix	1.1	4.8	7.4	0.017	0.013
120	20 Mpix	2.5	9.3	14.5	0.004	0.002
120	45 Mpix	1.6	6.1	10.3	0.004	0.002

Source: *compiled by the author*

The data demonstrates the systematic dependence of the accuracy of digital terrain models on two key parameters: the flight altitude of the UAV and the resolution of the sensor installed on board. These parameters determine the GSD of the images, which in turn directly affects the density of the point cloud, the clarity of contour definition, and the accuracy of geometric reconstruction. The analysis covered six flight configuration options, which varied between altitudes of 60, 80 and 120 metres for two sensors: 20 Mpix (DJI Phantom 4 RTK) and 45 Mpix (Zenmuse P1 on DJI Matrice 300 RTK). The results showed that the lowest GSD values, and therefore the highest accuracy, were achieved at a flight altitude of 60 m. At the same time, the 45 Mpx sensor provided a GSD of 0.8 cm/px, while the 20 Mpx sensor provided 1.2 cm/px. Accordingly, the planimetric errors were 3.2 cm for high resolution and 4.5 cm for lower resolution. The difference in elevation accuracy is even more noticeable: 5.1 cm versus 7.8 cm. These values indicate the possibility of using UAV data for topographic mapping at a scale of 1:500 under optimal survey parameters. Statistical analysis using the Wilcoxon criterion confirmed the reliability of these differences ($p = 0.031$ for planimetric coordinates and $p = 0.028$ for elevation). When moving to an altitude of 80 m, the predicted increase in GSD to 1.8 cm/pixel (20 Mpix) and 1.1 cm/pixel (45 Mpix) occurred. The planned errors increased to 6.7 cm and 4.8 cm, respectively, and the altitude errors to 10.2 cm and 7.4 cm. In both cases, the improvement in accuracy due to the use of 45 Mpix was statistically significant ($p < 0.05$). This confirms the ability of high-resolution sensors to partially compensate for the deterioration in accuracy caused by an increase in flight altitude.

The worst results were recorded at an altitude of 120 m. Here, the GSD reached 2.5 cm/pixel (20 Mpix) and 1.6 cm/pixel (45 Mpix). Planar errors increased to 9.3 cm and 6.1 cm, and elevation errors to 14.5 cm and 10.3 cm, respectively. Even under such conditions, the advantage of high resolution remained. The Kraskel-Wallis criterion confirmed statistical significance ($p = 0.004$ and 0.002), indicating a noticeable effect of the sensor type with the same flight geometry. Thus, the analysis revealed clear trends: with an increase in flight altitude, the accuracy of the models decreases; cameras with a resolution of 45 Mpix provide consistently better results at all levels; the interaction between GSD and SfM/MVS algorithms forms a critical limit for acceptable error in surveying tasks. For industrial practice, it is advisable to choose a height of up to 80 m in combination with a high-resolution sensor, which is the optimal compromise between performance, flight safety and model accuracy.

To study the impact of control network density on the accuracy of digital terrain model construction, a series of test processing of photographic data with identical flight, sensor and image overlap parameters was conducted. All models covered an area of approximately 12.5 hectares and were constructed in the same software environment using SfM/MVS algorithms. The only difference was in the number of control points used: a full set (18 points), a set reduced by half (9 points), and a minimum acceptable set (6 points). Following Table 3, reducing the number of control points led to a gradual deterioration in the accuracy of digital models in both planimetric and elevation measurements. The most favourable outcomes were observed when using a complete network of points, while partial or minimal coverage resulted in increased errors and reduced spatial reliability. Statistical analysis confirmed the significance of the identified differences, confirming the significance of sufficient density and uniform distribution of control points to ensure reliable geometric reconstruction.

Table 3. *Influence of the number of control points on model accuracy*

Number of control points	Average planned error (cm)	Average maximum error (cm)	Research area (ha)	p (planned error)	p (maximum error)
18	3.4	4.8	12.5	0.019	0.011
9	5.7	7.2	12.5	0.019	0.011
6	8.9	11.5	12.5	0.019	0.011

Source: *compiled by the authors*

The results demonstrated a dependence of the accuracy of digital terrain models on the density of the network of ground control points used in the external orientation of photogrammetric models. This is fundamentally essential for surveying, where even minor geometric errors can lead to significant systematic errors in calculating rock mass volumes, determining bench deformations, and controlling development contours. An experimental comparison of three processing scenarios with 18, 9 and 6 control points quantitatively assessed the degree of influence of the reduction in the number of benchmarks on spatial accuracy. A complete set of 18 control points, evenly distributed around the perimeter and in the central parts of the survey area, ensured the highest accuracy: the average planimetric error was 3.4 cm, and the elevation error was 4.8 cm. At the same time, the maximum local deviations did not exceed 7 cm; therefore, the model can be used with confidence for large-scale mapping (1:500) and volume calculations with an accuracy of 2%.

Reducing the number of control points to 9, while maintaining symmetry and covering the edges of the model, led to an increase in the planimetric error to 5.7 cm and the elevation error to 7.2 cm. These values are already close to the limits acceptable for 1:1,000 scale surveying, especially in the case of detailed documentation of relief changes. The critical point was the reduction of the number of benchmarks to a minimum set of 6, which can be used for external orientation without reorienting the scene. In this case, the average plan error increased to 8.9 cm, and the elevation error to 11.5 cm. In addition, there was an increase in the internal deformation of models, particularly in peripheral areas, where errors reached 14-16 cm. This effect is explained by a decrease in network rigidity in conditions of insufficient control point coverage. Statistical analysis using the Kraskel-Wallis criterion confirmed the significance of these changes ($p = 0.019$ for planimetric and $p = 0.011$ for elevation errors), indicating the critical role not only of the number but also of the configuration of point placement.

From a technical point of view, the lack of control points leads to a violation of the conditions for fixing the external orientation of the model, an increase in uncertainty in the optimisation of photogrammetric connectivity of images, and a deterioration in micro-relief reconstruction. This is evident when using SfM/MVS algorithms, which require spatial stability for accurate calculation of camera positions. Although modern UAVs are equipped with RTK modules that provide precise positioning, this data is not sufficient for metric assurance without ground verification. Thus, the results of the study show that the optimal scenario for balancing accuracy and cost is to use at least 9 benchmarks, evenly distributed around the perimeter and in the centre of the site. In situations where maximum accuracy is required (e.g., for marginal reserve calculations), it is recommended to use a full set of 18 points. In turn, reducing the number of points to 6 may be acceptable only for indicative mapping or when resources are limited, but it does not meet the requirements of mine surveying control in active mining conditions.

As part of the assessment of the effectiveness of software tools for automated calculation of rock mass volumes, three specialised software platforms were tested: 3D Survey, Pix4Dmapper and Trimble Business Centre. The calculations were based on the same photogrammetric model of a 12.5-hectare site, constructed using a 45-megapixel sensor at a flight altitude of 80 metres. To compare the accuracy of the calculations, a model obtained from TLS data (Leica ScanStation P40) with an error of 2 mm was used as a reference. Following Table 4 and Figure 1, the results of the volume calculations varied depending on the software selected, demonstrating significant differences in accuracy. The smallest errors were characteristic of one of the software packages, while the others showed higher levels of deviation from the reference value. Statistical analysis confirmed the significance of the identified discrepancies, indicating different processing algorithm efficiencies in each of the software environments.

Table 4. *Comparison of software for calculating rock mass volumes*

Software	Calculated volume (m^3)	Absolute deviation from the standard (m^3)	Processing time (hours)	p (volume)	p (processing time)
3D Survey	12,750	210	2.6	0.033	0.027
Pix4Dmapper	12,580	380	2.2	0.033	0.027
Trimble Business Centre	12,690	270	1.5	0.033	0.027

Source: *compiled by the authors*

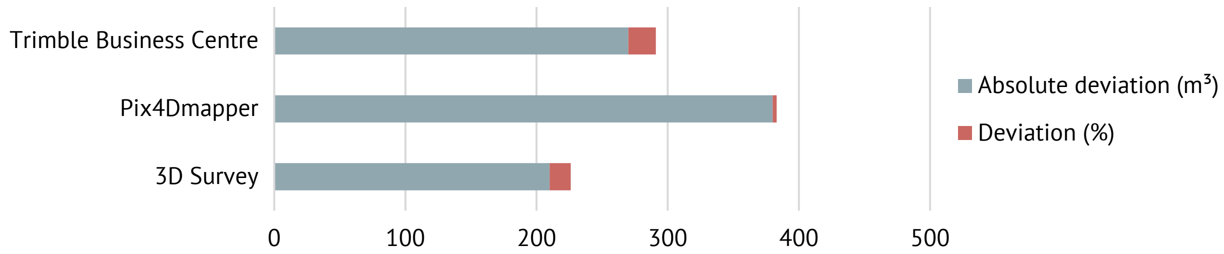

Figure 1. *Graph showing the dependence of volume calculation errors in different software platforms*
Source: *compiled by the authors*

A comparison of three leading software packages, 3D Survey, Pix4Dmapper and Trimble Business Centre, in the context of calculating rock mass volumes revealed significant differences in both the accuracy of the results and the time required for processing. Although all three software products are based on photogrammetric reconstruction and digital surface modelling methodologies, the algorithms, point cloud densification parameters, interpolation methods, and geometric segmentation methods implemented in them differ significantly. This, in turn, causes not only discrepancies in the results but also in the stability of the model when the input parameters change.

