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Applied scientific and systemic problems of the related ore-dressing plants interaction in the event of decommissioning the massif that separates their quarries

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Abstract

Purpose. Determining the possible and substantiating expedient alternate design and engineering decisions regarding the stage of spacial union of the adjacent quarries belonging to various owners by mining the rock pillar between the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih" and the quarry of PJSC "Southern Mining Factory" with involvement into mining the reserves, extraction of which is possible within the existing mining and land allotments.

Methods. It was used an integrated methodological approach, including mining and geological analysis of the rock massif between two adjacent quarries, which is subject to decommissioning; technical-economical analysis of the operational efficiency of the ore-dressing plant when decreasing the ore mine productivity as a result of cleaning-up the deposit; theoretical substabtiation of design and engineering decisions regarding the quarry objects parameters in the specified conditions and with the efficient development of a rock pillar that separates quarries.

Findings. The state of the projects and plans for the development of mining operations in the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih" and the quarry of PJSC "Southern Mining Factory" has been analyzed, which, in the coming years, indicates their spacial union. It has been revealed that the decommissioning of the rock pillar between the quarries is complicated both spacely and technologically, especially as a result of seismic restrictions, but the proposed solutions and measures simplify and make safe this stage as much as possible. The problem has been defined of reduce in the loading at the dressing plants proportionally to the decline in ore output. The technical-economical calculations substantiate that the corresponding sequential decommissioning the enrichment sections of the ore-dressing plants is expedient at one of the two cooperating ore mining and processing plants.

Originality. An integrated approach has been improved regarding the evolution of mining and processing enterprises at the stage when their quarries approach to the maximum depths and final contours by taking into account adjacent ore mines as a single complex dynamic system. The analytical substantiation of drilling and blasting technology of the rocks destruction has been adapted to the specific conditions of decommissioning the pillar adjacent to both quarries.

Practical implications. It is distinguished their high level of suitability for implementation and use in the designing of mining operations development in the quarries of PJSC "ArcelorMittal Kryvyi Rih" and PJSC "Southern Mining Factory".

Keywords: *quarry, rock massif, blasting, ore-dressing plant, concentrated product, iron content*

1. Introduction

The iron-ore Kryvbas, almost throughout its existence, has been developed under the conditions of the permanent expansion of the dominant mining and metallurgical system: the existing mines increased their production capacities, new ones were built, and, consequently, the infrastructure for their provision, as well as the very technologies were created, complicated and improved. However, everything was aimed specifically at expansion and few people dealt with "post-industrial" problems, once very distant, but inevitable, which, when approaching the final stages of quarry fields mining, are developed into a serious problem. The issues of resource-commodity interaction of mining and processing enterprises (MPEs) as components of precisely a single system – the mining and metallurgical complex – were resolved very superficially. The possibilities of technological interaction were not almost studied at all, despite the fact that the quarry fields of some of the neighbouring ore mines were mined out more and more intensively [1]-[6]. However, in the conditions of mutual overlapping the zones of technological impacts of two quarries, fundamentally new problems arise, especially when using mass explosions. In these cir-

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cumstances, the transition to a systematic principle of a scientific support for surface mining operations is inevitable. And it should be noted that even though the most studies focus on optimizing drilling and blasting operations as two separate ones, there are already some publications in which it is proposed [7] the Systemic Dynamic Interactive Model (SDIM) for drilling and blasting operations, which uses Vensim software as a powerful dynamic tool for modelling and optimization in deterministic and non-deterministic conditions. It has been proved that complex optimization, in contrast to the deterministic approach, is more effective. Under these conditions, the possibilities of planning, designing and increasing the efficiency of mass explosions are greatly expanded due to the use of the latest communication technologies and computer systems, laser measuring technologies, drilling machines equipped with GPS, new explosives, charge structures and means of their controlled explosion, measuring the effectiveness of explosives and assessing the explosin results [8], [9].

The research has advanced significantly relative to the preliminary weakening and pre-splitting the rocks, as well as to control the reverse blasting and filtering of explosive gases, when forming by an explosion of medium discontinuity deliberately oriented into the space of massif [10]; as well as to control seismically [10], [11] and for the safety of mass explosions [11]. It has been reliably determined how the distribution, transfer and use of explosive energy affects the specific charge and the formation of the volumetric stress state of massif. Theoretical results are consistent with numerical models and the latest experimental tests [12], [13]. But most of the Kryvbas iron-ore quarries are approaching the final design contours and require serious updating the technologies to take into account this specificity. Therefore, theoretical research and experimental refinements of the explosion action under these conditions require a more in-depth development. Modern approaches to planning the mining operations development are based on the assumption that the parameters of the external and internal environment will be relatively constant, and, therefore, do not provide for changing the main characteristics of the quarry in the long run. In addition, the existing methods of planning the mining operations do not take into account the relationship between the mining operations mode and ore output in a quarry, under the condition of providing by the quarry of a standard of the reserves ready for extraction in case of change in the productivity [14]-[16]. In most studies aimed at determining the development system parameters when planning the mining operations, in the process of determining the working site width with a specified ore output in a quarry, only the length of the active front of ore and overburden rocks is taken into account at the moment of assessment [17], [18]. At the same time, the influence on it of a change in the working site width, which is in the fact that with an increase in the working site width, the front length decreases, is not considered.

That is why the purpose of the article is to analyze adjacent quarries as a single industrial-economical system, the integration of which increases as their technologically active zones come closer.

