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Mykola Stupnik*
Doctor of Technical Sciences, Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0003-3318-3889

Vsevolod Kalinichenko
Doctor of Technical Sciences, Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0002-1938-2286

Mykhailo Fedko
PhD in Technical Sciences, Associate Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0002-8437-3175

Serhii Pysmennyi
PhD in Technical Sciences, Associate Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0001-5384-6972

Mykhailo Hryshchenko
Senior Lecturer
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0002-9365-1886

Development of highly efficient technologies for extracting rich iron ores at deep levels of Kryvbas mines

Abstract. About half of the rich iron ore mined in the Kryvbas mines is extracted applying various types of sublevel caving systems. At the same time, ore haulage in the mining panels is carried out exclusively by scraper equipment, which does not meet modern requirements in terms of miners' working conditions, productivity and safety. The aim of the work was to develop more efficient flowsheets for the extraction of rich iron ores applying the sublevel caving system. This was achieved primarily through the employment of self-propelled underground loaders, haulers and dumpers (LHDs) and other technical solutions for ore. The new flowsheets for the development of iron ore deposits applying the sublevel caving system based on the use of the mentioned self-propelled machinery for haulage are proposed. This is achieved by using, in addition to the main draw level,

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*Corresponding author

where only this self-propelled machinery operates, an additional draw level with the use of scraper equipment, for which the drill drift is reused. This ensures more intensive mining of panels, thereby reducing the cost of maintaining workings and improving ore extraction rates. Another option, designed for mining deposits with a thickness of up to 30-35 m, involves application of inclined compensation rooms, which makes it possible to create rooms of sufficient volume even in low-strength ores, as well as combined ore haulage by self-propelled LHDs and scraper equipment. To increase the efficiency of the self-propelled LHDs, productivity of which is significantly higher than that of scraper equipment, it is possible to employ one self-propelled machine for the simultaneous haulage of ore from two adjacent panels. Thus, the main advantages of the proposed mining system options are an increase in the intensity of panel mining, a significant reduction in the loss of ore on the footwall of the deposit, and the possibility of employing self-propelled machinery in the conditions of Kryvyi Rih iron ore basin mines

Keywords: iron ore raw materials; underground mining; mining technology; sublevel caving; ore haulage; self-propelled equipment

Introduction

Naturally rich iron ores in Kryvbas – which was, is, and will remain Ukraine's primary iron ore base – are extracted exclusively underground (Bazaluk *et al.*, 2024). Mining is conducted at depths of 1,100-1,400 m. To extract these ores, a variety of systems are employed, including sublevel-room and sublevel caving systems. The current proportion of these systems is approximately equal, but as mining depths increase and conditions deteriorate, the share of the sublevel caving system is expected to gradually increase.

The optimisation of sublevel caving technology for mining deposits is the focus of numerous publications. These works provide a detailed history of the system's evolution, present various operational variants, and outline paths for their improvement. It should be noted that while existing technologies offer a number of benefits, including simple design and limited development work, they do not provide the use of imported self-propelled loaders, haulers and dumpers (LHDs). O. Bazaluk *et al.* (2022) proposed a block mining technology that employs high-performance self-propelled equipment. This method eliminates the need for drawpoints, drawbells, and draw niches, which are rather dangerous and labour-intensive to create. Conversely, M. Stupnik *et al.* (2021) observed that the use of such equipment necessitates larger-cross-section workings. The stability of these workings is expected to deteriorate as mining depths increase, and their maintenance will be associated with a rise in both labour and material costs. Based on an analysis of development trends and existing problems at Kryvbas mining enterprises, M. Stupnik *et al.* (2023) concluded that traditional means of ore haulage from stopes using scraper equipment are currently inefficient. Nevertheless, through technical re-equipment, the implementation of self-propelled LHDs would allow for an increase in ore extraction indicators. This can be achieved by the simplification of mining panel bottom designs, a reduction in the volume of preparatory-development work, and the mechanisation of the most labour-intensive operations.

Addressing the issue of mitigating broken ore losses on the footwalls of deposits during sublevel caving, I. Lutsenko *et al.* (2017) proposed replacing the broken ore that enters the "dead" zone on the footwall with waste rock. This is achieved by drilling and caving the waste rock during bulk blasting. A separate study by A. Kosenko *et al.* (2024) examined different bottom designs for ore extraction and haulage employing self-propelled LHDs. These designs can be trench-, drawbell-, pocket-like, and integrated haulage and transportation workings. In their research, S. Pysmennyi *et al.* (2020) demonstrated that the application of a trench-like bottom is the most suitable method for the complex geomechanical conditions encountered in the Kryvbas mines. The primary justification for this is its enhanced stability and the reduced costs required for its creation. A. Mazhitov *et al.* (2020) and M. Stupnik *et a*l. (2023) conducted comprehensive research using mathematical modeling to compare the stability of various compensation room shapes. Based on these studies, the authors concluded that the compensation rooms of the vaulted (arched) and parabolic shapes offer the best stability. A critical review of scientific literature enabled an evaluation of existing sublevel caving system variants to develop solutions for their application in the challenging mining-geological conditions of the Kryvbas mines.

