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DEVELOPMENT OF AN EFFICIENT PROCESS SCHEME FOR BREAKING HIGH-GRADE IRON ORES OF LOW STRENGTH AND STABILITY DURING SUBLEVEL CAVING

Introduction. *The main part of rich iron ores (73%) is mined in the Kryvyi Rih iron ore basin, most of which (160.5 million tons) are characterized by a low strength and stability.*

Problem Statement. *One of the most important operations of slope excavation, which significantly affects the productivity of delivery vehicles and a crushing and processing complex, the quality and completeness of extraction of rich iron ores of a low strength and stability, is drilling and blasting operations to form a compensation space with maximum, in terms of stability, dimensions and to hammer the main stock of the panel into it.*

Purpose. *The purpose is to develop an efficient process scheme for breaking off reserves of rich iron ores of a low strength and stability, given the stress-strain state, efficient length of wells, and the quality of ore mass crushing.*

Material and Methods. *The structural and functional analysis of the systems for the development of sublevel caving, the numerical calculations with the analysis and assessment of the parameters of outcrops of compensation chambers, the analysis and assessment of practical experience and scientific achievements in the field of increasing the efficiency of the ore breakage process, the analysis of techniques for the calculation of the parameters of drilling and blasting operations in the extraction of iron ores, the design of process schemes for breaking rich iron ores and their feasibility assessment.*

Results. *For the first time, in this study, there has been developed a resource-saving version of the process scheme for the formation of a triangular-shaped compensation chamber and the hammering of the main stock of a breakage panel on it in the course of developing rich iron ore deposits of a low strength and stability, which allows practically raising the efficiency by 7.8—18%, depending on the conditions of the breakage panel operation.*

Conclusions. *The author has established the dependences of the angle of inclination of the inclined outcrop of the compensation chamber and the line of least resistance. given the stress-strain state, the breakage energy intensity coefficient, the specific costs of breakage, and the efficiency on the distance of the breakage panel to the rocks of the hanging side across the strike of the ore deposit with one and two contacts of the breakage panel with collapsed host rocks.*

Keywords: iron ores, stress-strain state, efficient length of boreholes, drilling and blasting operations, least resistance line, and well diameter.

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In the bowels of Ukraine, there are iron ore reserves, the bulk of which is concentrated in the Ukrainian crystalline shield in the Kryvyi Rih iron ore basin [1]. Most of the reserves of high-grade iron ores are located in the Saksaganskyi ore region of Kryvbas [1]. In this area, the *Rodina* mine that is one of the most powerful in Kryvyi Rih in terms of salable ore reserves and high iron content (52—69%) has been being developed at the Kryvyi Rih iron ore plant, [1, 2]. In the field of the *Rodina* mine, the largest deposit is *Osnovnyi-95* that contains 160.5 million tons of high-quality iron ore, which makes up 90% of the deposit's reserves (Fig. 1) [3]. The *Osnovnyi-95* deposit is characterized by a low strength (the ultimate strength for uniaxial compression is 30—40 MPa) and stability [3].

The *Osnovnyi-95* deposit in the *Rodina* mine field is developed according to the frontal-diagonal scheme [3]. The main part of the panels has two vertical contacts with the collapsed host rocks, which makes it possible to use only inclined compensation chambers, changing their location and orientation within the breakage panel (Figs. 2 and 3) [3].

To destroy the ore mass, the NKR-100MPA drilling rig is employed, which is not efficient, but the large-scale use of self-propelled drilling equipment that is more productive, is complicated by mining and geological conditions [2]. The length of the blast holes in the fan exceeds 30—35 m, which contributes to their significant deviation from the design axis [4]. At the same time, a significant part of them is lost as a result of the impact of the stress-strain state of the massif on them. This leads to poor-quality crushing of the ore massif and, as a consequence, to a deterioration in the qualitative and quantitative indicators of extraction during the bottom discharge of ore from the breakage panels [5].