The objective of the above stated is to determine the possible and to substantiate the appropriate alternate design and engineering decisions, including:

– the parameters of the quarry sides elements, working sites, horizons and zones of the latter when they approach to the final contours;

– adjusting the level of optimal loading the ore-dressing plant in accordance with changes in ore output of the MPE;

– the sequence and methods for decommissioning the rock massif separating adjacent quarries at the stage of their spacial union, taking into account the factors influencing on each of them (blasted rock fragments dispersion, seismic impact of mass explosions, etc.).

The research results are presented using the example of a stage of the rock pillar mining between the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih" and the quarry of PJSC "Southern Mining Factory" with involvement into mining the reserves, extraction of which is possible within the existing mining and land allotments.

2. Methodology

The study is structurally grouped into three directions, characteristic of quarries transition to the lower horizons. The first of them is related to the technical and economical analysis of the systematic decrease in ore output of the quarry that is natural for this stage and the corresponding regulation of the enrichment sections number at the ore-dressing plant of one of the related mining and processing enterprises; the second direction is focused on the mining-geometrical analysis of the massif between two adjacent quarries and approval of the general quarry plan for mining operations with involvement of ore from this massif in productive development; and the third one is directly focused on the technology of mining operations using a drilling and blasting method. The distinguished studies are consistent with the theoretical substantiation of design decisions for the quarry development under the specified conditions and the planning of mining operations.

3. Results and discussion

Soon or late, but the deposits are depleted, even such as iron ore, and at a certain stage, the marked expansion is changed with stagnation, which is preceded by a rapidly growing amplitude of iron ore quality fluctuations in the cargo flows of the quarries (Fig. 1).

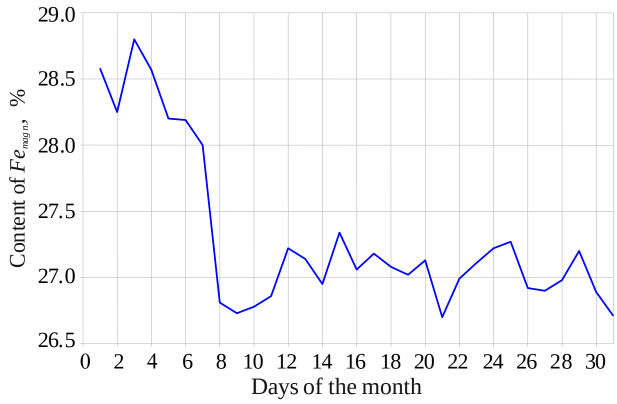

Figure 1. Fluctuations in the iron content of ore flow in the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih" mining department in January 2017

With the transition to deeper horizons, not only quality indicators, but also the ore output volumes decrease, and the disproportion increases in the comparative productivity at different mining and processing plants of the iron-ore basin.

The first signs of these patterns begin to appear now, and an example of this, although not direct, but very convincing, is the site of the Kryvyi Rih iron-ore formation, which is being mined out by the neighboring mining and processing enterprises: PJSC "Southern Mining Factory" and PJSC "ArcelorMittal Kryvyi Rih".

The working project prepared by Pivdenhiproruda [19] considers the development of a rock pillar between the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih" mining department and the quarry of PJSC "Southern Mining Factory" with involvement into mining the reserves, extraction of which is possible within the existing mining and land allotments.

It has been determined while working out the calendar plan that without advancing the No. 3 quarry southern side, the annual disposal of ore horizons in the central part will be 2-3, and the introduction of new ones – no more than one, which leads to a gradual reduction in the front of mining operations in the quarry and, as a consequence, a decrease in ore output capacities. In this regard, only the timely commissioning of the southern section could support the unoxidized quartzite output in the No. 3 quarry at a specified level of 20 mln tons per year.

But this refers to an adjacent massif, mining of which, regardless of its affiliation, will seriously affect the neighboring quarry, both in mining-geometrical term and under the influence of technological factors, especially mass explosions.

It is these factors that determine the emphasized by the authors necessity in a systematic principle of designing and managing the quarries, as well as planning the development of mining operations in them, when either a couple or a group of quarries is considered as a system. And under these conditions, first of all, three most important aspects are actualized of adjusting the strategy for the further development of cooperating plants:

1. Raw material and commodity.
2. Technologically organizational.
3. Design and planning.

And here a situation arises that, being unprecedented for Kryvbas, is considered as typical in the coming years, with account of the following.

An analysis of the development projects of mining and processing enterprises in Ukraine indicates that most of them with a design capacity will operate for another 15-20 years, after which it will start to decline steadily: when cleaning-up the productive ore deposits, or – quarry horizons that are maximum in design depth. At the same time, a problem arises of corresponding decrease in loading the dressing plants and other fixed assets proportionally to the decline in ore output.

The technical-economical calculations indicate that the corresponding to the specified, the sequential removal of ore enrichment sections of ore-dressing plants from MPEs is inevitable reality in this trend. And here a very serious, almost unexplored today, and in many ways unexpected problem arises, the essence of which is that the enrichment process, although implemented by a set of enrichment sections, which from the point of view of control are discrete technological units, but it still occurs at ore-dressing plants – a system which is the only medium that includes not only subsystems – enrichment sections, but also system-wide and therefore large-scale invariable components (buildings and structures, general crushing-and-sorting and other technological complexes, unified transport and storage systems, energy and engineering networks, common fixed assets and resources, door-to-door infrastructure, systems of support, management, logistics, etc.). Therefore, the ore-dressing plant is a completely integrated establishment, extremely complex functionally and cumbersome structurally, and most importantly – intentionally designed exclusively for the full scale of the object, both in design and by program. That is why, the ore-dressing plant as a system not only does not have adaptive flexibility in terms of the large-scale variability of the active number of its discrete units – enrichment sections, but on the contrary – in design and by program it is precisely maximally protected in relation to any deviations from design indicators. As a result, by reducing the number of working sections, the mining and processing enterprise is not able to proportionally reduce the cost for maintaining the ore-dressing plant, and therefore, spends them in full force [20].