An analysis of the literature indicated that the implementation of classical mining systems employing self-propelled equipment is not viable under the conditions prevalent in Kryvbas. Nevertheless, given the complex mining and geological conditions of the Kryvbas deposits (i.e. low ore strength and stability, as well as inconsistent thickness and dip angles of ore bodies), it is advisable to apply specific concepts previously proposed by researchers. A significant limitation of these earlier studies, however, is that their authors failed to consider the significant depth of the underground mining operations. The depth of mining is a crucial factor in the mining of ore deposits, as it substantially modifies the stress field around underground workings. This not only complicates operations but also imposes specific constraints, particularly on the cross-sectional area of the workings. These constraints, in turn, directly dictate the type and size of the self-propelled equipment that can be used and the service life over which the workings can be maintained without incurring significant costs.

Given rather challenging conditions associated with extracting these ores – resulting primarily from the inadequate strength and stability of the ore and host rock, as well as the significant manifestation of rock pressure – a common constraint in these systems is the exclusive use of an inefficient means for ore drawing and haulage (i.e. scraper equipment). This equipment fails to provide sufficient productivity or safe working conditions for miners. A prominent issue at these depths is the heightened stress-strain state of the rock massif, which demands a deliberate approach to the selection of compensation room shapes. The chosen shape is crucial, as it is a major determinant of both operational safety and overall ore extraction indicators. Consequently, the improvement of systems employing sublevel bulk caving for rich iron ore mining at depths exceeding 1,200 m represents a highly relevant research problem that this work seeks to resolve.

Materials and Methods

The research employed a comprehensive approach, combining a literature review, a graphical-analytical method, and mathematical modelling. The graphical-analytical method served to calculate the primary parameters of underground workings considering the stress-strain state of the rock massif. This approach also facilitated the determination of their optimal spatial arrangement within the mining block, the feasibility of their construction, and their potential negative influence on adjacent mining panels and workings. The primary results of these calculations were subsequently presented in research papers supported by the Ministry of Education and Science of Ukraine. For the analytical component of the research, the authors employed the finite element method. This method enabled them to ascertain the normal, tangential, and equivalent stresses around the workings as a function of the deposit's mining-geological conditions and the cross-sectional area of the underground working.

To study the stress-strain state, the equivalent stress coefficient was employed. It allowed the arbitrary three-dimensional stress state of a rock massif area to be represented as a single, positive equivalent stress value, as noted in the works of B.M. Andreev *et al.* (2015), M.R.S. Seyed *et al.* (2025), and A.R. Abdiev *et al.* (2025). Additionally, this approach enabled the calculation and determination of stress in a heterogeneous rock massif under complex mining-geological conditions, consistent with the research of S. Pysmennyi *et al.* (2018). By applying the generalised Hooke's law, equivalent stresses were determined based on the physical and mechanical properties of the rocks and the depth of development using the formula (Tayebi *et al.*, 2019):

$$\sigma = \sqrt{\frac{(\sigma_z-\sigma_x)^2+\left(\sigma_x-\sigma_y\right)^2+\left(\sigma_y-\sigma_z\right)^2}{2}}, \text{ MPa} \quad (1)$$

where σ – the equivalent stresses that occur in the rock massif around the working, MPa; σ_z – the principal vertical stresses, MPa; σ_x, σ_y – the principal horizontal stresses, MPa.

Equivalent strains of the rock massif around the working were determined by the expression:

$$\varepsilon = \frac{1}{1+\mu}\sqrt{\frac{(\varepsilon_z-\varepsilon_x)^2+\left(\varepsilon_x-\varepsilon_y\right)^2+\left(\varepsilon_y-\varepsilon_z\right)^2}{2}}, \quad (2)$$