The purpose of the study is to develop an efficient process scheme for breaking off reserves of high-grade iron ores of low strength and stability, given the stress-strain state, efficient length of wells, and the quality of ore mass crushing.

To achieve the purpose, the following tasks have been solved:

1. To study the influence of the forms of compensation chambers on the efficiency of breaking the main ore reserve of the panel.
2. To study the existing schemes of breaking the ore massif in complex geomechanical conditions of deep mine horizons.
3. To study the influence of well patterns, drilling and blasting parameters and the order of well blasting on the quality of ore crushing.
4. To study the influence of the stress-strain state of the ore massif and the forms of compensation chambers on the efficiency of its breakage.
5. To develop an efficient process scheme for breaking high-grade iron ores in deposits of low strength and stability.

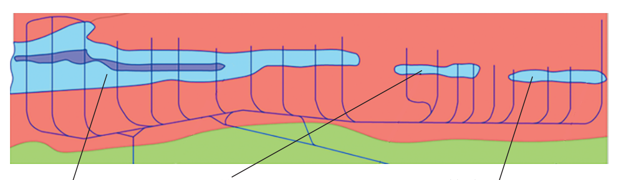

Fig. 1. Plan of the retractable horizon 1390 m in the field of the *Rodina* mine

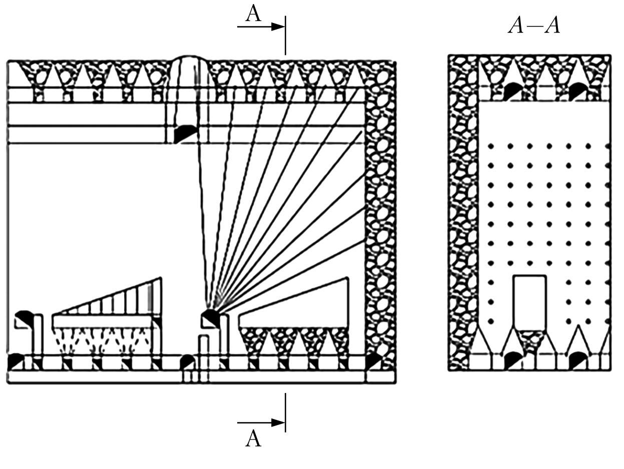

Fig. 2. Scheme of drilling out reserves of breakage block panels with the location of fans of deep wells along the strike of the ore deposit

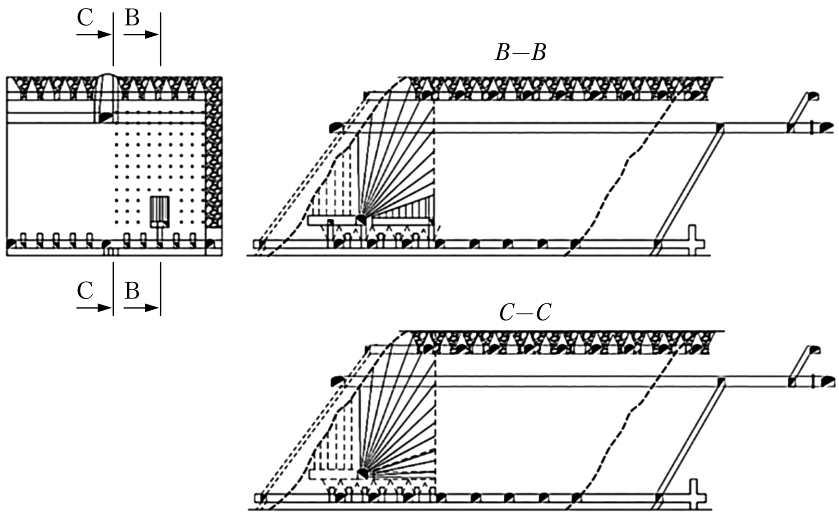

Fig. 3. Scheme of drilling out reserves of breakage block panels with the location of fans of deep wells across the strike of the ore deposit