Given the above, the authors have studied and proposed, as a variant to solve the problem, the sequential closure of the enrichment plants at mining and processing enterprises, the productivity of which decreases in the group of plants to a critical value determined by the developed criterion, the essence of which is the ratio of the costs for maintaining its own ore-dressing plant at mining and processing enterprise and the profit from the sale of enriched products. And after reducing the profitability of ore processing to a minimum level (with account of the need for costs to maintain in full the ore-dressing plant operation), the closure of the ore-dressing plant becomes inevitable and the criterion for assessing the efficiency of the mining and processing enterprise is reduced to comparing the costs for mining merchantable ore and the profit from its sale as already finished products.

In this case, there are two stages of decommissioning the ore-dressing plant:

1st stage – operation of a plant with declining productivity, and, hence, the corresponding sequential decommissionning, dismantling and sale of that part of the equipment that is not loaded caused by this decline;

2nd stage – dismantling and sale of equipment, structures and materials after a complete plant shutdown.

Simplistically, the criterion has the form:

$$\sum C_{ODP} \le V_c P_c - V_{ODP} P_O \,, \tag{1}$$

where:

C_{ODP} – costs for maintaining the ore-dressing plant;

V_{ODP} – ore volumes processed by the ore-dressing plant;

V_c – volumes of the resulting concentrate;

P_c – price of concentrate;

P_o – price of ore.

The costs for maintaining the ore-dressing plant can be expressed as follows:

$$C_{\ ODP} = V_C C \,. \tag{2}$$

If $V_c = V_{ODP}\gamma$, then the costs for maintaining the ore-dressing plant are of the form:

$$C_{\ ODP} = V_{ODP}\ \gamma\ C \,, \tag{3}$$

where:

C – production costs of enrichment;

g – output indicator of the concentrate at the ore-dressing plant.

Based on the expression (1), the ratio can be written as:

$$V_{ODP}\,\gamma\,C \le \left(V_{ODP}\,\gamma\,P_C - V_{ODP}P_O\right). \quad (4)$$

When being reduced and transformed, expression (4) takes the form:

$$C \le \left(P_C - \frac{P_O}{\gamma}\right). \quad (5)$$

If to take the production costs value as the minimum admissible (boundary) for the functioning the ore-dressing plant, then the graphs can be plotted that will allow to determine the range of the production costs values at the variable prices for concentrate and ore with various indicators of concentrate output. Figure 2 shows the dependence of the minimum production costs on the level of prices of concentrate with various price values of the ore at the concentrate output of *g* = 39%, in Figure 3 – at *g* = 40%.

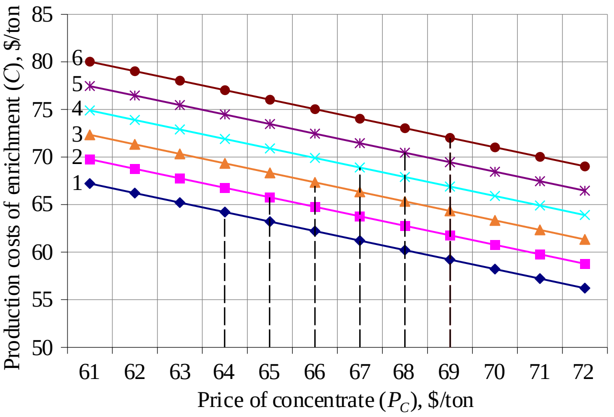

***Figure 2.** Dependence of the minimum production costs of the ore-dressing plant on the level of prices of concentrate with various price values of ore at the concentrate output of g = 39%; ore price: 1 – 50 $/ton; 2 – 51 $/ton; 3 – 52 $/ton; 4 – 53 $/ton; 5 – 54 $/ton; 6 – 55 $/ton*

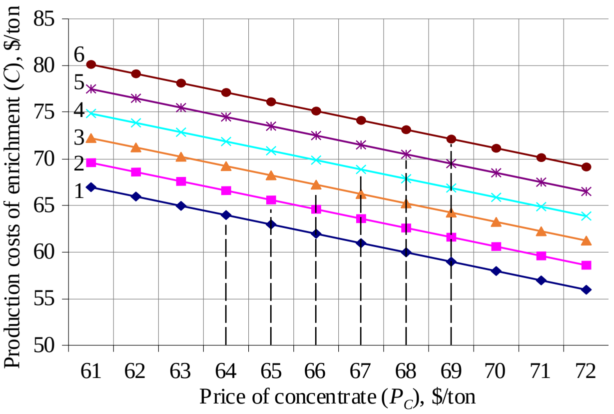

***Figure 3.** Dependence of the minimum production costs of the ore-dressing plant on the level of prices of concentrate with various price values of ore at the concentrate output of g = 40%; ore price: 1 – 50 $/ton; 2 – 51 $/ton; 3 – 52 $/ton; 4 – 53 $/ton; 5 – 54 $/ton; 6 – 55 $/ton*

In the graphs, the dotted line indicates the minimum price of concentrate, at which, taking into account the price of ore and production costs, it is necessary to make a decision on decommissioning the entire ore-dressing plant or its part (section), as well as redirecting the ore flow to another mining and processing enterprise.