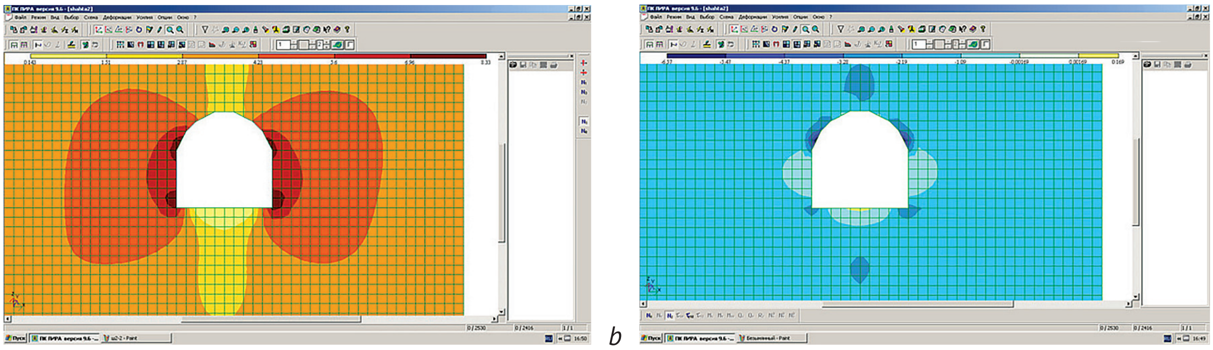
where ε – the equivalent strains that occur in the rock massif around the working; μ – the Poisson's ratio; ε_z – the vertical linear strains; ε_x, ε_y – the horizontal linear strains along and across the strike of the deposit, respectively.

The following input parameters were adopted to study the principal and equivalent stresses: model dimensions – 25×25 m; grid size – 0.25×0.25 m; nodal connection type – triangular; nodal load: vertical – 18,000 Pa, horizontal – 8,000 Pa, Poisson's ratio – 0.22; modulus of elasticity – 2×10^3 Pa; volume weight of rocks – 34,000 N; arched working width – 3.5 m.

Mathematical modeling was used to solve the problem of rock massif stability around the underground working, applying the theory of elasticity for a body in equilibrium under given external forces. At each point, a component of the stress tensor was calculated to simultaneously satisfy equilibrium within the body and on the contour of the working. The shear stress tensor, relative to the equivalent stress, is described by the following matrix:

$$D = \begin{vmatrix} \sigma_x-\sigma & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y-\sigma & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z-\sigma \end{vmatrix}, \quad (3)$$

where D – the stress tensor at the point under study; σ_i – the stresses of the internal forces arising in the massif, N/m^2; τ_i – the tangential stresses arising in the massif, N/m^2. The stress tensor thus describes the strain state at a given point in a solid body. When the equilibrium of the stress tensor is disrupted, linear and angular strains occur in the rock massif on the contour of the working. The results of the calculations are shown in Figure 1.



a b

Figure 1. *Stress distribution around the underground working with a cross-sectional area of 10 m^2 at a depth of 1,350 m*
Notes: *a – equivalent; b – vertical*
Source: *developed by the authors*

The conducted research established the optimal parameters and rational placement of underground workings, confirming their adherence to the primary requirements for mining rich iron ore deposits. The crucial requirement considered was the safety of the miners. Furthermore, the completed studies on parameters of workings integrated the risks of technological seismicity, a factor which, as recommended by A. Matayev *et al.* (2024), warrants careful consideration. Following the findings of A. Salkynov *et al.* (2023), strain processes within the rock massif were also taken into account, as they can compromise the stability of workings in weak ores, especially under conditions of high rock pressure at deep levels. The model was constructed by incorporating the stress and strain relationships for fractured rocks, as proposed by Chong *et al.* (2021). This involved adapting the model's parameters to reflect changes in the actual stress-strain state of the workings, thereby enhancing the reliability of the calculation results for the complex structure of the ore massif. In the design of stoping flowsheets, particular emphasis was placed on maximising ore extraction indicators and increasing labour productivity. The unique aspect of the research presented here is that individual technological processes were examined within a comprehensive framework using the graphical-analytical method. Consequently, this allowed for the development of improved sublevel caving system variants, which employ self-propelled equipment and are tailored to the specific conditions of rich iron ore extraction in the Kryvbas mines.

Results

Experience of leading mining companies that extract minerals underground shows that improving their extraction technology is practically impossible without the employment of modern equipment, particularly self-propelled LHDs, the use of which at the Kryvbas mines, as already noted, is hindered by the rather complex geological and technical conditions of ore deposit mining. Taking into account the specific application of this technology in both leading global mining companies and the Kryvbas mines, and building on the results of prior research, the authors of this work developed two new variants of the sublevel caving system. These variants, employing self-propelled LHDs for ore extraction and haulage, are designed to extend their applicability in challenging conditions when working with iron ore deposits of different thicknesses. Furthermore, variations in the elemental composition of the rocks were incorporated to improve the accuracy of ore body boundaries, as recommended by D. Shihov *et al.* (2024). A specific variant of the sublevel caving system developed in this work, intended for mining thick ore deposits, is presented in Figure 2.