6. To establish the efficiency of the implementation of the proposed process solutions in practice.

The purpose has been achieved by applying the comprehensive research method with structural and functional analysis of the systems for the development of sublevel caving, the numerical calculations with the analysis and assessment of the parameters of outcrops of compensation chambers, the analysis and evaluation of practical experience and scholarly research achievements in the field of increasing the efficiency of the ore breakage process by justifying the explosion parameters, given the required grade composition of the ore mass (the size of the average linear piece of blasted ore mass), the analysis of the methods for calculating the parameters of drilling and blasting operations in the extraction of iron ores, the design of process schemes for breaking rich iron ores and the assessment of their feasibility.

The analysis of the theory and practice in the field of technology of destruction of rocks by explosion has shown that the design of the optimal process scheme of ore breakage should ensure: the safety of mining; minimum unit costs for the ore breakage processes, release and delivery; convenient conditions for high-performance work when performing operations on drilling and loading wells, as well as switching the explosive network. A decrease in the amount of oversized output, which is due to the deviation of the wells, is achieved due to: a decrease in the length of each well; their orientation as large as possible to the horizontal; correction of the value of the line of least resistance depending on the angle of the well placement and the presence of inclusions in the ore massif of rocks with a higher strength. The volume of wells drilled shall be consistent with the fracturing of the massif, increasing the total volume of drilling and blasting operations with a clearly pronounced insignificant network of fractures so that the minimum number of ore sections, which are separated by cracks, is in the intervals between explosive charges. The efficiency of breaking rocks in a stress-strain state depends on the interaction of static and dynamic stresses. These stresses are due to the influence of rock pressure and the explosion of an explosive charge. Therefore, the effectiveness of breakage can be ensured only if the charges of explosives are located within the unloading zone between the outcrop surface and the boundary between the unloading and reference pressure zones.

From the analysis of studies in the field of geomechanical substantiation of structural elements

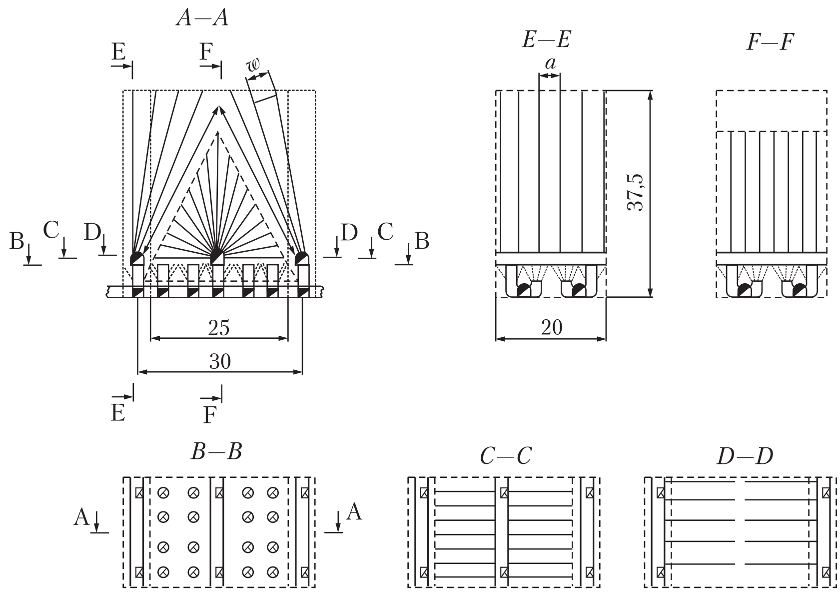

Fig. 4. Scheme of breaking out the reserves of breakage panels in the process of mining the *Osnovnyi-95* deposit in the *Rodina* mine field of the Kryvyi Rih Iron Ore Plant PJSC