3D Survey demonstrated the highest level of accuracy. When modelling based on 45 Mpix images from a height of 80 m and GSD 1.1 cm/pix, the programme calculated a volume of 12,750 m^3, with an absolute deviation from the reference laser model of only 210 m^3 (1.6%). This is due to the flexibility in configuring dense cloud algorithms, adaptive noise masking, and multi-stage camera position optimisation. However, the processing time was 2.6 hours, which is the highest among the platforms studied. This may limit its use in production environments where the speed of documentation updates is critical. Pix4Dmapper, although designed with a focus on fast and automated processing of drone data, demonstrated lower metric accuracy. The calculated volume was 12,580 m^3, which corresponds to a deviation of 380 m^3 (≈3%). The main sources of error were fewer points in the condensed model, aggressive noise removal filters, and less accurate geometric correction of polygon edges. The processing time of 2.2 hours indicates relative efficiency while maintaining automation, but the compromise in accuracy makes this platform less suitable for high-precision mine surveying.

Trimble Business Centre demonstrated the best balance between accuracy and productivity. With a result of 12,690 m^3 (deviation of 270 m^3 or 2.1%) and the shortest processing time of 1.5 hours, Trimble Business Centre demonstrates high efficiency in volume calculation. A distinctive feature of this software is its deep integration with GNSS data, automatic polygon closure, high-precision TIN model construction, and boundary closure control, which is critical for reporting surveying documents. In addition, Trimble Business Centre has a convenient interface for generating volume reports in PDF and DWG formats. ANOVA analysis showed statistically significant differences in both accuracy ($p = 0.033$) and time consumption ($p = 0.027$) between the platforms. This indicates the objective existence of differences that must be considered when choosing a tool for surveying support. Therefore, for tasks where metric accuracy is a priority, 3D Survey should be used. In situations with limited time, the Trimble Business Centre. Pix4Dmapper is best used for training purposes or in medium-priority projects where accuracy is of secondary importance.

Discussion

This study confirmed the high potential of UAVs in surveying open-pit mines. The results demonstrated the advantages of UAV photogrammetry over traditional geodetic methods in terms of data collection speed, coverage area, update frequency, and automated processing. A similar advantage was also noted in studies by J. Shahmoradi *et al*. (2020) and R. Le Roux *et al*. (2025), who studied the use of UAVs in quarries of varying depths. According to their findings, photogrammetric models can reduce time consumption by 60-75% compared to classical approaches. This correlates with the results of the study, where data collection time was reduced to 20-40 minutes compared to 4-8 hours in traditional scenarios. The established dependence of the accuracy of digital terrain models on flight altitude and sensor type confirms the conclusions of H. Dai & J. Jiying (2022) and Y. Gül *et al*. (2020), investigating the role of GSD in the accuracy of digital surface model construction. Both authors note that optimisation of resolution is critical to achieving accuracy acceptable for surveying purposes. In the presented study, the best results were achieved when shooting from a height of 60 m with a 45 Mpx camera, which provided a GSD of 0.8 cm/px and an elevation error of 5.1 cm. This is consistent with the conclusions of H. Dai & J. Jiying regarding the advisability of using shooting heights of up to 70 m to ensure a balance between coverage and accuracy.

Despite the overall positive trend in UAV performance, D. Dawei *et al*. (2020) express scepticism about their suitability for work in areas with dense vegetation, where reconstruction accuracy is significantly reduced. This is partly confirmed by the study, which found a deterioration in model accuracy during the summer due to excessive reflection and shaded areas. At the same time, the use of high-resolution cameras and improved SfM/MVS algorithms, as demonstrated in the study, minimises the impact of vegetation noise. Thus, the arguments of D. Dawei *et al*. are valid, but only in the absence of technological adaptation to complex conditions. Analysis of sensor performance showed a systematic advantage of a 45 Mpx camera over a 20 Mpx camera at all altitude levels. This conclusion is consistent with the results of A. Kabadayi (2022) proved in laboratory modelling the critical impact of resolution on the accuracy of altitude estimates. According to the observations of A. Kabadayi, a 1 Mpx increase in resolution improves the accuracy of digital terrain models by an average of 3-5%, which corresponds to the dynamics of the data obtained in the study. Similar results in the field are described by J. Wu & M. Saito (2024), who noted that a GSD below 1 cm/pixel is a critical threshold for 1:500 scale mapping tasks.

In the context of analysing the number of control points, the results of the study confirm the conclusions of J. Hao *et al*. (2023) and Y. Astor *et al*. (2022), arguing that reducing the number of control points below 9 leads to systematic model deformations. The study in question showed an increase in the planned error from 3.4 cm to 8.9 cm when the number of points was reduced from 18 to 6. A similar effect was described by J. Hao *et al*. when testing external orientation algorithms without full control of the scene edges, which causes geometry distortion at the periphery. Y. Astor *et al*. also emphasise the significance of spatial symmetry of the control network for the stability of SfM reconstruction. At the same time, G. Yüksel (2022) questions the advisability of using more than 6 control points when using UAVs with RTK navigation. Following the study, the accuracy of RTK photogrammetry eliminates the need to install a complete network of control points. The study partially refutes these claims, since when using only RTK data, the average height error exceeded 11 cm, which does not meet surveying standards for a scale of 1:500. This leads to the conclusion that the position of G. Yüksel does not incorporate the potential instability of the RTK signal in quarries, where signal shielding by bench walls is possible.

Regarding the accuracy of software tools, the results of the study indicate a statistically significant advantage of 3D Survey over Pix4Dmapper and Trimble Business Centre in terms of volume calculation accuracy. This correlates with the conclusions of I. Daou *et al*. (2022) and Y. He *et al*. (2024). I. Daou *et al*. emphasise the flexibility of optimisation algorithms and precise noise filtering control in Metashape, while Y. He *et al*. highlights the improved stability of results in complex terrain geometry. Both authors conclude that Metashape is suitable for tasks with high metric accuracy requirements, which is consistent with the detected deviation of only 1.6% from the reference volume in the presented study. At the same time, the evaluation of Pix4Dmapper's performance showed its lower accuracy (3% deviation) compared to other platforms. This conclusion is confirmed by the study by H. Lu *et al*. (2023), highlighting the simplified structure of point cloud densification in Pix4Dmapper and the excessive aggressiveness of noise removal algorithms. Similar results were presented by O. Ajayi & J. Ajulo (2021), also noting the low stability of edge polygons. Thus, this study confirms the limitations of Pix4Dmapper in high-precision calculations in complex conditions.

Trimble Business Centre proved to be optimal in terms of accuracy and processing time, as confirmed by the findings of C.V. Le *et al*. (2020) and H. Susilo *et al*. (2024). C.V. Le *et al*. noted that Trimble Business Centre provides integration with GNSS data and efficient automatic generation of TIN models, which reduces time consumption. H. Susilo *et al*. emphasised the boundary closure control function as critical for surveying tasks, which was also found in the presented study. The results of the Trimble Business Centre showed a deviation of only 2.1% with a minimum processing time of 1.5 hours. However, several researchers point to alternative approaches to volume calculation that are not related to photogrammetry. For example, M. Loots *et al*. (2022) and W. Ling *et al*. (2024) advocate the superiority of TLS, arguing that it offers higher accuracy and independence from weather conditions. Their conclusions are based on an analysis of TLS system errors, which do not exceed 5 mm. However, the study shows that when optimal shooting parameters are observed, UAV photogrammetry can provide a deviation of only 210 m^3 from the reference model, which is sufficient for most production tasks. In addition, the time and resources required for TLS significantly exceed the costs of UAVs, which raises doubts regarding the versatility of the approach proposed by M. Loots *et al*.

