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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:

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

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:

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

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):

$$\sigma_{eq} \geq R_s \cdot k_{st}, \quad (3)$$

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

$$\sigma_{eq} = A + B, \text{MPa}, \quad (4)$$

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

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

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

$$f_r = \frac{R_s}{R_{st}}, \quad (7)$$

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.

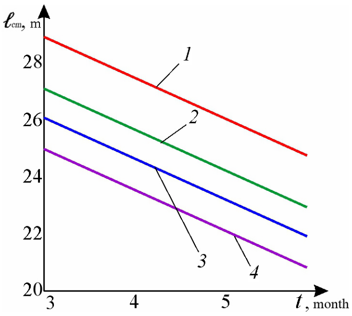

Figure 1. *The relationship between stope length along the strike ℓ_{cm} and block mining time t*

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).

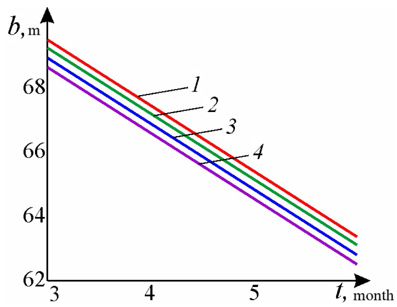

Figure 2. *The relationship between stope length along the dip b and block mining time t*

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.

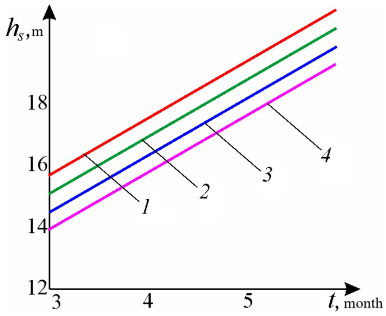

Figure 3. *The relationship between inter-level crown thickness h_s and block mining time t*

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).

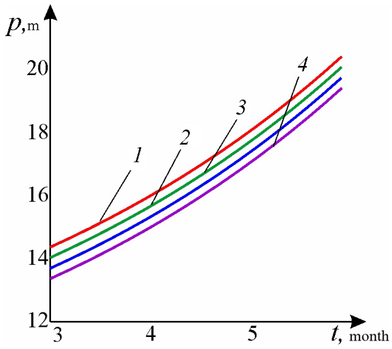

Figure 4. *The relationship between inter-room pillar width p and block mining time t*

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.

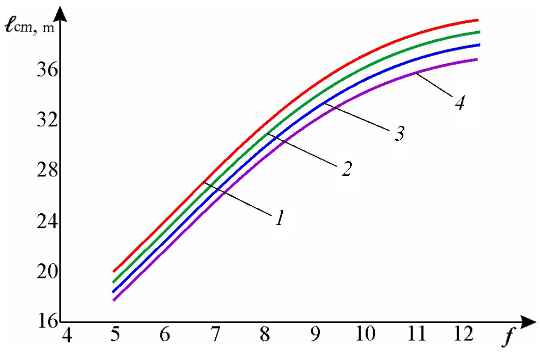

Figure 5. *The relationship between the room length along the strike ℓ_{cm} and the hanging wall rock strength f*
Notes: *1, 2, 3, 4 – mining depths of 1,000, 1,100, 1,200, 1,300 m, respectively*
Source: *the authors' own development*

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.

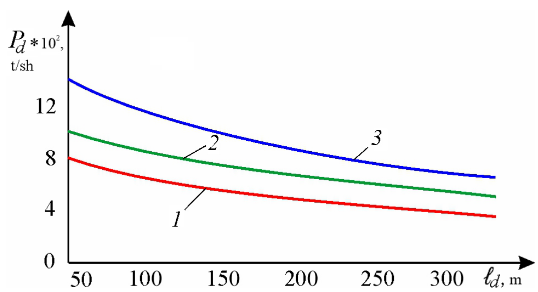

Figure 5. *The productivity of self-propelled machines P_d as a function of haulage distance ℓ_d*
Notes: *1, 2, 3 -XUL307, ST-3,5; TORO-400D, respectively*
Source: *based on the authors' own calculations*

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.