of development systems, it has been found that during the development of *Osnovnyi-95* deposit, depending on the location of the breakage panel across the strike of the ore deposit from the hanging to the lying side, it is possible to form different volumes of compensation chambers [6]. Thus, at the hanging side, compensation chambers with an increased volume of 35% and 60% can be located; in the middle part, the usual volume is 20 and 30%; at the recumbent side the volume is small and makes up 5 and 10%, respectively, when the panel has two and one contact with collapsed waste rocks [6]. This makes it possible to use a chamber version of the sublevel caving technology at the hanging side, in the central part of the deposit, the technology of sublevel caving with breaking the ore massif into an inclined compensation space, and at the lying side, the option of sublevel caving with breaking the ore massif in a compressed environment with the simultaneous formation of receiving funnels [6]. However, such an approach to solving the problem requires a change in technological operations as the work front moves away from the rocks of the hanging side of the ore deposit, which is very irefficient. As for the length of the wells, a significant part of them is still characterized by a length that exceeds 30—35 m.

Since inclined outcrops are the most stable [7], it is proposed to use a compensation chamber in the form of an isosceles triangle (triangular). On the basis of this, a process scheme for breaking out the reserves of breakage panels during the development of the *Osnovnyi-95* deposit in the field of the *Rodina* mine has been developed (Fig. 4).

The essence of the developed technological scheme of ore breakage lies in the fact that in the center of the breakage panel, at the height of the cutting horizon, there is a cutting opening, from which ascending fans of deep wells or rod holes are drilled. After that, first of all, a set of fans of deep wells or sucker-rod holes is blown up at the border of the breakage panel with the simultaneous formation of the corresponding receiving funnels. After the release of the chipped ore through the outlet beams, a vertical cut-off slot of a triangular shape is formed, into which deep wells or rod boreholes are punched, with a turn of the cor-

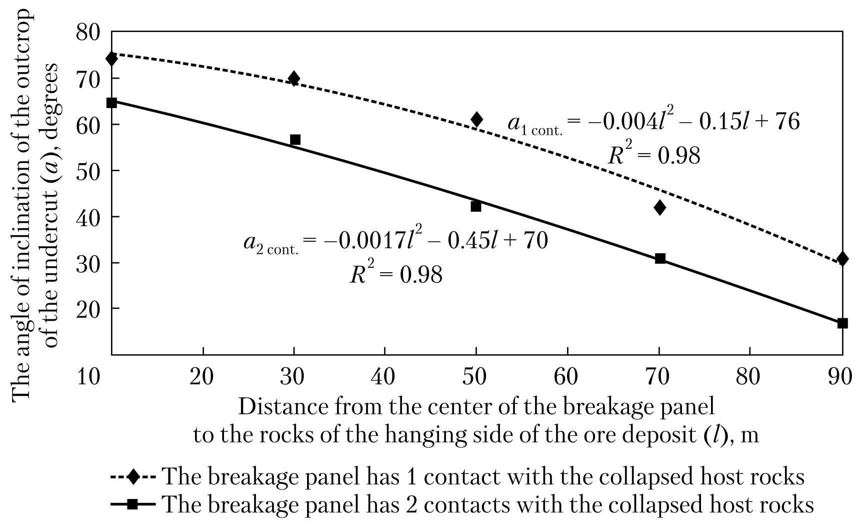

Fig. 5. The dependence of the angle of inclination of the inclined outcrop of the triangular compensation chamber on the location of the breakage panel from the hanging side rocks across the strike of the ore deposit, for a different number of contacts with the host rocks

responding funnels, to form a triangular compensation chamber.

Based on the recommendations on the volume of compensation space formation in the conditions of the *Rodina* mine [6], with the use of the Instruction ... [8], the slope angles αo (Fig. 4) of the inclined outcropping of the triangular compensation chamber to its base have been calculated, depending on the location of the breakage panel to the hanging side rocks across the strike of the ore deposit, for a different number of contacts with the host rocks (Fig. 5).