Another critical position is represented by V. Reinprecht & D. Kieffer (2025) and Y. Zhu *et al*. (2024), highlighting the low reliability of photogrammetry in cases of limited visibility or large elevation differences. V. Reinprecht & D. Kieffer emphasise problems with image overlap in terraced areas, while Y. Zhu *et al*. highlight the risk of errors due to uneven lighting. The corresponding risks are partially confirmed in the study, but their impact was reduced by high overlap (80% frontal, 70% lateral) and exposure correction. Thus, the shortcomings outlined by the authors are not critical when optimal shooting conditions are maintained. P. Amatya *et al*. (2021) and S.I. Jiménez-Jiménez *et al*. (2021) also made a significant contribution to the development of the model preparation methodology. J. Zhao *et al*. emphasised the need to transform models into local coordinate systems for further integration into the GIS environment, which is fully implemented in the study. T. Bamford *et al*. considered the effectiveness of using combined RTK + GCP approaches as a basis for ensuring high accuracy. This combination was used in the study and reduced the georeferencing error to 1.5-2 cm without excessive deployment of the control network.

Summarising the above results, it is possible to conclude that the use of UAV photogrammetry in surveying practice ensures a high level of accuracy, efficiency and flexibility, provided that optimal parameters for surveying, processing and georeferencing are observed. The identified dependencies between flight altitude, sensor type, control network density and software selection form the basis for the development of adaptive survey protocols tailored to specific tasks. Despite certain technological limitations, the results of the study indicate the feasibility of widespread UAV implementation in the field of spatial monitoring of open-pit mining.

Conclusions

The study confirmed that the introduction of UAVs into mine surveying for open-pit mining significantly improves the productivity, efficiency and safety of monitoring work compared to traditional geodetic methods. UAV-based photogrammetric systems can be used to survey large areas with minimal personnel involvement, ensuring a high data update frequency and digital model density of over 100 points per square metre, which exceeds the performance of classic GNSS surveys by 10-20 times. Despite slightly lower absolute accuracy, spatial positioning indicators remain within the limits acceptable for scales of 1:500 and 1:1,000. The study established that the combination of flight altitude and sensor resolution has a critical impact on model accuracy. The best results were achieved at an altitude of 60 metres and with a 45 Mpix sensor, which provided a planned error of 3.2 cm and an altitude error of 5.1 cm. Statistically significant differences ($p < 0.05$) confirm the sensitivity of the models to changes in shooting parameters. The density of the control network also determines the quality of the results. When the number of control points was reduced from 18 to 6, the planned error increased to 8.9 cm, and the height error to 11.5 cm, accompanied by internal deformations of the models, especially in the edge areas. The data obtained confirmed the need to ensure a minimum threshold of 9 evenly spaced benchmarks for stable geometric orientation of the models. A comparison of the three software packages revealed that 3D Survey demonstrated the highest accuracy in volume calculations, Trimble Business Centre demonstrated the fastest processing, and Pix4Dmapper occupied an intermediate position on both criteria. The identified statistically significant differences can be used for a targeted selection of software according to the requirements of accuracy or processing speed. The main limitation of the study is that it was conducted in an open quarry with limited terrain complexity, which requires verification of the conclusions obtained in areas with different types of geomorphology and climatic characteristics. Further research should focus on improving algorithms for automatic data processing and adapting methods to variable terrain and seasonal fluctuations.

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Conflict of Interest

None.

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Інноваційне використання БпЛА та фотограмметрії для автоматизації маркшейдерського супроводу відкритого видобутку корисних копалин

Анотація. Метою дослідження було оцінити можливості фотограмметрії на базі безпілотних літальних апаратів (БпЛА) для автоматизації просторового моніторингу у відкритому видобутку корисних копалин. Методологія включала порівняльні польові експерименти, проведені у червні-вересні 2024 року на гранітних кар'єрах. Обльоти БпЛА виконувалися на висотах 60, 80 і 120 метрів з використанням сенсорів роздільної здатності 20 Мпікс та 45 Мпікс для аналізу впливу висоти польоту та характеристик сенсора на просторову точність. Отримані результати засвідчили пряму залежність точності цифрових моделей рельєфу від висоти польоту та характеристик сенсора. Зі збільшенням висоти до 120 метрів похибки зростали до 6,1 см (планова) і 10,3 см (висотна). Камера з більшою роздільною здатністю демонструвала стабільно вищу точність на всіх рівнях висоти, що підтверджено статистичним аналізом ($p < 0{,}05$). Додатково встановлено критичну роль щільності мережі наземних контрольних точок: скорочення їх кількості з 18 до 6 спричинило збільшення планової похибки з 3,4 см до 8,9 см, а висотної – з 4,8 см до 11,5 см, із суттєвими локальними деформаціями моделей на периферії. У межах порівняння трьох програмних платформ для автоматизованого обчислення обсягів гірничої маси найменшу похибку зафіксовано у 3D Survey (1,6 % від еталонного лазерного сканування), тоді як Trimble Business Center продемонстрував найвищу продуктивність (1,5 години обробки проти 2,6 години в 3D Survey). Статистично значущі відмінності ($p = 0{,}033$) свідчать про важливість обґрунтованого вибору програмного забезпечення відповідно до пріоритетів точності чи швидкості. Практична значимість дослідження полягає у можливості впровадження отриманих результатів підприємствами гірничої промисловості, маркшейдерськими службами та інженерно-геодезичними підрозділами для підвищення точності, продуктивності та безпеки моніторингу при мінімізації витрат людських і технічних ресурсів

Ключові слова: просторовий моніторинг; планові похибки; густота хмари точок; фотокартографія; автономний літальний апарат; геодезичні прилади; цифрова модель

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Increasing the efficiency of dust extraction at crusher feeding points

Abstract. The loading of crushers at mining and processing facilities is accompanied by intensive emissions of fine particulate dust, which deteriorates working conditions, increases the risk of occupational respiratory diseases, and causes additional abrasive wear of process equipment. The problem is particularly relevant where the use of water-based dust suppression methods is limited due to sludge formation, high water consumption, and difficulties in their application during the cold season. The aim of this study was to develop a design for a crusher feed hopper enclosure and to provide a scientific basis for a method of calculating the extraction parameters required to ensure uniform removal of contaminated air along the entire material loading zone. Mathematical modelling of air-flow dynamics was carried out using the static pressure method and the momentum equation. The model considered the air flow in a longitudinal extraction duct with a variable-width slot. It was established that respirable dust fractions with particle sizes of up to 10 μm predominate in the workplaces of crushing and screening plants, representing the greatest health hazard to workers. It was demonstrated that one of the causes of dust escaping from beneath the enclosure is the unevenness of extraction velocities along the duct. A mathematical model was developed to determine the variable width of the longitudinal extraction slot as a function of the distance from the extraction connection point. It was established that, to ensure a stable extraction velocity, the slot width should gradually decrease from the closed end of the duct towards the point where the extraction system is connected. Analytical relationships were obtained for calculating the geometrical parameters of triangular-section ducts that prevent dust deposition inside the system. A design for a mobile extraction enclosure for a crusher feed hopper was proposed, incorporating longitudinal slots of variable width and a hinged connection to the extraction duct. The practical significance of the results lies in the localisation of dust emissions and the reduction of dust

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concentrations in the workplace air by ensuring uniform extraction of contaminated air along the entire length of the crusher feed hopper

Keywords: dust aerosol; respirable fraction; emission localisation; slotted extractor; static pressure; air flow; enclosure

Introduction

Enterprises in the mining and processing industries are among those with the highest risk of dust pollution. One of the most significant sources of air pollution in the workplace is the loading of crushers, during which a considerable amount of fine dust is released as a result of free fall, impact and the crushing of mineral raw materials. Respirable particles measuring up to 10 μm pose a particular hazard, as they are capable of remaining suspended in the air for long periods and penetrating deep into the human respiratory system. Iron ore mining operations are characterised by the presence of significant amounts of free silicon dioxide in the dust, the effects of which are linked to the development of silicosis, chronic lung diseases and other occupational pathologies.