In this case, it is necessary to consider the prime costs for transporting ore to the ore-dressing plant of another mining and processing enterprise, because the price of ore at the inlet of the ore-dressing plant will be increased by the expenses value:

$$P_{O2} = P_{O1} + PC_{tr}, \quad (6)$$

where:

P_{O2} – ore price at the ore-dressing plant of another mining and processing enterprise;

P_{O1} – ore price at the ore-dressing plant of MPE, where it was mined;

PC_{tr} – prime costs for transporting ore from the first to the second mining and processing enterprise.

An increase in the ore price at the ore-dressing plant of another mining and processing enterprise will affect the production costs of enrichment, but due to an increase in ore volumes at the inlet of the enrichment process, an increase in the production costs will not be proportional.

To determine the necessity of decommissioning the ore-dressing plant and redirecting the ore flow of incoming ore to another mining and processing enterprise, an algorithm has been developed using the objective function *C* = *f*(*Xi*, *Yi*, *Zi*, *Ki*) → min, which helps to make a decision based on whether the enrichment production facility is profitable at current prices of ore and concentrate.

It is known that the prices of ore and concentrate are not constant, fluctuations in the price for concentrate have a very wide range: over the past decade, it ranged from 120 $/ton in 2007 to 65 $/ton in 2017, and the pessimistic prediction of iron ore prices looks like it falls below the level of 50 $/ton.

Therefore, the presence of an algorithm for determining the necessity of decommissioning the ore-dressing plant at the mining and processing enterprise, where the processing costs are higher than the selling price of the concentrate, is a very relevant scientific issue.

In the end, during the two specified above periods, the enriched products cost (in the first period) will be influenced – indirectly – by the profit from the sale of funds of sequentially closed enrichment sections (subperiod). And the production costs for merchantable ore as a finished product after the complete enrichment cessation (second period) will be influenced by the proceeds from the sale of fixed assets and other assets of the ore-dressing plant in general.

By all means, the sale of dismantled as well as integral fixed assets, which were decommissioned, is reflected in the financial performance of the mining and processing enterprise as a whole. But, conditionally, it is possible to correlate such cashflow with the production costs of products in these periods – solely for the estimated motivation of management decisions.

1-st period:

$$C_{epj} = \frac{\left\{TC_{epj} - \left[\sum\left(P_{di} - C_{dsi}\right) + \sum \Delta_i P_i\right]\right\}}{V_{epj}}, \quad (7)$$

where:

C_{epj} – the enriched products cost in the *j*-th subperiod;

TC_{epj} – total cost of the enriched products produced in the *j*-th subperiod;

P_{di} – proceeds from the sale of the *i*-th decommissioned assets in the *j*-th subperiod;

C_{dsi} – the cost of dismantling and selling *i*-th resources in the *j*-th subperiod;

$\Delta_i P_i$ – associated savings from the reduction of *i*-th resources consumption in the *j*-th subperiod (direct – included in the cost of ore enrichment);

V_{epj} – volumes of enriched products produced in the *j*-th subperiod.

2-nd period:

$PC_{mo2} = ...,$ (similarly);

$$PC_{mo2} = \frac{TC_{mo2} - \left[\sum\left(P_{di} - C_{dsi}\right) + \sum \Delta_i P_i\right] + \sum REM_{ODP}}{V_{mo2}}, \quad (8)$$

where:

PC_{mo2} – the production costs for merchantable ore in the 2-nd period;

REM_{ODP} – residual expenses for maintaining the ore-dressing plant.

This approach does not provide an accurate determination of specific technical-economical indicators, but at the same time it enables, although very simply, but extremely quickly and visually assess whether each transition period is being "mitigated", which are largely extreme for MPE. When reducing the volumes of ore enrichment, this is compensated by almost simultaneous material proceeds inflow, which makes possible to determine in advance and, therefore, to plan the generalized parameters of the studied systems and the time required for the preparation, as well as timely preventive implementation of measures to reorganize the technological ore-dressing plant and integrated cargo flows at the mining and processing enterprise.

In addition, the raw material and commodity aspect also causes the need in specification of reserves and state of ore deposits at the corresponding stage, as well as specific production program. In the studied case, this is a massif between the quarries of PJSC "Southern Mining Factory" and the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih".

With the purpose to intensify mining operations in the southern direction of the No. 3 quarry, the rock pillar is proposed to be mined in two stages [19]:

– at the first stage, mining operations are conducted within the boundaries allowing to preserve the railway track operation in the area of causeway;

– at the second stage (after removal of all service lines from the pillar) - to the border of the existing land allotment.

Since more than 170 mln tons of unoxidized quartzite are located in the pillar between the No. 3 quarry and the quarry of PJSC "Southern Mining Factory", expanding the boundaries of mining operations in the quarry with the involvement of mining the pillar reserves is one of the main measures for the timely disclosure and preparation of the work front on unoxidized (magnetite) quartzite.

The approximate volume of unoxidized ore reserves in the quarry of the first stage, with the possible inclusion into mining of off-balance reserves of the northern side (due to an increase in the slope angle), is 498 mln tons. In the southern part of the quarry at the first stage there are about 87700 mln tons of unoxidized quartzite.

The upper part of the quarry southern side is a temporary nonworking side up to 150 m high, in the lower part of which there are automobile cross-over roads. Since the mining of this section by means of frontal working is complicated, the project provides for the steep layers mining with a transverse arrangement of faces and a gradual transition to frontal mining. The project allows organizing the temporarily non-working sections in the working zone of the quarry with reclamation with working sides of 30-45 m height, safety berm of 10 m width and catching berm of 30 m width.