Figure 5 shows that the value of the angle of inclination of the inclined outcrop changes according to the polynomial quadratic dependence on the distance from the rocks of the hanging side across the stretching of the ore deposit, decreasing from 74.5° to 30.1°, with one contact of the panel with the collapsed host rocks and from 66 to 16.7°, with two contacts. Thus, the closer the panel center is to the hanging side rocks, the higher the triangular compensation chamber and the greater the number of steeply dipping and vertical wells, which are characterized by a lesser degree of curvature (Fig. 4) [9].

Then, for the conditions of the development of the *Osnovnyi-95* rich iron ore deposit (the ore strength factor $f = 4$ points; the vertical area of the outcrop varied from 94 to 563 m^2, depending on the angle of inclination of the outcrop of the triangular compensation chamber, for conditions when the breakage panel has one contact with the collapsed host rocks and within the range from 47 to 328 m^2, for the conditions when the breakage panel has two contacts with the enclosed host rocks, the horizontal outcropping area is 325 m^2, the depth of mining is 1360 m; Poisson's ratio is 0.3) according to the methods [10—12], the coefficient k_σ (Fig. 6) and the lines of least resistance have been calculated for breaking the ore into the inclined compensation chamber according to the specific consumption of explosives, depending on the location of the center of the breakage panel from the rocks of the hanging side across the strike ore deposit, with a different number of contacts with collapsed host rocks (Fig. 7).

Figure 6 features that the value of the value of the breakage energy intensity coefficient changes according to a power-law dependence on the distance from the rocks of the hanging side across

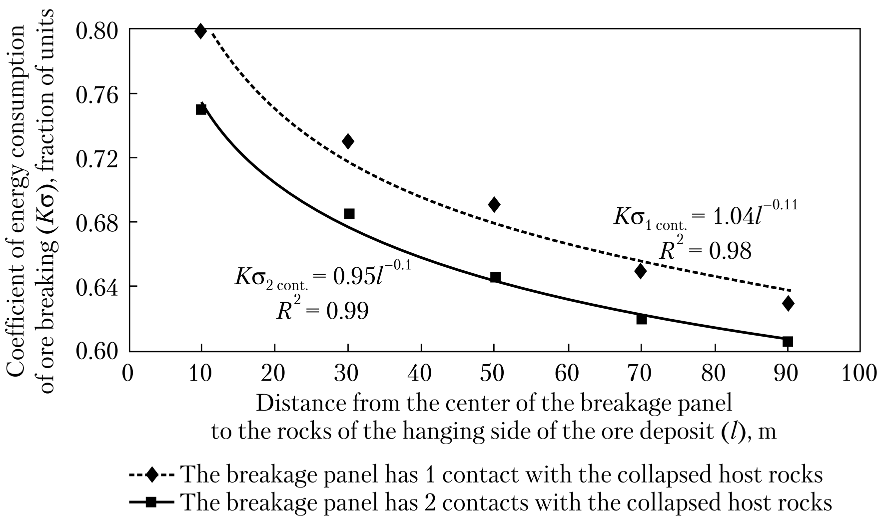

Fig. 6. The dependence of the coefficient of energy consumption of rock breakage on the location of the breakage panel from the rocks of the hanging side across the strike of the ore deposit, for a different number of contacts with collapsed host rocks