Water is the most common agent used for dust suppression, as it allows dust particles to agglomerate due to the capillary effect. The works of O. Lapshyn *et al.* (2023) and M. Beltran-Marquez *et al.* (2025) examined water spraying systems based on moistening the material to prevent the release of fine dust that pollutes the air in the workplace. This is one of the most common methods, implemented by installing nozzles directly above the feed hoppers of crushers. However, intensive water spraying leads to water wastage, over-moistening of the raw material and the formation of liquid slurry. Attempts to address this problem by optimising the chemical composition of spray solutions and introducing electrostatic fine-particle spraying technology were investigated in the work by Y.-H. Oh *et al.* (2026).

The use of surfactants improves the wettability of dust, making it heavier and easier to capture than with plain water (Xu *et al.*, 2023). The use of aqueous solutions of calcium chloride salts increases the surface tension of the water film between dust particles and slows down moisture evaporation, which ultimately allows for the efficient use of water resources in dust control (Zhao *et al.*, 2021). However, the main drawbacks of using water are the formation of sludge and the need to organise a water supply recycling cycle (settling tanks, transfer pumps, etc.), the formation of deposits on the internal surfaces of machinery, limited water use during the winter months, as well as the increased cost of dust collection, significant water consumption and energy expenditure, as confirmed by the study by Y. Li *et al.* (2026). This confirms that rational management of a company's water resources and high efficiency in the removal of respirable dust fractions cannot be achieved solely through wet methods.

Researchers M. Ji *et al.* (2022) proposed the use of air-mechanical foam to reduce dust load, as it requires less water and ensures the material's surface is covered, forming a continuous layer. However, this method can only be effective when the foam covers the surface of stationary material with a continuous layer. When feeding a crusher, the uniformly accelerated motion of the falling material and the resulting upward air currents will carry the foam away along with the dust, as the foam is a mixture of gas and liquid in the form of bubbles, which do not bind all the dust in the loose rock. Within the overall set of measures to control dust during the feeding of crushers, water spraying is regarded as an effective complement to the main measures. However, in many cases, the implementation of this method requires the reconstruction and re-equipping of crusher feeding points, which entails significant capital expenditure; furthermore, for coarse mineral feedstock in the initial stages of crushing, the proposed methods are ineffective. The methods mentioned above may, on the one hand, be effective under specific conditions, but on the other hand, their use is limited due to existing shortcomings.

The most effective way of containing dust emissions is considered to be enclosing the sources of dust emissions, in particular the loading zones of crushers (National Institute for Occupational Safety and Health, n.d.). Enclosing crushing equipment and loading zones prevents 80-90% of dust from entering the air at workstations. When combined with other dust suppression methods and measures, the greatest effectiveness is achieved in containing dust emissions and reducing dust concentrations in the workplace. An analysis of current methods indicates that the unloading of bulk materials without enclosures and extraction systems is, in all cases, accompanied by intense dust emissions. Fine dust generated as a result of the extraction and processing of minerals is characterised by high hydrophobicity, whilst the large droplet size of the irrigation liquid reduces the efficiency of its capture (Xu *et al.*, 2023). When comparing methods and means of dust suppression during crusher feeding, it can be concluded that the most effective solution is a combination of different methods, provided that crusher feeding points are equipped with enclosures fitted with local extractor pipes for connection to extraction systems. Thus, the aim of this study was to develop a design for a crusher feed hopper enclosure and to provide a scientific justification for the method of calculating aspiration parameters to ensure uniform extraction of contaminated air throughout the entire loading zone.

Materials and Methods

The study analysed research into the particle size distribution of dust at crushing and screening plants and the aerodynamic mechanisms of dust emission during the loading of crushers; a mathematical model of airflow in a slotted air duct was developed, and a design for a mobile extraction enclosure was proposed to localise dust emissions during the loading of crushers. The analysis included scientific studies published predominantly between 2021 and 2026 in international peer-reviewed journals, containing research findings on dust particle-size distribution, the processes governing its dispersion in workplace air, the effectiveness of dust suppression, and the aerodynamics of extraction systems.

The object of the study was the process of localising dust emissions during the loading of crushers with mineral raw materials using an extraction enclosure with slotted extraction. The subject of the study was the aerodynamic behaviour of air flows in an extraction air duct with a slot of variable width, which determines the uniformity of contaminated-air removal along the crusher feed hopper. The theoretical basis of the study is the classical static-pressure aerodynamic method combined with the momentum equation. This approach made it possible to account for changes in static pressure along the air duct resulting from the entrainment of additional air masses through the extraction slot and pressure losses due to friction. Unlike simplified empirical calculation methods, the use of the momentum equation provides a physically justified description of the processes governing the formation of air flows in slotted extraction devices.

The main research method was mathematical modelling of the air-flow movement in the collecting air duct of the extraction enclosure. The object of calculation in the developed mathematical model was the continuous volume of air flow moving inside the collecting longitudinal air duct of the extraction enclosure through an extraction slot of variable width. The air duct was considered as a continuous-extraction collector with a transit outlet for the dust-air mixture to the ventilation unit. The following assumptions were made when developing the mathematical model: the air-flow coefficient through the slot μ and the aerodynamic friction resistance coefficient λ were assumed to be constant along the entire length of the extraction slot and air duct, respectively; the velocity distribution across the cross-sections of the air duct was assumed to be uniform; the momentum of the air entering through the slot, projected onto the axis of the duct, was assumed to be zero. These assumptions made it possible to use the momentum equation to determine the excess static pressure ΔP at any point in the system.

The initial parameters of the mathematical model were: the length of the air duct (the geometric length of the localisation zone of the crusher's feed hopper) l, m; the cross-sectional area of the air duct F, m^2; the suction velocity of the air flow in the slit, which ensures the capture (extraction) of respirable dust particles ϑ_x, m/s; the air density ρ, kg/m^3. In accordance with the developed mathematical model and the aerodynamic method of static pressures, the calculation determines the width of the longitudinal slot δ_x in an arbitrary cross-section. Calculating this value enabled precise geometric adjustment of the opening to compensate for the drop in static pressure and maintain a stable suction velocity along the entire length. The rationale for the method of calculating air ducts with a longitudinal slot, based on the static pressure method, is set out below.

A key drawback of many standard aspiration systems is uneven suction: the flow is stronger closer to the fan, whilst in more distant sections it is insufficient for dust collection. The proposed method has resolved this problem through the geometric adaptation of the air duct's suction slot. In suction air ducts with a slot, the average air velocity inside the duct is determined by the formula:

$$\vartheta = \mu \cdot \sqrt{2 \cdot (P_a - P)/\rho} = \mu \cdot \sqrt{-2 \cdot \Delta P/\rho}, \quad (1)$$

where μ – the flow coefficient; P – the static pressure inside the air duct; P_a – the static pressure outside the air duct; $\Delta P = P - P_a$ – the excess static pressure; ρ – the density of air. Taking formula (1) into account, the air flow rate Q at a suction slot of width δ is described by the relationship:

$$Q = \mu \cdot \delta \sqrt{2 \cdot (\pm \Delta P)/\rho}. \quad (2)$$

It can be seen from equation (2) that, for uniform air intake, the width of the slot must vary along the entire length of the air duct. To ensure uniform air intake through a slot in an air duct of constant cross-sectional area F and length l, the width of the longitudinal slot at any cross-section x is determined by the following equation:

$$\delta_x = \frac{F \cdot \vartheta}{l \cdot \vartheta_x} = \frac{Q}{l \cdot \vartheta_x}. \quad (3)$$

The air intake velocity at the slot in an arbitrary cross-section x is described by the relationship:

$$\vartheta_x = \mu \cdot \sqrt{(2/\rho) \cdot (P_a - P_x)}. \quad (4)$$

To determine the excess pressure ΔP in aspiration air ducts, the equation of momentum is used. In this case, pressure losses due to flow are not taken into account, and the projection of the volume of air drawn in through the slot onto the axis of the duct is equal to zero. For the volume of air inside a suction air duct with a longitudinal slit, the momentum equation, projected onto the axis of the air duct, takes the form:

$$P_0 \cdot F - P_x \cdot F - \int_0^x \tau_x \cdot P dx = \rho F \vartheta_x^2, \quad (5)$$

where $x = 0$ – the cross-section at the start of the air duct on the closed end; x – the cross-section at the opposite end near the air outlet at a distance corresponding to the length of the air duct, meaning $x = l$; τ_x – the friction stress, $\tau_x = \lambda/4 \cdot \rho\vartheta_x^2/2$; λ – coefficient of aerodynamic friction drag. If the value of the frictional shear stress τ_x, into equation (5) and all terms of the equation are then divided by F, the following equation is obtained

$$P_0 - P_x - \int_0^x \frac{\lambda}{d_0} \cdot \frac{\rho \vartheta_x^2}{2} dx = \rho \vartheta_x^2. \quad (6)$$