Removing the local service lines and dismantling the transshipment site on the southeastern side of the quarry (+70/82 m horizon) at the first stage enables to start decommissioning the temporarily nonworking side and expand the quarry field southward, after which it is planned to begin mining operations on the causeway. For this, it is planned to arrange a face blind pass on the roof of the causeway (+92 m mark) and mine out +82 m horizon using the ESh 6/45 dragline excavator onto the railway transport. Mining out +82 m horizon is expected from west to east. After +82 m horizon is mined out, +70 m horizon is involved into mining using the Terex RH-170 hydraulic excavator with shipment onto the railway transport.

To ensure the necessary stability of the +70 m horizon bench, it is supposed to load it by ESh 6/45 dragline with overburden rocks in the volume of 30 thousand m^3, which will be delivered by automobile transport from the lower horizons of the quarry western side.

In the same period, it is planned to mine out the +66/70 m subbench by the Terex RH-170 hydraulic excavator onto the automobile transport. Thus, a site (70-100 m wide) is formed on the southeast quarry side at +66 m mark, which will enable to operate for two Terex RH-170 hydraulic excavators.

In the future, it is planned to mine out unoxidized ore from the southern quarry section in the volume of 310 thousand tons (+30 and +15 m horizons). Mining operations are planned on four benches of the southern quarry side (+54, +42, +30 and +15 m horizons) with the rocks shipment onto automobile transport. The working sites are being arranged on the upper horizons (+54 and +42 m), and transportation lines are built leading to them to start mining operations. Mining out the rock mass from the +30 and +15 m horizons is planned by only one Terex RH-170 hydraulic excavator.

The subsequent period – the extraction of about 1 mln tons of unoxidized ore from the southern quarry side using two Terex RH-170 hydraulic excavators (+0, -15, -30, -45 and -60 m horizons) onto the automobile transport. After completion it is planned to combine the systems of automobile cross-over roads of the southern side (+78 and -60 m horizons and -60 and -225 m horizons). In subsequent years, this will give an ability to begin setting the eastern side on the final contour.

In the future, it is planned to mine out more than 4 mln tons of unoxidized ore on seven benches of the southern quarry side (-75, -90, -105, -120, -135, -150 and -165 m horizons) with shipment onto automobile transport. Since the extraction volumes for each horizon do not exceed 310 thousand m^3, it is planned to use only one Terex RH-170 hydraulic excavator and only one EKG-10 excavating machine.

This is followed by mining of about 8700 mln tons of ore from the southern quarry section on eight benches of the southern quarry side (-90 and -195 m horizons), of which two (-90 and -105 m) are placed in the final position of the first stage. The rock mass transportation from the -90 m and -195 m horizons is performed by automobile transport; shipment on eight benches in the southern quarry part is performed by means of two Terex RH-170 hydraulic excavators.

After that, about 4400 mln tons of unoxidized ore are mined out from the southern quarry side on seven benches (-120…-210 m horizons), with shipment onto automobile transport. The total volume of mining operations in this section is about 1600 mln m^3, with extraction by only one Terex RH-170 hydraulic excavator.

For the transition to the second stage of mining out the causeway, it becomes necessary to build and commission cyclical conveyer technology (CCT) on the southeast quarry side. Thus, it would be possible to organize the direct transportation of unoxidized ore to the ore-dressing plant without transfer between stations in the area of the causeway. The design capacity of the CCT southeastern complex is assumed to be at the level of 20 mln tons of unoxidized ore per year. In this case, the existing CCT on the western quarry side is supposed to be redirected to oxidized quartzites (after the commissioning the southeastern CCT complex).

When drawing up a time schedule for mining out the field for the period 2010-2020, the mining-engineering parameters of all sections for priority mining have been considered [19]. According to the main indicator of mining-engineering conditions of mining operations – through the overburden ratio, it has been found that the western and southern sections are the most preferable; their forced mining within the open horizons not only will give a significant ore volume, but also allow to expand the quarry bottom, which in the next period would provide the necessary front of mining operations at lower horizons. Development of mining operations southward during the period 2010-2020, was intended as part of the first stage of mining the rock pillar. Intensive pillar development is expected after 2020. Prior to that, it is necessary to perform the removing all service lines of the No. 3 quarry from the south side, build a CCT complex on the southeast side, and also prepare transportation lines within the eastern and western sides of the quarry for the possibility of conducting mining operations southward in the upper horizons with their subsequent deepening.

In order to expand the working zone, flattening is also assumed of northern and eastern quarry sections, which have worse mining-engineering characteristics than the sections of the western and southern sides, after which conditions are created for deepening the quarry. Despite the relatively low average overburden ratio of 0.22 m^3/t, it is supposed till the accounting period to conduct mining operations in the quarry with an average current ratio of 0.33 m^3/t. With this ratio, it seems possible to intensify mining operations by increasing the overburden extraction volume. This will allow to get the working zone of the quarry under a state that ensures the presence of a normative front of mining operations with a working sites width of 45-50 m.

The parameters of the quarry working zone development were determined by the graph for mining unoxidized ferruginous quartzites, taking into account the oxidized quartzites extraction at the level necessary for this.

The main measures for the time schedule implementation are:

– execution of design volumes of overburden mining operations;

– beginning the causeway mining out;

– construction and commissioning the southeast complex of CCT;

– upgrading of mining and transport equipment.

Mining operations technology and production processes mechanization in this zone of this period provides for the following [19].

When decommissioning the causeway between quarries, it is envisaged to follow the existing technology and mechanization of production processes with the corresponding changes, conditioned by the reconstruction of mining and transport scheme in the quarry, with subsequent replacement of obsolete, physically worn-out equipment and the acquisition of a new one to increase the rock mass output in the quarry.