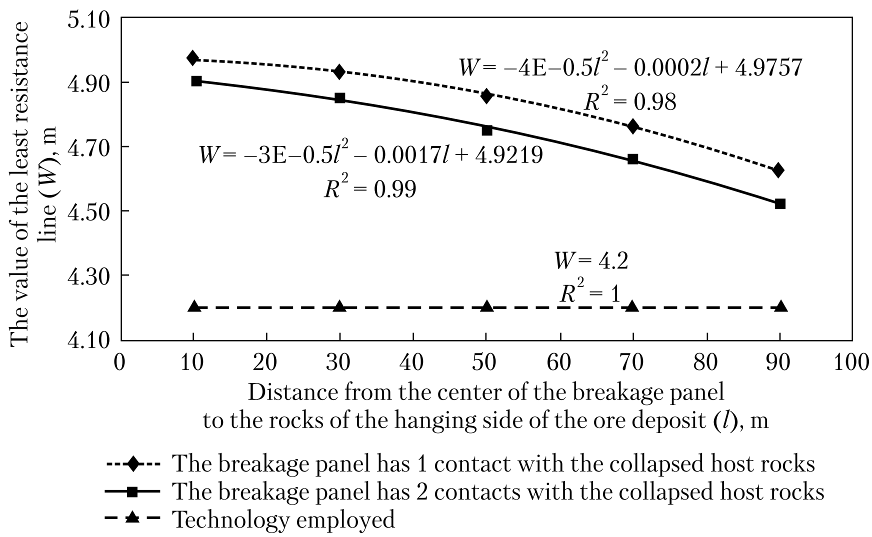

Fig. 7. The dependence of the line of least resistance on the distance of the breakage panel from the rocks of the hanging side across the strike of the ore deposit, for a different number of contacts with collapsed host rocks

the strike of the ore deposit, decreasing from 0.8 to 0.63, with one contact of the panel with the collapsed host rocks and from 0.75 to 0.61, with two contacts. Thus, the farther the center of the panel is from the rocks of the hanging side, the lower the coefficient of energy consumption of the chipping. This fact is also confirmed by numerous experimental studies carried out in [13].

Figure 7 shows that the line of least resistance, given the stress-strain state, changes according to the polynomial quadratic dependence on the distance from the rocks of the hanging side across

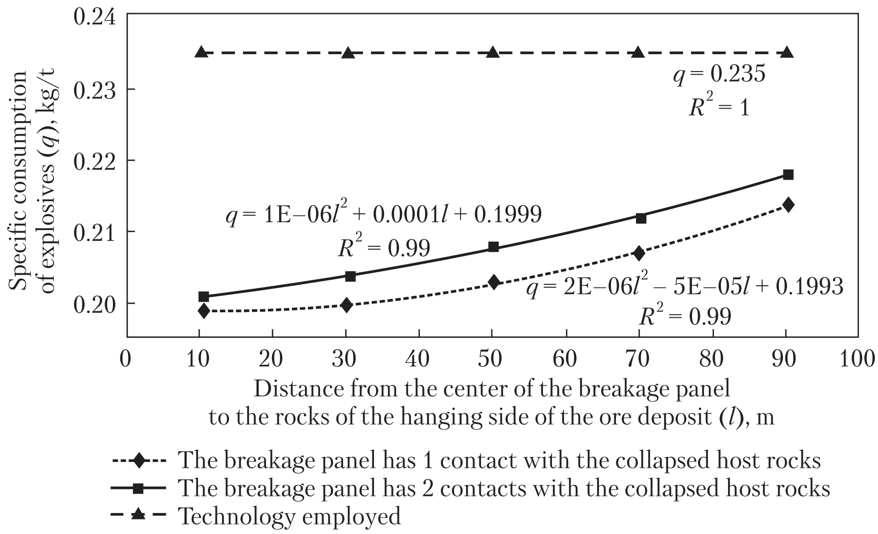

Fig. 8. The dependence of the specific consumption of explosives for breaking the ore reserves of the breakage panels, depending on the distance of the breakage panel from the hanging side rocks across the strike of the ore deposit, for a different number of contacts with the host rocks