For uniform air intake $\vartheta_x = \vartheta x/l$. Substituting ϑ_x into formula (6) and integrating gives:

$$P_x = P_0 - \frac{x^2}{l^2}\left(2 + \frac{\lambda x}{3d_0}\right)\frac{\rho \vartheta^2}{2}, \quad (7)$$

where d_0 – the equivalent diameter of the air duct. If ϑ_x, calculated using formula (4), and P_x, calculated using formula (7), are substituted into formula (3), the slot width at an arbitrary cross-section x is calculated using the following formula:

$$\delta_x = \frac{1}{\sqrt{\frac{1}{\delta_0} + \frac{\mu^2 x^2}{F^2}\left(2 + \frac{\lambda \cdot x}{d_0}\right)}}, \quad (8)$$

where δ_0 – the slit width at the start of the air duct on the closed end, meaning at $x = 0$. It is evident from equation (8) that the slit width will be at its greatest at $x = 0$, which is at the start of the air duct on the closed end. As x increases to $x = l$, the slit width will be at its smallest. Consequently, the maximum slot width must be such that the dust suction velocity along the entire length of the slot is not less than the permissible value. To this end, the maximum slot width δ_0 must be calculated using the formula:

$$\delta_0 = \frac{Q}{l \cdot \vartheta_x}. \quad (9)$$

For an air duct with a cross-section in the form of an isosceles triangle, the equivalent diameter d_0 is calculated using the formula:

$$d_0 = \frac{2ah}{a + 2b}, \quad (10)$$

and the cross-sectional area F is calculated using the formula:

$$F = \frac{1}{2} ah, \quad (11)$$

where a – the base of the isosceles triangle; b – the side of the isosceles triangle; h – the height of the isosceles triangle. Consequently, the change in static pressure P_x along the air duct from its closed end at $x = 0$ to the outlet at $x = l$ is described by equation (7). This equation takes into account both the dynamic component of the flow and friction losses, where d_0 – the equivalent diameter of the air duct.

To ensure a stable dust extraction rate, the slot width δ_0 must be at its maximum at the closed end of the air duct and gradually decrease to its minimum value near the extraction unit. Formula (8) was used to calculate the slot width at an arbitrary cross-section x. The proposed method is universal and allows the calculation to be adapted to the specific shape of the air duct. For example, for extraction systems with an air duct cross-section in the shape of an isosceles triangle (which is often used to prevent dust from settling on the walls), the area F and the equivalent diameter d_0 are determined in terms of the geometric parameters of the base a, the side b and the height h. Thus, the proposed method for calculating the variable slot width δ_x is modern and scientifically sound, enabling high extraction efficiency to be achieved at the feeding points of crushers throughout the entire feeding zone by equalising the suction velocity distribution. This minimises dust ejection zones and prevents energy wastage due to excessive ventilation at specific points in the system.

Results and Discussion

Particle size distribution of dust and its hazard to workers

Mineral raw materials and bulk materials unloaded into the crusher contain fine dust formed as a result of rock fragmentation by blasting in a quarry or mine, as well as from friction between pieces of material or impacts of pieces against various surfaces during transport and transhipment. Fine dust is characterised by high hydrophobicity; it is capable of remaining suspended for long periods and contaminating the air. An analysis of recent studies on the particle size distribution of dust in crushing and screening plant areas has shown a predominance of respirable dust fractions up to 10 μm. The study by Z. Liu *et al*. (2023) established that over 84% of the dust in the air of a crushing plant consists of particles up to 2.5 μm in size, which remain suspended for a long time and are characterised by high mobility. Research by A. Penchala *et al.* (2025) found that the ratio between dust fractions of 1 μm, 2.5 μm and 10 μm remains virtually unchanged even at a height of 30 m above the dust emission source, indicating their high resistance to settling and their ability to remain in the atmosphere of industrial facilities for extended periods.

The research findings presented in the work by V. Shapovalov (2019) indicated that airborne dust levels at workplaces in the crushing and screening plants of Kryvyi Rih generally exceed health standards. Furthermore, most of the dust in the air at these workplaces contains free SiO_2 in the form of quartz and has a particle size of up to 5 μm. It is precisely the fine dust fractions measuring up to 5 μm that pose the greatest risk to workers' health, as confirmed by the study by K. Vanka *et al*. (2022), as well as in the study by O. Chencheva *et al*. (2023) on the pathogenesis of occupational lung diseases. Silicon dioxide, also known as silica, is a chemical compound commonly found in quartz, the grains of which have sharp edges. As iron ore components are more difficult to grind than quartz, the relative content of silicon dioxide in airborne dust may be higher than in rock. Inhaling dust containing silicon dioxide is harmful to human health, as it can become trapped in the lungs, causing inflammation and scarring of the lung tissue. This condition is known as silicosis and can lead to permanent lung damage or even the death of the patient (Vanka *et al.*, 2022).

Dust particles larger than 50 μm are trapped in the nose, nasopharynx, trachea and large bronchi when inhaled. Although these particles do not reach the lungs, they cause mechanical irritation of the mucous membrane, leading to chronic rhinitis and laryngitis. According to the findings of G. Liu *et al.* (2026), this dust also contributes to secondary contamination of the work area through resuspension caused by air currents and the operation of equipment. Dust particles measuring 15-10 μm are trapped in the upper respiratory tract and small bronchi. It is this fraction that is responsible for the development of occupational bronchitis. Dust particles measuring up to 10 μm reach the alveoli of the lungs, although they are mainly trapped in the upper respiratory tract. Modern medicine, notably K. Vanka *et al.* (2022), classifies this fraction as "thoracic". It is critical because particles of this size are capable of absorbing toxic substances and microorganisms onto their surface, transporting them deeper into the respiratory system.

The greatest danger is posed by ultrafine dust particles measuring up to 2 μm (the respirable fraction), as they remain in the lungs for a prolonged period and damage lung tissue (Liu *et al.*, 2026). This is fully confirmed by the results of pathogenesis studies (Vanka *et al.*, 2022). Such dust is ingested by alveolar macrophages, triggering a cascade of inflammatory reactions, leading to fibrosis of the lung tissue (silicosis, anthracosis) and the potential entry of nanoparticles into the systemic circulation. Irritation of the upper respiratory tract in the early stages is accompanied by a tickling sensation in the throat, coughing and the expectoration of contaminated sputum. This is due to the body's defensive reflexes – sneezing, coughing and bronchial activity. Prolonged exposure to dust causes inflammation of the upper respiratory tract, the symptoms of which include dryness of the mucous membranes, reduced sputum production, a dry cough and hoarseness.

The greatest danger to human health arises when dust penetrates deep into the lungs, where it comes into contact with lung tissue, bronchioles and alveoli. When dust enters the lungs, its harmful components are absorbed in large quantities due to the extensive surface area of contact, causing irritation to the lungs and systemic toxicity. Dust that enters the lungs and accumulates over a long period of time causes the growth of connective tissue (fibrotic nodules) around each alveolus; this tissue is unable to react with oxygen in the air, oxygenate the blood or remove carbon dioxide during exhalation. Prolonged accumulation of dust contributes to the growth of hardened lung tissue, as a result of which part of the lungs loses the ability to perform its function – to absorb oxygen and release carbon dioxide. A lack of oxygen causes shortness of breath whilst walking or performing physical work, weakens the body's immune system and reduces work capacity, and contributes to the development of diseases of the heart and other organs. Such symptoms are characteristic of fibrogenic dust, which contains silicon dioxide, iron oxides and other substances (Chencheva *et al.,* 2023). Prolonged exposure to such dust is the main cause of occupational respiratory diseases among workers.

Aerodynamic mechanisms of dust emission during the loading of crushers

The amount of contaminated air entering production premises during the feeding of crushers depends primarily on the type of crushing equipment, as well as on the physical and mechanical properties of the raw material – for example, the material's hardness, moisture content, particle size distribution and other factors. During unloading, the bulk material draws air down to the bottom of the crusher's feed hopper, creating excess pressure. At the lowest points of the material's fall, as it strikes the surface with dynamic impact, there is intense dust emission and air pollution, which is carried by air currents to the workstations.