A distinguishing feature of this system is the use of parabolic or vaulted compensation rooms within the mining panels, which are oriented with their long side across the strike of the deposit. This design enhances the stability of the rooms. To substantially mitigate broken ore losses on the footwall, the system also incorporates an additional draw level with scraper haulage, which supplements the main draw level that operates exclusively with self-propelled LHDs. To minimise the volume of development work, this additional level is proposed to be a repurposed drill drift that was previously driven through the footwall rocks. Based on this technology, the deposit is developed in mining blocks 60 m long along the strike. These blocks are vertically divided into two sublevels of approximately equal height within a single level (75-80 m). Block preparation involves the following: from a footwall haulage drift *1*, access crosscuts *2* are driven at 60-meter intervals; from these crosscuts, block ventilation-and-manway raises *3* are created to connect to the upper ventilation level; an inclined runaway *4* is driven in the footwall rock to provide access for self-propelled equipment to the intermediate sublevels (one runaway per mine wing).

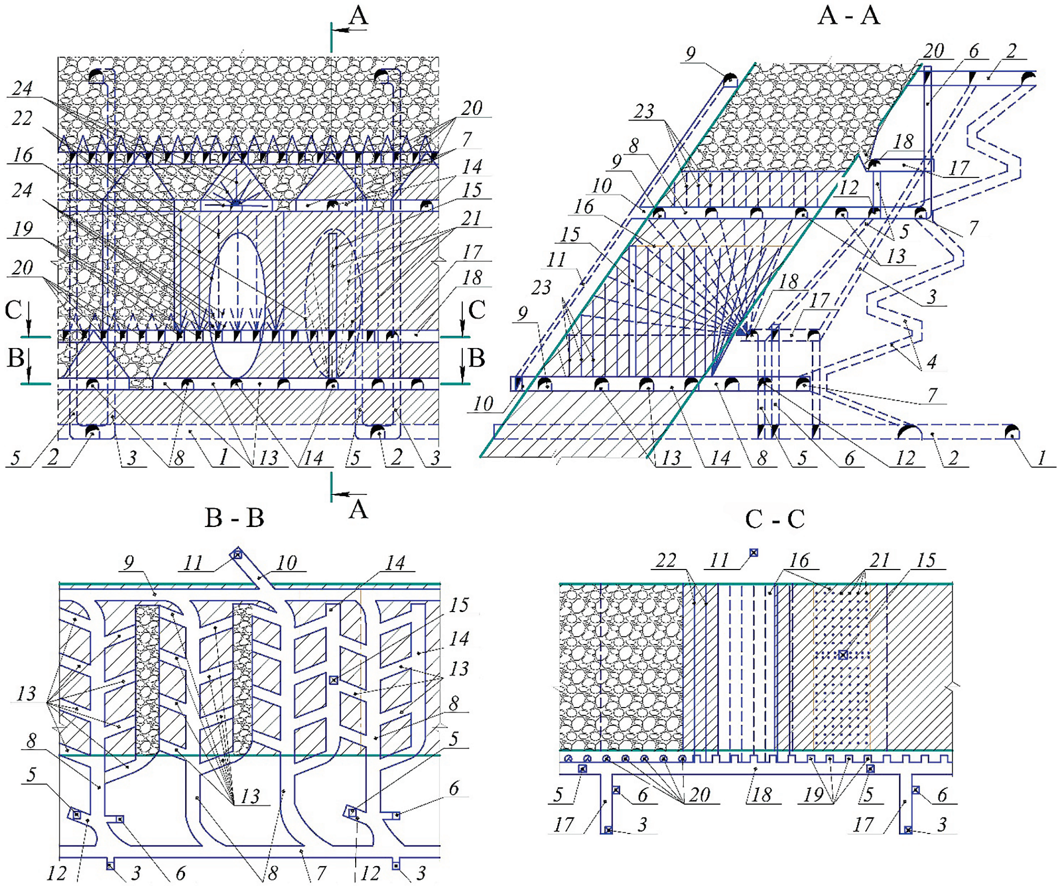


Figure 2. *The developed variant of the sublevel caving system for mining thick steep iron ore deposits with combined ore haulage by self-propelled LHDs and scraper equipment*
Source: *developed by the authors*

Development work begins with the creation of orepasses *5* and service raises *6* to facilitate the driving of other workings and support activities on the intermediate sublevels. At the ore drawing and haulage level, where self-propelled LHDs will be used, sublevel haulage drifts *7* are driven in the footwall rock 15-20 m from the ore body's contact. From these sublevel haulage drifts drifts, haulage crosscuts *8* are driven every 20 m. In the hanging wall, these crosscuts are connected to each other by a ventilation drift *9*, which is then connected via a ventilation crosscut *10* to a ventilation raise *11*. Depending on the mine's ventilation scheme, this raise can connect to either the upper ventilation level or the sublevel dirty-air collecting drift.