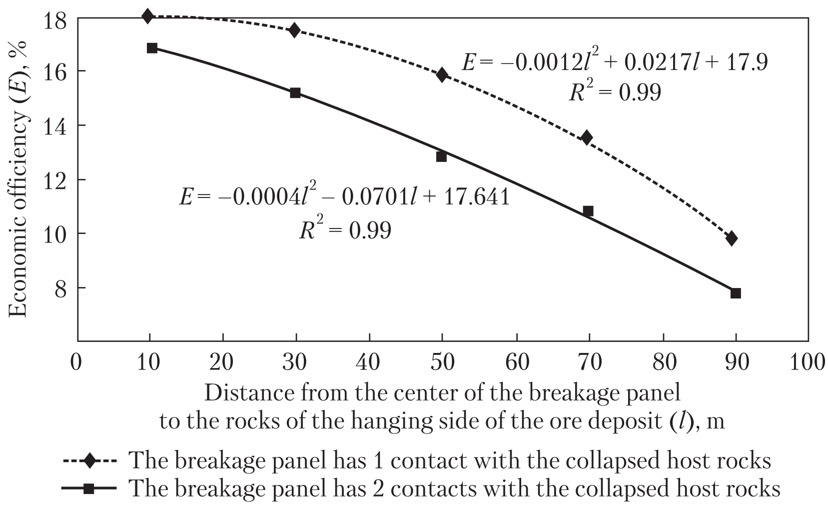

Fig. 9. The dependence of the efficiency of breaking out the reserves of the breakage panels on the distance of the breakage panel from the rocks of the hanging side across the strike of the ore deposit, for a different number of contacts with the collapsed host rocks

the stretching of the ore deposit, decreasing from 5 m to 4.6 m, with one contact of the panel with the collapsed host rocks and from 4.9 to 4.5 m, with two contacts, and without taking into account the stress-strain state, the line of least resistance is 4.2 m. Thus, the closer the center of the panel is to the rocks of the hanging side, the greater the value of the line of least resistance, since in this case the least stresses act in the rock mass. Therefore, it is necessary to take into account the stress-strain state when determining the parameters of drilling and blasting operations.

To determine the costs of breaking the ore massif, in the conditions of the development of deposits of rich iron ores *Osnovnyi-95* in the field of *Rodina* mine, the specific costs of explosives for breaking have been established, the value of which ranges from 0.22 to 0.25 kg/t, the average value is 0.235 kg/t. By means of the calculated coefficient of breakage energy intensity (Fig. 6), the specific consumption of explosives for breaking the ore mass given the stress-strain state is determined. On the basis of the calculations, the graphs of the specific consumption of explosives for breaking the ore reserves of the breakage panels, depending on the distance of the breakage panel from the rocks of the hanging side across the strike of the ore deposit and the number of contacts with the collapsed host rocks, are plotted (Fig. 8).

Figure 8 shows that the specific consumption of explosives changes according to the polynomial quadratic dependence on the distance from the rocks of the hanging side across the strike of the ore deposit, increasing from 0.199 kg/t to 0.214 kg/t, with one contact of the panel with the collapsed host rocks and from 0.20 t to 0.218 kg/t, with two contacts, and without taking into account the stress-strain, the specific consumption of explosives is 0.235 kg/t. Thus, the farther the panel center from the rocks of the hanging side, the greater the consumption of explosives, given the stress-strain state, but the better the crushing of the ore massif.

Figure 9 features that the efficiency values changes according to the polynomial quadratic dependence on the distance of the panel from the rocks of the hanging side across the strike of the ore deposit, decreasing from 18.0% to 9.8%, with one contact of the panel with the collapsed host rocks and from 16.9 % up to 7.8%, with two contacts.

Thus, on the basis of this study, it has been established that the developed scheme allows, without changing the process solutions, mining the ore deposit with breakage panels in terms of thickness through reducing only the angle of inclined outcrops of the triangular compensation chamber when the front of the cleaning works moves from the hanging to the lying side of the ore deposit. The formation of triangular compensation chamber enables reducing the unit costs of face heading, in comparison with the inclined compensation chamber used in the *Rodina* mine, due to a decrease in the volume of sinking (compensation) orts, cut-off raising and drilling chambers. The destruction of the main stock of the panel during ore breakage onto a triangular compensation chamber from two boreholes located at the boundary of the contours of the breakage panel, allows reducing the volume of borehole deviations by up to 42%, depending on the location of the center of the breakage panel to the rocks of the hanging side and the number of contacts with the collapsed hollows. rocks, at the same cost of boreholes, in comparison with the technology used in the conditions of the *Rodina* mine.