Furthermore, the process of the material's vertical fall is also accompanied by dust emission, which is carried into the workspace by transverse air currents. According to the findings of G. Liu *et al.* (2026), the air entrained during the handling of bulk materials is the primary factor in dust emission. The researchers demonstrate that during industrial processes, such as the feeding of crushers, the velocity of air flows at the boundary of the falling material creates turbulence that carries dust beyond the confines of the enclosure, and the volume of air entrained by the bulk material is directly proportional to the drop height. On the other hand, the operation of crushers is accompanied by the formation of airflows inside the crusher housing, which carry dust into the air at workstations. The mechanism by which updrafts are formed and the amount of dust generated are determined by the specific operating characteristics of the crushers. In their study, A. Saramak & Z. Naziemiec (2019) confirmed that the intensity of dust emission depends not only on the hardness of the ore but also on the aerodynamic characteristics of the crushers. In the study by I. Petrenko *et al.* (2024), researchers analysing dust sources at mining and processing plants concluded that cone and jaw crushers have different levels of dust emissions due to differences in the aerodynamics of their housings. During the operation of jaw crushers, compressed air is periodically expelled at a frequency equal to the number of jaw oscillations.

In this process, dust-laden air is carried by airflows from the crusher chamber to the feed opening and onwards to the work areas. The formation of upward flows within the cavity of a cone crusher is caused by the interaction of the working parts and the oscillation of the cone within the volume of air confined by the machine's housing. In this case, the velocity of the updrafts inside the crusher's feed hopper reaches 0.5 m/s, and 0.2 m/s during idle operation. During the loading of the cone crusher, the flow of rock mass is further crushed upon impact with the surface of the cone, and the resulting fine dust is carried by the upward air currents into the workshop air. In their study, K. Vanka *et al.* (2022) demonstrate that the most hazardous respirable dust (up to 5 μm) is released precisely at the moment of dynamic impact of the material against the surface. Figure 1 illustrates dust emission during the unloading of a dump truck into the feed hopper of a cone crusher.

Figure 1. *Dust generation during the unloading of a dump truck into the feed hopper of a cone crusher*
Source: *compiled by the authors*

The highest levels of dust emission are observed during the operation of a hammer crusher, in the housing of which an excess pressure of 20-30 N/m^2 builds up. During the operation of hammer crushers, the rotating rotor creates excess pressure inside the housing and directs airflows that carry dust from the feed opening into the working chamber. However, researchers A. Saramak & Z. Naziemiec (2019) concluded that a jaw crusher generates less fine dust per tonne of product compared to other machines, in particular a cone crusher, where constant friction creates a stable dust cloud.

An analysis of current methods and means of controlling dust emissions during the loading and operation of crushers allows to identify the most effective approaches to addressing this issue. The most effective way to localise dust emissions remains the installation of enclosures at crusher loading points, fitted with local extraction ducts for connection to extraction systems. According to NPAOP 0.00-1.82-18 (2018), fitting crusher loading points with extraction enclosures is a mandatory legal requirement. The geometric shape of the enclosure must be suited to the aerodynamics of the airflows for the relevant dust emission sources and have an optimal internal volume. If the internal volume of the enclosure is too large, it hinders the formation of the necessary directed airflows and requires the extraction of a greater volume of contaminated air. If the internal volume of the enclosure is too small, the airflows carry dust into the workspace, thereby reducing the efficiency of the extraction system. To direct the flow towards the extraction zone, the enclosure's outlet pipe, connected to the extraction system's air duct, must ensure uniform extraction of the entire volume of dust-laden air. At the points where the enclosure meets the process equipment, a tight seal must be ensured to prevent dust from being carried into the working area of the production premises. The design of the enclosure should be simple, convenient during operation and/or during repairs, and should not obstruct access to the working parts of the crushers. Consequently, enclosing the crusher feeding points is crucial for localising dust emissions and reducing dust concentrations at workstations.

An analysis of dust emission sources during crusher feeding indicates that the main cause of air pollution is not only the crushing process itself, but also the aerodynamics of the interaction between the material and the air. To neutralise dust emission sources, the extraction system must not only extract air but also compensate for the excess pressure created by the ejective effect. Modern science confirms that static pressure is a key factor in ensuring a uniform flow during extraction. Thus, the static pressure method is used to design an extraction duct with a slot. In their study, W. Nie *et al.* (2024) demonstrated that standard extraction systems create areas of uneven pressure. The study confirms that optimising the geometry of air ducts and equalising flow velocities reduces dust concentration by 84% by eliminating recirculation zones. In the study by Y. Song *et al.* (2022), which focuses on edge and slot extractors, the authors mathematically demonstrate that the system's energy efficiency (energy savings of up to 96%) is achieved precisely through the precise regulation of the suction opening width to compensate for the drop in static pressure along the length of the device.

The study by Y. Gao *et al.* (2024) examined in detail how a change in slot size radically alters the static pressure profile. The study confirms Equation (8), indicating that as the distance from the suction source increases, the aperture must be geometrically adjusted to maintain aerodynamic performance. An analysis of current methods for calculating aspiration systems allows the following conclusions to be drawn in favour of the proposed method. Studies by W. Nie *et al.* (2024) and Y. Song *et al.* (2022) confirmed formula (7) in the context that the static pressure P_x is not linear along the air duct due to friction losses λ and the "attachment" of new air masses. This makes the proposed calculation method, based on the momentum equation, significantly more accurate than simplified methods. All the analysed models show that, for a constant slot width, the suction velocity decreases geometrically with distance from the fan. Formula (8) for determining the variable width δ_x at an arbitrary cross-section x is the mathematical solution to this physical problem and an essential tool for overcoming pressure non-uniformity.

The transition from traditional systems with a constant cross-section to the proposed method for calculating the variable slot width makes it possible to overcome the main problem of aspiration at crusher feed points – aerodynamic non-uniformity. The achieved accuracy in velocity stabilisation is a compelling argument in favour of the energy efficiency of the developed system. Optimisation prevents air from being "drawn in" at points near the fan, which, according to the work of Y. Song *et al.* (2022), reduces the system's overall energy consumption by 15-20% whilst maintaining dust capture efficiency. Recent research in the field of industrial extraction and aerodynamics confirms that the static pressure method is the most appropriate for slotted air ducts for the following reasons.

Unlike empirical methods, the use of the momentum equation in projections onto the axis ensures mathematical accuracy and allows for the physical nature of the air flow to be taken into account when it is drawn in at an angle of 90° (where the velocity projection onto the axis is zero). Equation (7) takes into account the aerodynamic drag coefficient λ and the equivalent diameter d_0. The proposed method allows the calculation of parameters for specific air duct shapes, such as an isosceles triangle, which is a practical solution for preventing dust accumulation inside the air duct itself due to its sloping walls.

Justification and design of the extraction probe for the crusher feed hopper

The efficiency of dust extraction at crusher feed points depends entirely on the design of the enclosure, which may not always be airtight. Taking into account the structure of the airflows that carry dust into the air at workstations during the unloading of loose mineral raw materials makes it possible to propose a design for the crusher feed hopper enclosure that effectively localises dust emissions and ensures uniform extraction of contaminated air along the feed hopper.

The enclosure is designed in the form of an inverted trough, the sides of which are fitted with rubber strips. The enclosure is positioned above the crusher's feed hopper and can be moved across it, depending on which side the dump trucks are unloading from. The cover's mobility allows for effective localisation of dust emissions when the crusher is fed alternately from different sides of the feed hopper, thereby resolving the issue of "dead zones" in the extraction process. Figure 2 shows the design of the feed hopper enclosure for a cone crusher, whilst Figure 3 shows the layout of the crusher feed hopper enclosure (top view).