From the haulage crosscuts *8* located above the access crosscut *2*, an unloading niche *12* is created and connected to an orepass *5*. Starting 8-10 m from the ore body contact, diagonal loading workings *13* are developed from these haulage crosscuts *8* at 10 m intervals in a staggered configuration along both directions. From the first such crosscut, located in the footwall rock, cut crosscuts *14* are driven through the panel centers. Subsequently, a cut raise *15* is developed upwards from the central part of these cut croscuts opposite a loading working to form a compensation room *16*. Service crosscuts *17* are 10 m above the main draw and haulage levels in the footwall rock. These crosscuts are connected to the block ventilation-and-manway, service and orepass raises (*3*, *6*, *5*, respectively). Drill drifts *18* are also created and will later be used as scraper drifts. From the drill drifts, drill niches *19* are driven towards the ore body and will subsequently be used as drawpoints

20. To create a compensation room, which is given a parabolic or vaulted (arched) shape for greater stability, rings of boreholes *21* are drilled from a cut crosscut *14*. For breaking the main ore reserve in the panel, rings of long holes *22* are drilled in the panel from the drill niches. Finally, to cave the pillars above the haulage crosscuts, borehole rings *23* are drilled from these crosscuts.

Ore reserves within each sublevel are mined using 20-meter-wide panels. The panels are arranged so that the cut crosscuts on the lower sublevel are driven directly under the haulage crosscuts of the upper sublevel. These haulage crosscuts are developed within temporary pillars, which prevents waste rock from breaking into the compensation rooms. Stoping begins with the creation of a compensation room in each panel. To achieve this, the cut raise is first widened to the full width of the compensation room's contour. Then, rings of long holes *21*, which are drilled from the cut crosscut *14*, are blasted in a series of blasts into this widened cut raise *15*. After each blast, the broken ore is drawn from the loading workings and hauled to the orepass by a self-propelled LHD. In parallel with the formation of the compensation room, the main ore reserve is drilled using rings of long holes *22* from the drill niches of the drill drift *18*. From these same drill niches *19*, blast holes *24* are also drilled to develop the drawbells. The drilling of the main ore reserve and the creation of the compensation room should be completed simultaneously. This ensures the shortest possible duration of the compensation room existence. Bulk caving of the main ore reserve is achieved through multi-row millisecond-delay blasting of long hole rings *22*. The holes are undercharged by 3-5 m from their collar to ensure the preservation of the drill drift. During the bulk blast, the blast holes *24* are also detonated. This develops the drawbells in the drill niches, which will later be used as drawpoints. As previously mentioned, the drill drift *18* will subsequently be used as a scraper drift (the "catching" level) to reduce ore losses on the footwall of the ore body. The drawing and haulage of the broken ore from the loading workings *13* to the orepass *5* are performed by a self-propelled LHD. To intensify ore drawing from the panel and further reduce ore losses on the footwall, ore drawing is also performed simultaneously on the "catching" level, and the ore is hauled to the orepass by a scraper. To mine iron ore deposits up to 30-35 m thick, the authors developed a variant of the sublevel caving system with combined ore haulage by self-propelled LHDs and scraper equipment. This system is illustrated in Figure 3.