The ore deposit is a thick steeply falling formation, broken by several disturbances and shifts. The host rocks are low-quality quartzrocks, crystalline schists, and other rocks. The ore deposit within the quarry field is covered by sedimentary rocks on the surface. The alluviation thickness within the unmined areas varies from 19 to 54 m, averaging 34 m. Physical and mechanical properties of ores, host rocks and overburden rocks are presented in Table 1.

Table 1. Physical and mechanical properties of ores, host rocks and overburden rocks

Rock name	Strength, *f*	Density, t/m^3
Unoxidized ferruginous quartzites	12-18	3.5
Oxidized ferruginous quartzites	4-18	3.3
Slates	8-14	3.0
Soft overburden rocks	1-3	1.8

As loading mechanisms it is intended to use:

– for mining out unoxidized and oxidized quartzites, as well as for extracting the overburden rocks – EKG-8I, EKG-10, Terex RH-170 hydraulic excavators, CAT 992G loaders;

– at transloading sites – EKG-8I, EKG-10 excavating machines;

– on the hard overburden rock dumps and for storing the oxidized quartzites – ESh 6/45, EKG-6.3, EKG-8I excavating machines.

Ore and overburden rocks of the deposit are hard rocks, requiring preliminary loosening by means of blasting. The fragmentation of hard rocks with a hardness coefficient *f* = 4-18 is assumed to conduct by the borehole charge method. Blast hole drilling is supposed to be carried out by roller drilling machines SBSh-250MN and Atlas Copco Pit Viper 275. Anemix should be used as an explosive. To initiate borehole charges, a blasting method using a non-electric Nonel type system is used.

To reduce the seismic impact intensity, blasting is supposed to be carried out using multirow delayed detonation, and explosive switching network – according to a sectional scheme. To perform delayed blasting, pyrotechnical relays RP-92 with nominal blasting decelerations of 20, 35 ms are used.

The explosion danger area for people in terms of fragments dispersion is taken 500 m when using Anemix R-70.

To form the slopes of benches when forming the permanent sides of hard rocks, the contour blasting of incline holes is planned for the drilling of which the Atlas Copco ROC-L8 machine is used.

Considering all the emphasized above peculiarities of the zone between two adjacent quarries, as well as the fact that almost the entire production program, envisaged by the Pivdenhiproruda working project, has been violated, in circumstances where the current state of the No. 3 quarry requires an immediate solution to this problem and does not allow for a sharp decline in ore output, the authors propose to apply the developed technology of rocks explosive destruction with a differentiated energy saturating the massif [21]. The adaptation of this technology to the studied conditions corresponds to them as much as possible and requires minimal modifications, taking into account the similarity of conditions and requirements for use, both operational and resource (types of explosive materials, explosive devices, etc.).

The technology is being implemented with account of the recommendation "to bond the massif from collapse before the charge explosion", but this can be performed not by constructing the bearing wall, according to the recommendation, but due to the priority explosion of charges in the second boreholes row from the slope. By means of explosion of the same row, a reflecting gap, symmetrical to the slope of the bench, is created. The first row is blasted due to delay, the duration of which ensures the forward and backward passage of the direct and tension waves of the first explosion through the massif, limited by the second row and slope (Fig. 4).

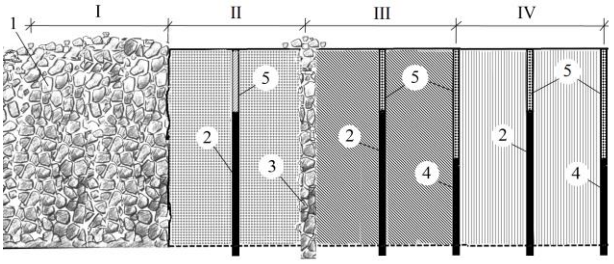

Figure 4. The method scheme of differentiated energy saturation of a rock massif with a reverse blasting symmetrically working borehole charges in benches with vertical slopes: 1 – blown up rock mass; 2 – charge for loosening the complete mass; 3 – reflecting gap; 4 – combined charge of incomplete mass for the reflecting gap formation and preliminary rocks weakening

To exclude the accelerated formation of fractures in the direction of the bench roof, the charge mass in the second row is reduced by 30-50%, increasing the length of the splitting material. And for the reflecting gap formation in the plane of the same row of boreholes, specially designed combined linear charges of directional action are used (Fig. 5) [21].

The high-explosive charges are firstly simultaneously initiated, which form linear stresses concentrators on the walls of the borehole and, in turn, blast the main charge with an explosive of low-high-explosive charge.

In the case of blasting the massif between the adjacent quarries, the seismic manifestation of mass explosions becomes of particular importance, since the objects of both plants are exposed to it. But at present, there are no universal theoretical methods for predicting the seismic explosive hazard in the quarries and for protecting the structures. Therefore, the main methods for assessing the seismic impact of an explosion are experimental measurements, processing and analysis of their results using various means of initiating an explosion in accordance with the rules for conducting rock explosions, which were studied by the authors.

The main factors that characterize the seismic impact of mass explosions in the quarry were adopted: mass of explosives on the degree of delay in explosive blocks – Q; the distance from the block to the observing point – R.