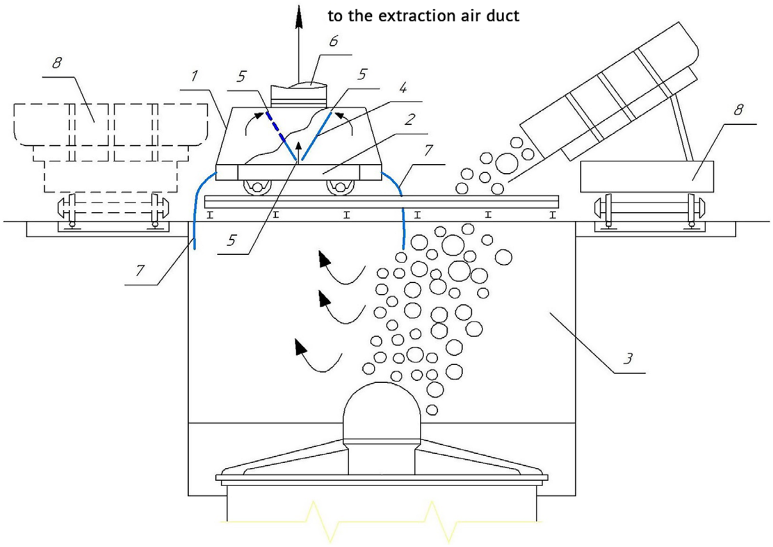

***Figure 2.** Enclosure of the feed hopper of a cone crusher*

***Notes:** 1 – enclosure body, 2 – frame, 3 – feed hopper of the cone crusher, 4 – V-shaped hood, 5 – longitudinal extraction slots, 6 – outlet connection, 7 – flexible material skirts, 8 – dump trucks*

***Source:** developed by the authors*

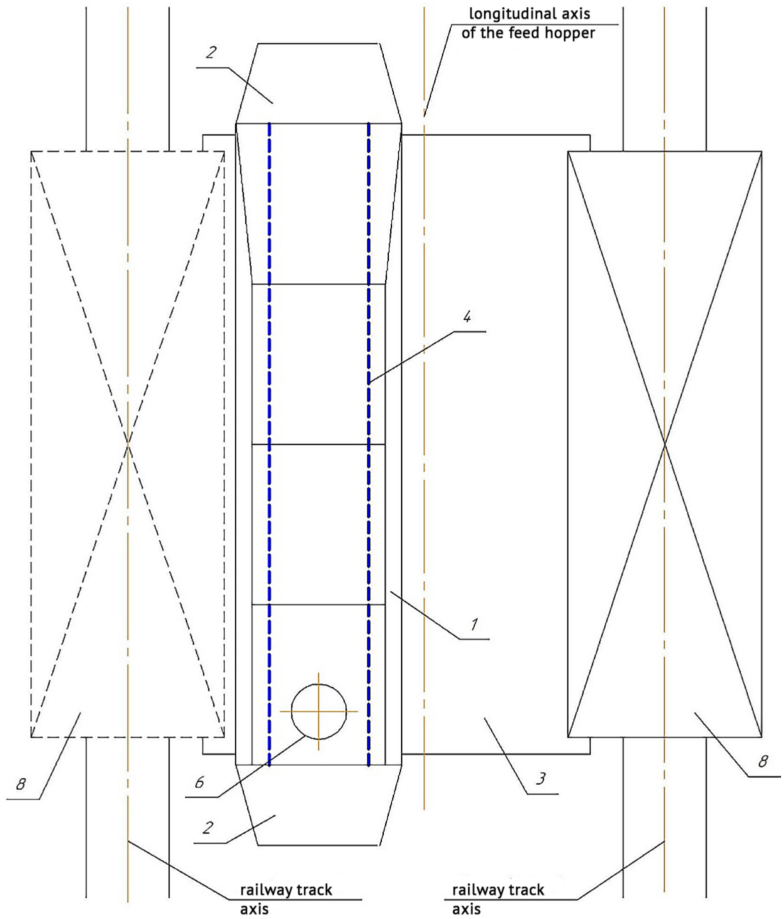

***Figure 3.** Layout of the feed hopper enclosure (top view)*

***Notes:** 1 – enclosure body, 2 – frame, 3 – feed hopper of the cone crusher, 4 – V-shaped hood, 6 – outlet connection, 8 – dump trucks*

***Source:** developed by the authors*

The enclosure of the feed hopper of the cone crusher consists of a body 1, which has a trapezoidal cross-section (Figure 2). The body 1 is mounted on a frame 2, which moves on wheels in a direction perpendicular to the longitudinal axis of the feed hopper 3 (Figure 3). Along both sides of the frame 2, skirts 7 made of an elastic material (used conveyor belt) are attached to prevent dust from being carried by air flows beyond the enclosure of the feed hopper. The entire enclosure structure is positioned above the feed hopper 3 between the railway tracks along which dump trucks 8 are delivered, preventing damage to the enclosure during material unloading. Thus, the enclosure covers part of the top of the cone crusher feed hopper, depending on which side the dump trucks are unloaded from. To stop the enclosure frame at the required position, KU-121 limit switches (Volianiuk & Mishchuk, 2020) or switches of another design (Dwyer Omega, n.d.) are installed. Limit switches are safety devices that automatically stop the enclosure when it reaches its extreme positions.

A V-shaped hood 4 with longitudinal suction slots 5 at the mouth and in the upper parts of the side walls is located in the cavity of the enclosure of housing 1 (Fig. 2). The V-shaped hood ensures the extraction of contaminated air, which is contained by the enclosure during unloading. As extraction takes place on one side of the enclosure (Fig. 3), the intake slots 5 have a variable width to ensure uniform air extraction along the entire length of the V-shaped hood 4, with the narrower width of the slots located on the side of the outlet pipe 6, which is connected to the air duct of the extraction system. The maximum slot width δ_0 will be on the opposite, closed end of the V-shaped hood 4 relative to the outlet pipe 6, where $x = 0$. Thus, as one approaches the inlet pipe 6, that is, as x increases to $x = l$, the slit width will decrease. The slit width at cross-section x is calculated using formula (8). The V-shaped hood 4 with longitudinal suction slots 5 acts as a suction air duct with a cross-section in the form of an isosceles triangle with base a, side b and height h, reduced to the base.

The dust removal device for receiving hoppers operates as follows. Before unloading the dump car 8, the housing 1 on the frame 2 is moved to the opposite side of the receiving hopper 3. The material unloaded from the dump car 8 draws air into the receiving hopper 3, creating excess pressure in its lower part, which causes dust to be carried into the air at the workstations. The upward flow of dust-laden air enters the cavity of housing 1 and, through the suction slots 5 of the V-shaped hood 4 and the outlet pipe 6, enters the aspiration system pipework. During the unloading of material from the dump truck 8, the aprons 7 prevent dust-contaminated air from escaping beyond the boundaries of the receiving hopper enclosure. Thus, the proposed enclosure design localises dust emissions during the unloading of bulk material and improves the efficiency of extraction at the crusher feeding points by ensuring uniform extraction of contaminated air along the receiving hopper.

It would be impossible to move the enclosure over the crusher's receiving hopper if the extraction duct were rigidly attached to housing 1 without the possibility of rotation. To solve this problem, a hinged connection must be provided between housing 1, outlet pipe 6 and the extraction duct. Figure 4 shows a diagram of the hinged connection between the extraction duct and the housing, whilst Figure 5 shows a diagram of the hinged connection between the extraction duct and the housing (top view).

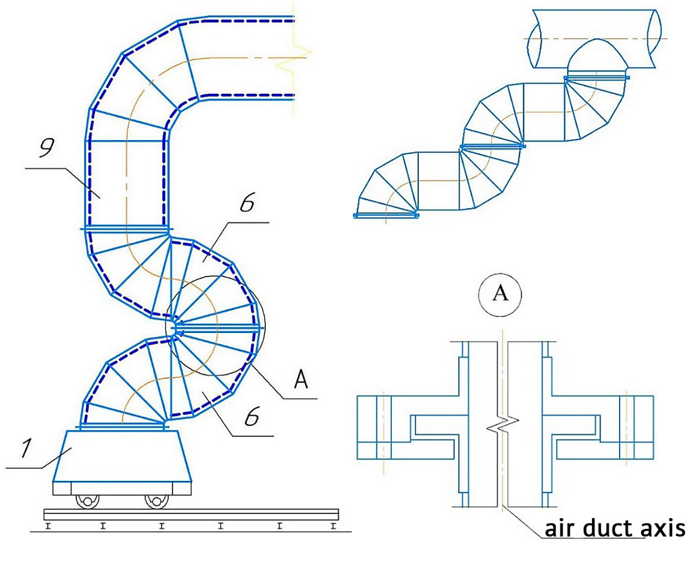

Figure 4. *Schematic of the hinged connection between the extraction air duct and the enclosure body*
Notes: *1 – enclosure body, 6 – outlet connection, 9 – extraction air duct*
Source: *developed by the authors*