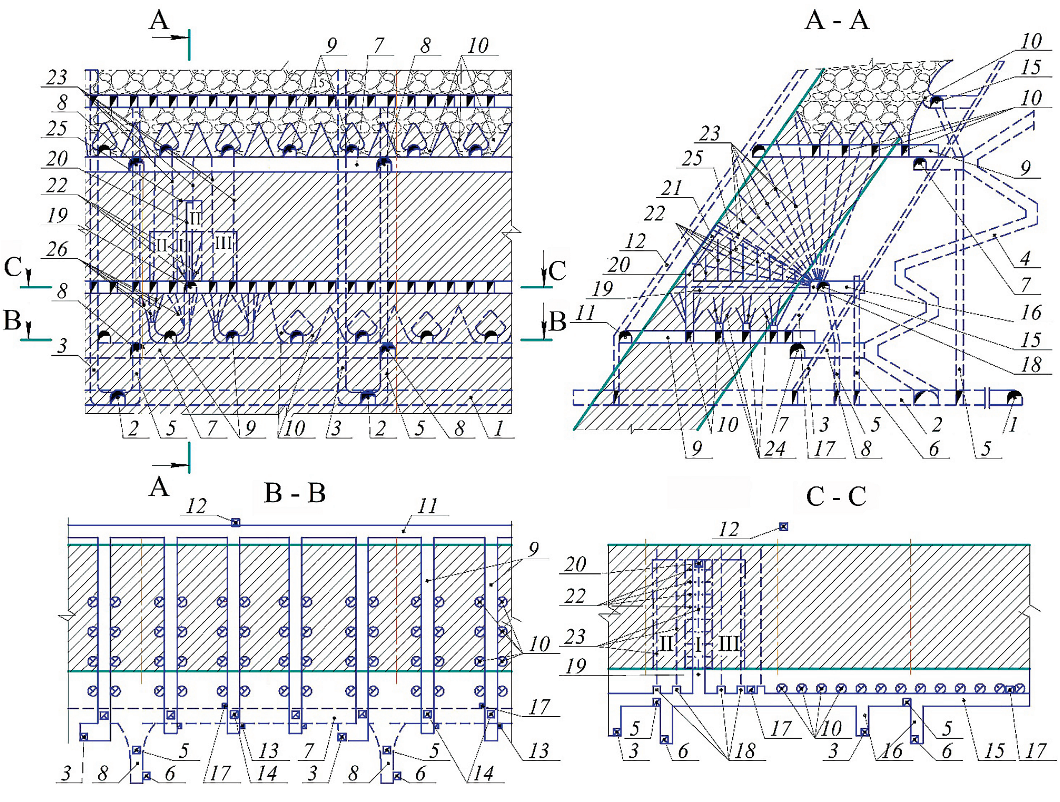


Figure 3. *The developed variant of the sublevel caving system for mining deposits up to 30-35 m thick with combined ore haulage by self-propelled LHDs and scraper equipment*

Source: *developed by the authors*

This variant was developed for use in deposits consisting of low-strength and low-stability ores. The combination of deep-level mining and high rock pressure presents a significant challenge for developing workings with a cross-sectional area of approximately 10 m², which is sufficient for the deployment of minimum-sized self-propelled LHDs (with a bucket capacity of 1.5-2.0 m³), thereby extending the scope of self-propelled equipment in complex mining-geological environments. The proposed technology involves mining the deposit in 50-60 m long blocks along the strike. These blocks are vertically divided into two sublevels of approximately equal height within a single level (75-80 m). The preparation of the block is practically no different from its preparation in the previous version (Fig. 2) and involves the following: from a footwall haulage drift *1* access crosscuts *2* are driven at 50-60-meter intervals; from these crosscuts, block ventilation-and-manway raises *3* are created to break through to the upper ventilation level; an inclined runaway *4* is driven in the footwall rock to provide access for self-propelled equipment to the intermediate sublevels.

Development work begins with the creation of orepasses *5* and service raises *6* to facilitate the driving of other workings and support activities on the intermediate sublevels. Haulage drifts *7* are driven in the footwall rock, the lower of which is located 10 m above the haulage level. These drifts are directly connected to the block ventilation-and-manway raise *3* and via unloading workings *8* – to the orepasses *5* and the service raise *6*. In the roof of the haulage drifts, scraper crosscuts *9* with drawpoints *10* are created. In the hanging wall, these crosscuts are connected to each other by a ventilation drift *11*, which in turn is connected to a ventilation raise *12*. Depending on the mine's ventilation scheme, this raise can connect to either the ventilation level. The scraper crosscuts are connected to the haulage drift via manways *13* and unloading apertures *14* that are covered with grizzly screens.

In the footwall rock, drill drifts *15* are driven 10 m above the floor of the scraper crosscuts *9*. These drifts will also be used as scraper drifts, connecting directly to the orepasses *5* and, via crosscuts *16*, to the service *6* and orepass *5* raises. When positioning these workings, it is also necessary to consider the refined boundaries of the ore bodies in zones of tectonic disturbances. To ventilate this level, air connections *17* are created from the drill drift *15* to the scraper crosscuts *9*. From the drill drifts, drill niches *18* are developed towards the ore body and will later be used as drawpoints *10* on this level. Additionally, cut crosscuts *19* are created, which connect to the cut raise *20* that is developed from one of the end drawpoints. To form the inclined slot *21* at the initial stage, rings of boreholes *22* are drilled from a cut crosscut *19*. To break the main ore reserve in the panel, rings of long holes *23* are drilled from the drill niches 18. Subsequently, blast holes *24* are drilled from the niches to develop the drawpoints into receiving drawbells.

The block within each sub-level is divided into two panels, each with a width of 25-30 m. Each panel is subsequently mined by two scraper crosscuts, with the main ore reserve caved into an inclined compensation room. The stoping process begins by creating an inclined slot *21* in each panel. For this, the cut raise is first expanded to the width of the slot by sequentially blasting paired blast holes drilled on both sides of the raise. Following the broken ore drawing on the expanded cut raise *20*, rings of blast holes *22* of varying heights are blasted in a series of blasts. Simultaneously, one row of drawbells is developed beneath them by detonating blast holes *24* drilled from the drawpoints *10*. Following each blast, the broken ore is drawn via the drawpoints and hauled to the unloading apertures by a scraper. Through the aperture, the ore then falls to the haulage drift, where a self-propelled LHD transports it to the orepass. After the inclined slot is formed, a portion of the long hole rings *23* situated above and on either side of the inclined slot are sequenially detonated in multiple blasts. This creates an inclined compensation room *25* of the necessary volume. Simultaneously, the drawbells are developed beneath the compensation room by blasting the blast holes *24* drilled from the drawpoints. The resulting broken ore is drawn after each blast.