In the course of the research, the dependences of the following values have been established: the angles of inclination of inclined outcrops of the triangular-shaped compensation chamber, which change according to the polynomial quadratic law, decreasing from 74.5° to 30.1° and from 66.3° to 16.7°; the coefficient of energy consumption of ore breaking into the triangular compensation chamber, which changes according to the power law, decreasing from 0.8 to 0.63 and from 0.75 to 0.61; the lines of least resistance when breaking the main stock of the breakage panel onto the triangular compensation chamber, which change according to the polynomial quadratic law, decreasing from 5 to 4.6 m and from 4.9 to 4.5 m; the specific consumption of explosives, which changes according to the polynomial quadratic law, increasing from 0.199 kg/t to 0.214 kg/t and from 0.201 kg/t to 0.218 kg/t; the efficiency of the proposed process solution, which changes according to the polynomial quadratic law, decreasing from 18.0% to 9.8% and from 16.9% to 7.8%, respectively, with one and two contacts of the breakage panel with the collapsed host rocks, on the distance of the location of the center of the breakage panel from the rocks of the hanging side across the strike of the ore deposit.

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РОЗРОБЛЕННЯ РАЦІОНАЛЬНОЇ ТЕХНОЛОГІЧНОЇ СХЕМИ ВІДБИВАННЯ БАГАТИХ ЗАЛІЗНИХ РУД НИЗЬКОЇ МІЦНОСТІ ТА СТІЙКОСТІ ПРИ ПІДПОВЕРХОВОМУ ОБВАЛЕННІ

Вступ. Основна частина багатих залізних руд (73%), розробляється у Криворізькому залізорудному басейні, більшість з яких (160,5 млн т) характеризується низькою міцністю та стійкістю.

Проблематика. Однією з найважливіших операцій очисної виїмки, що значним чином впливає на продуктивність засобів доставки та дробильно-збагачувального комплексу, якість і повноту вилучення багатих залізних руд низької міцності та стійкості, є буропідривні роботи з утворення компенсаційного простору максимальних, за умовами стійкості, розмірів та відбивання на нього основного запасу панелі.

Мета. Розроблення раціональної технологічної схеми відбивання запасів багатих залізних руд низької міцності та стійкості на основі урахування напружено-деформованого стану, раціональної довжини свердловин та якості подрібнення рудної маси.

Матеріали й методи. Конструктивно-функціональний аналіз систем розробки підповерхового обвалення, чисельні розрахунки з аналізом і оцінкою параметрів відслонень компенсаційних камер, аналіз та оцінка практичного досвіду і наукових досягнень в галузі підвищення ефективності технологічного процесу відбивання руди, аналіз методик розрахунку параметрів буропідривних робіт при видобуванні залізних руд, технологічне проєктування схем відбивання багатих залізних руд та їхня техніко-економічна оцінка.

Результати. Вперше розроблено ресурсозберігаючий варіант технологічної схеми утворення компенсаційної камери трикутної форми та відбивання на неї основного запасу очисної панелі при розробці покладів багатих залізних руд низької міцності та стійкості, яка дозволить у практичних умовах підвищити економічну ефективність на 7,8–18% залежно від умов відпрацювання очисної панелі.

Висновки. Встановлено залежності зміни кута нахилу похилого відслонення компенсаційної камери, лінії найменшого опору при урахуванні напружено-деформованого стану, коефіцієнту енергоємності відбивання, питомих витрат на відбивання та економічної ефективності від відстані очисної панелі до порід висячого боку вхрест простягання рудного покладу при одному та двох контактах очисної панелі з обваленими вмісними породами.

Ключові слова: багаті залізні руди, напружено-деформований стан, раціональна довжина свердловин, буропідривні роботи, лінія найменшого опору, діаметр свердловини.