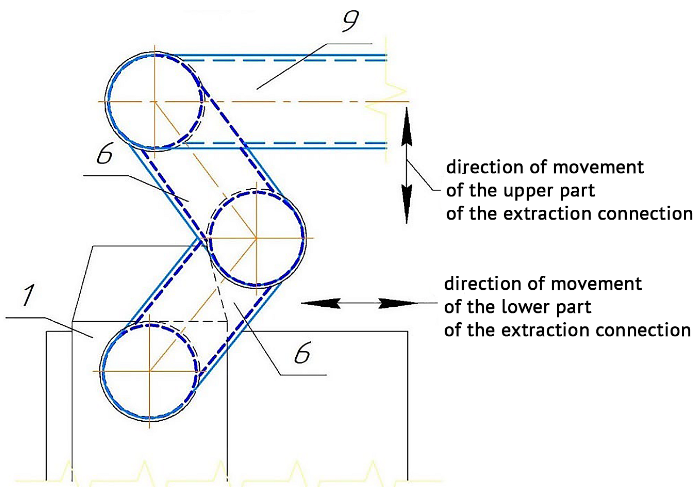

Figure 5. *Schematic of the hinged connection between the extraction air duct and the enclosure body (top view)*
Notes: *1 – enclosure body, 6 – outlet connection, 9 – extraction air duct*
Source: *developed by the authors*

To allow rotation, the outlet connection 6 consists of at least two parts, which are connected by hinges to each other, to the enclosure 1 and to the extraction air duct 9 (Figures 4 and 5), thereby eliminating air ingress from outside in extraction systems of different capacities. The three hinged connections allow the position of the outlet connection 6 to be changed simultaneously in two directions when the enclosure 1 is moved. As the enclosure 1 moves, the outlet connection 6 changes its position simultaneously in two directions due to the three hinged connections (Figure 5). At the same time, the position of the extraction air duct 9 remains unchanged. When the enclosure 1 is moved in the opposite direction, the kinematics of the outlet connection 6 occur in the reverse direction. Thus, the three hinged connections of the outlet connection prevent air ingress during operation of the extraction system and allow the enclosure to be moved over the crusher feed hopper, thereby eliminating the problem of "dead zones" in the extraction system.

A comparison of the proposed design with contemporary international developments shows that it is consistent with current trends in the improvement of local dust extraction systems. For example, a study by B. Tian *et al.* (2023) established that the efficiency of slotted extractors is largely determined by the relationship between the geometric parameters of the slot and the uniformity of extraction velocity distribution along its length. The proposed design also utilises longitudinal extraction slots; however, unlike the study cited, it features a variable slot width along the V-shaped hood, which ensures a more uniform air flow and more even extraction of contaminated air along the entire length of the intake hopper. In the study by T. Wu *et al.* (2023), a dust-suppression enclosure is proposed for an open-cast quarry crushing plant, the effectiveness of which is achieved by creating a closed circulation flow inside the enclosure. A common feature with the proposed design is the use of the principle of localising dust directly in the area where it is emitted. At the same time, the proposed design is distinguished by the presence of a mobile enclosure capable of moving over the feed hopper depending on the unloading point of the dump trucks, which eliminates "dead zones" in the suction process and improves the efficiency of the extraction system.

Experimental studies by Q. Feng *et al.* (2025) demonstrated that the efficiency of partially enclosed extraction systems during the transfer of bulk materials depends significantly on the area, location and extraction velocity through the ventilation openings. In contrast to these designs, the proposed enclosure utilises a V-shaped hood with a system of longitudinal slits of variable width, ensuring an even distribution of air flow throughout the entire dust emission zone. Furthermore, the use of flexible aprons and a hinged air duct connection makes it possible to simultaneously improve the enclosure's airtightness and maintain its mobility. Thus, the main advantages of the proposed design compared with known modern solutions are the enclosure's mobility, the elimination of "dead zones" in the extraction process, the uniform extraction of contaminated air along the feed hopper due to the variable-width slits, and the ability to operate effectively during the sequential unloading of material from different sides of the crusher.

Conclusions

The processes of feeding a crusher via conveyors, dump trucks or tippers into an open hopper or receiving funnel generate a huge amount of dust, which pollutes the air in the workplace. Mineral raw materials and bulk materials unloaded into the crusher contain fine dust capable of remaining suspended in the air for long periods and polluting the air. At the same time, airborne dust levels at workplaces exceed health standards, and most of the dust in the air contains free SiO_2 in the form of quartz and has a particle size of up to 5 μm. It has been established that fine dust (particles up to 5 μm) poses the greatest risk to workers' health, as it is capable of penetrating deep into the lungs and causing occupational diseases. Inhaling dust containing silicon dioxide is harmful to human health and can lead to permanent lung damage and silicosis.

The amount of contaminated air entering production premises during the loading of crushers depends mainly on the physical and mechanical properties of the raw materials and the type of crushing machinery, the operation of which is accompanied by the formation of upward air currents. The most effective solution for localising dust emissions and reducing dust concentrations at workstations is a combination of various methods for controlling dust emissions during the loading of crushers, provided that the crusher loading areas are equipped with covers fitted with local extractor ducts for connection to extraction systems. A key factor in improving the efficiency of extraction at crusher loading points is ensuring uniform air intake along the entire length of the loading hopper. The method proposed in this sduty for calculating air ducts with a longitudinal slot of variable width, based on the static pressure method, allows the suction velocity profile to be levelled out. This minimises dust escape zones and prevents energy wastage due to excessive ventilation, ensuring high efficiency of the extraction system regardless of the distance of the section from the fan.

Taking into account the structure of the air flows that carry dust into the air at workstations during crusher loading, a design is proposed for a cover over the crusher's feed hopper, which effectively localises dust emissions and improves the efficiency of dust extraction at the crusher loading points by ensuring uniform extraction of contaminated air along the feed hopper. The cover is positioned above the crusher's feed hopper and can be moved over it, depending on which side the dump truck is to be unloaded from. To enable the enclosure to be moved over the crusher feed hopper, its outlet connection consists of at least two parts and has three hinged connections, which prevent air ingress during operation of the extraction system and allow the enclosure to be moved over the crusher feed hopper, thereby solving the problem of "dead zones" in the extraction system. In the future, it is planned to extend the scope of research into the dynamics of air flows inside the hood, taking into account the turbulence that arises when large volumes of material fall. Investigating the influence of the internal volume and shape of the hood housing on the aerodynamics of updrafts for various types of crushers, to ensure maximum extraction efficiency. Identifying the optimal parameters for for combining extraction with spray irrigation or foam-generating systems for hydrophobic dust, in order to avoid excessive wetting and a reduction in ventilation efficiency.

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Conflict of Interest

None.

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Підвищення ефективності аспірації місць завантаження дробарок

Анотація. Процеси завантаження дробарок на підприємствах гірничодобувної та переробної промисловості супроводжуються інтенсивним виділенням дрібнодисперсного пилу, що погіршує умови праці, підвищує ризик розвитку професійних захворювань органів дихання та спричиняє додатковий абразивний знос технологічного обладнання. Особливої актуальності проблема набуває в умовах обмеженого використання водних методів пилопригнічення через утворення шламу, значні витрати води та складність їх застосування в холодний період року. Метою даної роботи було розроблення конструкції укриття приймальної воронки дробарки та наукове обґрунтування методу розрахунку параметрів аспірації для забезпечення рівномірного відсмоктування забрудненого повітря вздовж усієї зони завантаження матеріалу. У роботі було застосовано математичне моделювання динаміки повітряних потоків на основі методу статичних тисків і рівняння кількості руху. Об'єктом моделювання був повітряний потік у повздовжньому всмоктувальному повітропроводі зі щілиною змінної ширини. Установлено, що на робочих місцях дробильно-сортувальних фабрик переважають респірабельні фракції пилу з розмірами часток до 10 мкм, які становлять найбільшу небезпеку для здоров'я працівників. Показано, що однією з причин виносу пилу з-під укриття є нерівномірність швидкостей всмоктування вздовж повітропроводу. Розроблено математичну модель для визначення змінної ширини повздовжньої всмоктувальної щілини залежно від відстані до витяжного вузла. Встановлено, що для забезпечення стабільної швидкості всмоктування ширина щілини повинна поступово зменшуватися від заглушеного кінця повітропроводу до місця підключення витяжної мережі. Отримано аналітичні залежності для розрахунку геометричних параметрів повітропроводів трикутного перерізу, що запобігають осіданню пилу в середині системи. Запропоновано конструкцію мобільного аспіраційного укриття приймальної воронки дробарки з повздовжніми щілинами змінної ширини та шарнірним приєднанням до витяжного повітропроводу. Практичне значення отриманих результатів полягає у локалізації виділення пилу і зниженні концентрації пилу в повітрі робочої зони за рахунок забезпечення рівномірного відсмоктування забрудненого повітря по всій довжині приймальної воронки дробарки

Ключові слова: пиловий аерозоль; респірабельна фракція; локалізація викидів; щілинний відсмоктувач; статичний тиск; повітряний потік; укриття

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