In the vertical projection, Roman numerals denote the stages of the inclined compensation room creation: I – formation of the inclined slot, II and III – the blasting of a portion of the rings of long holes situated above and on either side of the inclined slot, thereby forming the inclined compensation room *25* within its designed contours. In parallel with the development of the inclined compensation room, the main ore reserve is drilled using rings of long holes *23* from the drill niches of the drill drift. From these same drill niches, blast holes *24* are also drilled to deploy the drawbells. It is essential that the drilling of the main ore reserve is completed simultaneously with the creation of the compensation room to ensure a minimal duration of the compensation room existence. Bulk caving of the main ore reserve is achieved through multi-row millisecond-delay blasting of long hole rings *23*. The holes are undercharged by 3-5 m from their collar to ensure the preservation of the drill drift. During the bulk blast, the blast holes *24* are also detonated. The drill drift will subsequently be used as a “catching” level to reduce broken ore losses in the “dead” zone on the footwall.

After the bulk caving of the ore in the panel, it is drawn and hauled according to the developed drawing schedule. The ore is drawn through the drawpoints and hauled by a scraper to an unloading aperture. From there, the ore falls onto the haulage drift, where a self-propelled LHD hauls it to the orepass. The ore drawn from the drawpoints on the "catching" level is hauled directly to the orepass by a scraper. To improve the efficiency of the self-propelled LHDs – whose productivity is significantly higher than that of scrapers for primary haulage in the stopes – one LHD can be used to haul ore simultaneously from two adjacent panels on opposite sides of the orepass. In this case, unloading workings *8* are used for the LHD to make a U-turn. Both proposed variants for the sublevel caving system facilitate the application of high productivity self-propelled LHDs for ore haulage even when mining iron ore deposits in the demanding conditions of the deep Kryvbas mines. The variant for mining thick deposits incorporates a parabolic or vaulted (arch) shaped compensation room, which improves its stability. This design mitigates the formation of critical tensile stresses in the surrounding rock massif, ensuring the room's integrity even in ores with low compressive strength (30-50 MPa) at depths of up to 2,000 m. This finding was supported by the research of W. Elrawy *et al.* (2020). The ability to create compensation rooms of required volume under these demanding conditions ensures effective ore fragmentation during bulk caving. This is achieved by maintaining the required ore loosening coefficient, which minimises the generation of oversize material and mitigates ore congestions during drawing, as highlighted by A. Kosenko *et al.* (2024). This approach also contributes to improved labour productivity and safety for ore drawing and haulage operations, while simultaneously reducing the costs associated with secondary crushing. It should also be noted that the implementation of an additional "catching" level facilitates a higher indicator of extraction within the panels. This, in turn, shortens the overall mining cycle, reduces the volume of re-timbering required for the haulage workings, and decreases broken ore losses on the footwall of the ore body.

Given that the predominant method of iron ore extraction in the Kryvbas mines involves breaking into a compensation space, considerable research was dedicated to identifying a more stable form for this space. For instance, A. Matayev *et al.* (2024) proposed a "reverse trench" shape for the tent-like compensation room. The accuracy of determining the equivalent mechanical properties of the rock massif was further enhanced by incorporating a digital characterisation of the fractured rock massif, based on the structural features of the deposit, as outlined in Huang *et al.* (2024). This approach facilitated a more refined calculation of the stress-strain state of the rock in areas subjected to high rock pressure. W. Elrawy *et al.* (2020) proposed to improve the mining of panels with this system by increasing the intensity of ore drawing with scrapers. To achieve this, the authors suggested almost halving the average haulage distance by driving only two to three pairs of drawpoints in the workings. Furthermore, A. Khorolskyi & A. Kosenko (2022) proposed increasing the efficiency of combined haulage by using more powerful (55 kW) scraper units equipped with multi-bucket scrapers. These units would operate in conjunction with a powerful self-propelled LHD (such as the TORO-400E).