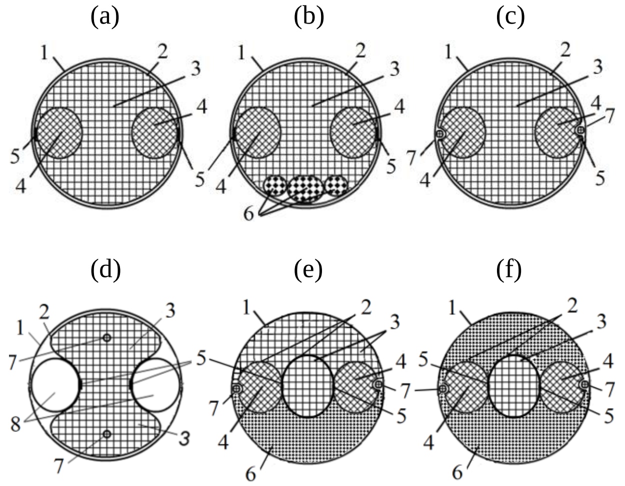

Figure 5. Cross section of borehole charges of doubled rows: 1 – borehole; 2 – polymer hose; 3 – low-high-explosive charge; 4 – linear high-explosive charge; 5 – places for hose soldering; 6 – inert dampers; 7 – detonating fuse; 8 – air-forming cumulative gutters

The main parameter characterizing the intensity, it is proposed to consider the vector modulus of the maximum vibrations (displacement) velocity of the soil at the structures base. It has been experimentally proved that in case of an instant explosion this parameter better correlates with the explosive mass and the distance to the observing point than the displacement amplitude, acceleration and the period of vibrations. To determine the proportionality between the level of seismic soil vibrations at a given point and the explosive mass during mass explosions in quarries, the ratio $Q = x^2R^3K^{-2}_f$ is recommended, where x – maximum permissible seismic vibrations velocity of soil near the security object, cm/s; K_f – seismic factor for a given area. When calculating the maximum value of the explosive mass, the K_f is determined experimentally in the course of monitoring the seismic safety of mass explosions, the maximum permissible seismic vibrations velocity – according to the method [22].

Since 2006 and till now, it has been carried out more than 70 experimental measurements of the seismic waves level during explosions in the Kryvbas quarries, provided that the detonating fuse and non-electrical Prima-Era and Nonel systems are used to initiate the explosion. The experimental results analysis makes possible to state:

– the level of seismic waves during explosions has never exceeded the standard level;

– the explosion initiation system significantly affects the mass explosions seismicity – when using the Prima-Era, Nonel systems, the seismic explosion impact is almost 30% less than in the case of using the detonating fuse;

– the explosion seismicity is influenced not by the initiation system itself, but by the maximum mass of explosive, which falls on the deceleration degree when using one or another initiation system: when using the detonating fuse – 810 kg, when using Prima-Era and Nonel systems – 331 kg.

Based on the monitoring data during 2007-2017, provided that the Prima-Era initiation system was used, the experimental seismic factor value has been obtained $K_f = 138 \pm 11$; in the case of detonating fuse application – $K_f = 110 \pm 12$. The obtained value of K_f in accordance with the method described above makes possible to determine the dependence between the maximum value of the explosive quantity and the seismic vibrations level that can occur as a result of the simultaneous initiation of the corresponding mass of explosive. The calculation results of the seismically safe mass of explosive under the condition of using the detonating fuse are shown in Figure 6, and for non-electric Prima-Era and Nonel systems – in Figure 7.

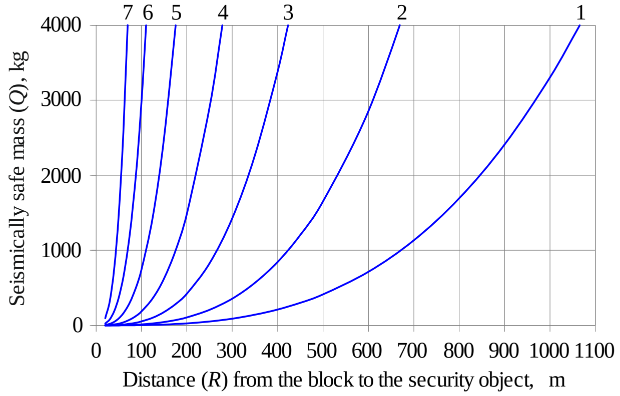

Figure 6. Dependences of the seismically safe mass of an explosive on the distance to the security object (for the initiation system "detonating fuse"): 1-6 number of points

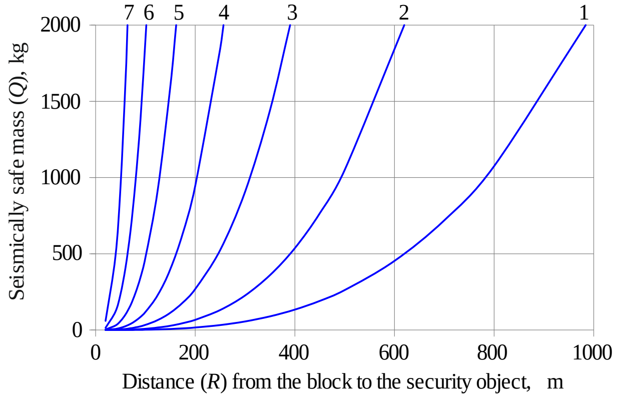

Figure 7. Dependences of the seismically safe mass of an explosive on the distance to the security object (for the initiation system Prima-Era and Nonel): 1-6 number of points

The obtained graphs are proposed for practical use when planning the mass explosions in the No. 3 quarry of PJSC "ArcelorMittal Kryvyi Rih".

The methodology of their use enables to quickly assess the seismically safe parameters of the explosion, which ensure the stability of the sides, slopes of the benches, structures at a specified permissible vibration velocity and is an important condition for improving the drilling and blasting operations, as well as for implementing the developed technology of decommissioning the considered massif between the quarries.