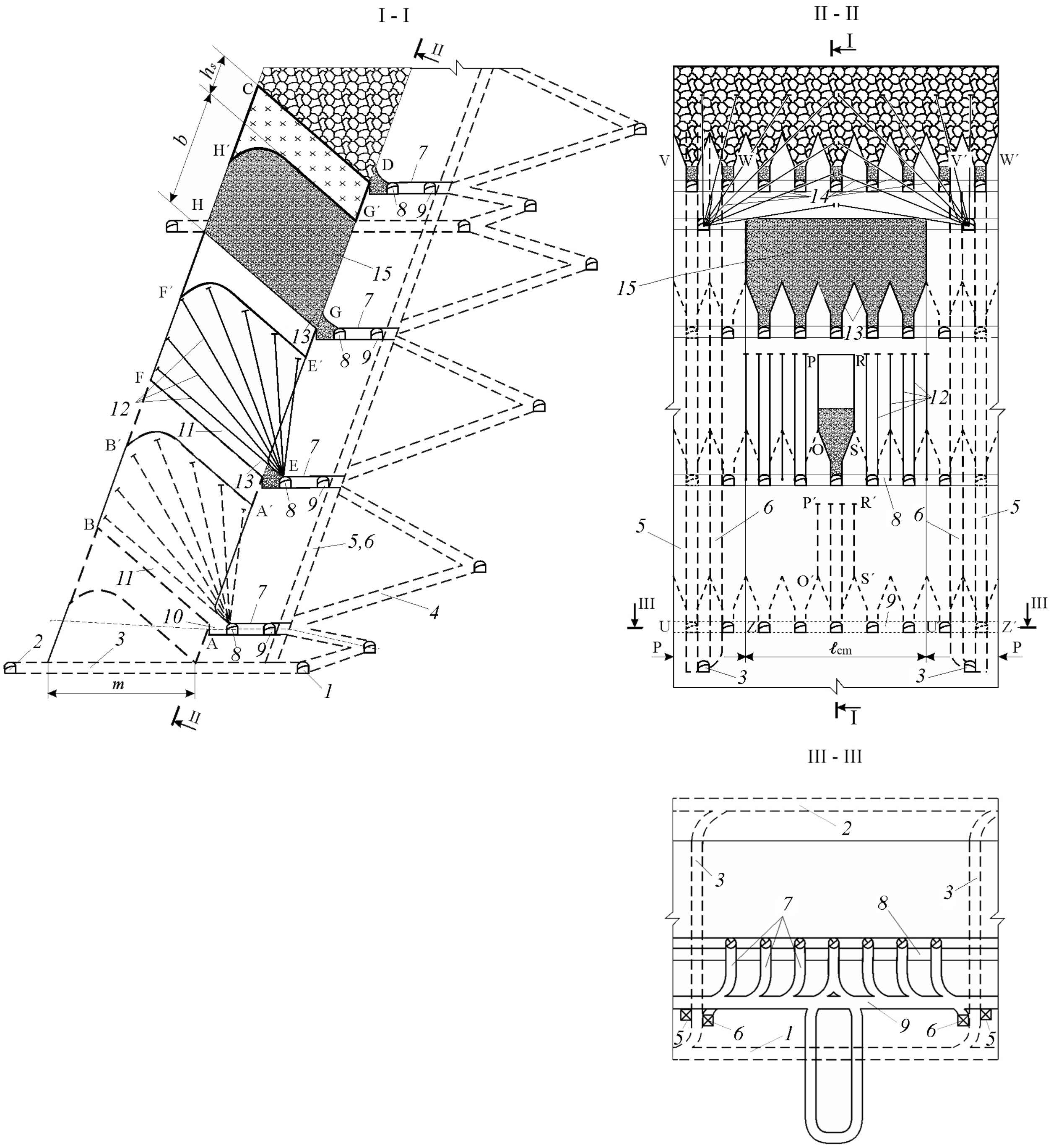

***Figure 7.** Sublevel room-and-pillar system for mining steep iron ore deposits*

***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 flowsheet 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 ціликів 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