In the variant developed for mining deposits up to 30-35 m thick, a combined ore haulage system using scrapers and self-propelled LHDs was proposed, as suggested by I.B. Bondarchuk *et al.* (2015) and O. Khomenko *et al.* (2015). This approach offers several key advantages. It provides better ore extraction indicators through areal drawing in the panels by scrapers and increases mining intensity by using LHDs for secondary haulage to the orepass. The additional "catching" level also contributes to these benefits. Furthermore, this system helps reduce the cost of maintaining haulage workings by utilising more stable scraper crosscuts instead of drifts, and by locating the larger cross-section workings for the self-propelled LHDs in the stronger and more stable rock of the footwall. To increase the efficiency of self-propelled LHDs – whose productivity for primary haulage in stopes is significantly higher than that of scrapers – it was proposed that a single LHD be used to haul ore simultaneously from two adjacent panels on opposite sides of the orepass. The use of an inclined compensation room in this variant allows for the creation of rooms of required volume, even in low-stability ores under high rock pressure. According to M. Stupnik *et al.* (2023), the roof of the room should have an inclination of at least 35-40 degrees to enhance its stability. This approach is supported by many years of successful practical experience of using compensation rooms of this shape at the deep levels of the Kryvorizka mine, owned by Kryvbaszalizrudkom JSC.

Conclusions

The developed variants of the sublevel caving system allow their application in the challenging conditions of deep Kryvbas mines for mining iron ore deposits of varying thicknesses. The use of self-propelled LHDs for ore haulage during stoping is expected to increase labour productivity in this process by approximately 1.5-2.0 times compared to the existing system employing scrapers. This also improves working conditions and safety. To enable the creation of compensation rooms of sufficient volume even in low-strength and low-stability ores, the system provides a parabolic, vaulted (arch) shape, or an inclined compensation room with an optimal roof inclination angle (no less than 35-40 degrees). This design ensures the necessary ore loosening coefficient for a specific ore type during bulk caving of the main panel reserve, which improves the quality of ore fragmentation and reduces the production of oversize material. Combined ore haulage with scrapers directly in the stopes and then with self-propelled LHDs to the orepass allows for a combination of better ore extraction (due to drawing across the entire panel area) and higher productivity during secondary haulage. At the same time, positioning the scraper workings across the strike of the ore body and locating the LHD workings in more stable footwall rock improves their stability and reduces the cost of maintaining the workings during operation. The use of an additional "catching" level in both variants helps reduce broken ore losses on the footwall and increases the mining intensity of the panels. This, in turn, shortens the overall mining time, which helps reduce the amount of re-timbering needed for the workings at the bottom of the panels, and the associated costs. Future research will focus on optimising the size of mining panels, as this significantly influences the mining time. The duration of mining is a key factor affecting the stability of workings, as well as the overall efficiency and safety of the operations.

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Conflict of Interest

None.

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Микола Ступнік
Доктор технічних наук, професор
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0003-3318-3889

Всеволод Калініченко
Доктор технічних наук, професор
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0002-1938-2286

Михайло Федько
Кандидат технічних наук, доцент
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0002-8437-3175

Сергій Письменний
Кандидат технічних наук, доцент
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0001-5384-6972

Михайло Грищенко
Старший викладач
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0002-9365-1886

Розробка високоефективних технологій видобутку багатих залізних руд на глибоких горизонтах шахт Кривбасу

Анотація. Близько половини обсягів багатих залізних руд, які видобувають на шахтах Кривбасу, здійснюють із використанням різних варіантів системи підповерхового обвалення. При цьому доставку руди у виймальних панелях виконують виключно скреперними установками, які не відповідають сучасним вимогам з точки зору умов праці гірників, її продуктивності та безпеки робіт. Метою роботи була розробка більш ефективних технологічних схем видобування багатих залізних руд системою підповерхового обвалення, що було здійснено, в першу чергу, за рахунок застосування на доставці руди самохідних навантажувально-доставочних машин (НДМ) та інших технічних рішень. Запропоновані нові технологічні схеми відпрацювання покладів залізорудної сировини системою підповерхового обвалення, які ґрунтуються на застосуванні на доставці самохідних НДМ. Це досягається застосуванням окрім основного горизонту випуску, де працюють виключно самохідні НДМ, додаткового горизонту випуску із використанням на ньому скреперних установок, для чого повторно використовують буровий штрек. Це забезпечує більш інтенсивне відпрацювання панелей, завдяки чому зменшуються витрати на підтримання виробок та покращуються показники вилучення руди. Інший варіант розроблений для відпрацювання покладів потужністю до 30-35 м, передбачає застосування похилих компенсаційних камер, що дає можливість утворювати камери достатнього об'єму навіть у рудах низької стійкості, а також комбіновану доставку руди самохідними НДМ та скреперними установками. Для підвищення ефективності використання самохідних НДМ, продуктивність яких є значно більшою ніж скреперних установок, передбачена можливість застосування одної НДМ для одночасної доставки руди з двох суміжних панелей. Таким чином, головними перевагами запропонованих варіантів систем розробки є підвищення інтенсивності відпрацювання панелей, суттєве зменшення втрат відбитої руди на лежачому боці покладу, а також можливість застосування самохідних НДМ в умовах шахт Криворізького залізорудного басейну

Ключові слова: залізорудна сировина; підземний видобуток; технологія розробки; підповерхове обвалення; доставка руди; самохідна техніка