As for the mining operations development, for the studied conditions, the authors propose to plan it with account of possible regulating the mining intensity of a quarry site on the basis of integrated and systematic accounting of mining and geological, technological and economical factors, considering their interconnection, which affect the size and order of the quarry working zone formation. Therefore, the mining operations development should provide a specified intensity of mining the deposit, which is determined by the maximum efficiency of the raw material base development at the plant, under the conditions of varying demand for iron ore products. Regulating the mining intensity of the quarry section is achieved by changing the inclination angles of the quarry working sides in the areas of mining operations concentration, as well as the length and quantity of these sections, which are determined by the optimal values of the working site width and the length of the mining operations active front, providing a standard volume of reserves ready for extraction for a specified ore output in a quarry [23]-[27].

4. Conclusions

Used in this work complex research principle and systematic synthesis of the obtained results make possible to substantiate a conceptually coherent logic and a sequence for the adjacent quarries development, as well as the operational content of the proposed technology in terms of their spacial union.

The most important results of the work are in concretization of:

– parameters and state of the pillar between adjacent quarries and its zonal suitability for mining;

– potential impact of the ore volumes extracted from the pillar on the ore-dressing plant loading;

– algorithm and parameters of the pillar development by drilling and blasting technology;

– an algorithm for planning the mining operations development and designing the mining intensity at a quarry site.

According to the authors, the practical application of the research results in terms of designing and planning works will significantly increase the adequacy of their decisions.

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The authors express their deep gratitude to the Head of the Research and Development Laboratory for quality control of iron ore raw materials, Professor A.A. Azaryan, as well as the staff of the Department of Open Pit Mining at Kryvyi Rih National University for their assistance when implementing the scientific developments and their introduction into production.

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Науково-прикладні та системні проблеми взаємодії суміжних гірничо-збагачувальних комбінатів на прикладі ліквідації масиву, розділяючого їх кар'єри

В. Азарян, С. Луценко, С. Жуков, А. Скачков, Р. Заярський, Д. Тітов

Мета. Визначення можливих і обґрунтування доцільних варіантів проектно-технологічних рішень щодо етапу просторового з'єднання суміжних кар'єрів різних власників на прикладі розробки породного цілика між кар'єром №3 ПрАТ "АрселорМіттал Кривий Ріг" і кар'єром ПрАТ "Південний гірничо-збагачувальний комбінат" з включенням до відпрацювання запасів, виїмка яких є можливою в межах існуючих гірничого та земельного відводів.

Методика. Використано комплексний методичний підхід, що включає гірничо-геологічний аналіз породного масиву між двома суміжними кар'єрами, який підлягає ліквідації; техніко-економічний аналіз ефективності експлуатації рудозбагачувальної фабрики при зниженні продуктивності рудника внаслідок доробки родовища; теоретичне обґрунтування проектних і технологічних рішень щодо параметрів об'єктів кар'єру за даних умов та продуктивної розробки розділяючого кар'єри породного цілика.

Результати. Проаналізовано стан проектів і планів розвитку гірничих робіт кар'єру №3 ПрАТ "АрселорМіттал Кривий Ріг" і кар'єру ПрАТ "Південний гірничо-збагачувальний комбінат", що свідчить про їх просторове з'єднання в найближчі роки. Виявлено, що ліквідація породного цілика між кар'єрами ускладнюється як просторово, так і технологічно, особливо внаслідок сейсмічних обмежень, але запропоновані рішення і заходи максимально спрощують й убезпечують даний етап. Встановлена проблема зниження завантаження збагачувальних фабрик пропорційна падінню видобутку руд. Техніко-економічні розрахунки доводять, що відповідне зазначеному послідовне виведення збагачувальних секцій рудозбагачувальних фабрик є доцільним на одному зі взаємодіючих ГЗК.

Наукова новизна. Вдосконалено комплексний підхід щодо еволюції гірничо-збагачувальних комбінатів на стадії наближення їх кар'єрів до граничних глибин та кінцевих контурів за рахунок врахування суміжних рудників як єдиної складної динамічної системи. Адаптовано аналітичні обґрунтування технології буро-підривного руйнування скельних порід до конкретних умов ліквідації міжкар'єрного цілика.

Практична значимість визначається високим рівнем придатності їх до впровадження та використання в проектуванні розвитку гірничих робіт кар'єрів ПрАТ "АрселорМіттал Кривий Ріг" і ПрАТ "Південний гірничо-збагачувальний комбінат".

Ключові слова: *кар'єр, породний масив, підривання, рудозбагачувальна фабрика, концентрат, вміст заліза*

Научно-прикладные и системные проблемы взаимодействия смежных горно-обогатительных комбинатов на примере ликвидации массива, разделяющего их карьеры

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Цель. Определение возможных и обоснование целесообразных вариантов проектно-технологических решений относительно этапа пространственного соединения смежных карьеров различных собственников на примере разработки породного целика между карьером №3 ЧАО "АрселорМиттал Кривой Рог" и карьером ЧАО "Южный горно-обогатительный комбинат" с включением в отработку запасов, выемка которых возможна в рамках существующих горного и земельного отводов.

Методика. Использован комплексный методический подход, включающий горно-геологический анализ породного массива между двумя смежными карьерами, который подлежит ликвидации; технико-экономический анализ эффективности эксплуатации рудообогатительной фабрики при снижении производительности рудника в результате доработки месторождения; теоретическое обоснование проектных и технологических решений относительно параметров объектов карьера при данных условиях и продуктивной разработки разделяющего карьеры породного целика.

Результаты. Проанализировано состояние проектов и планов развития горных работ карьера №3 ЧАО "АрселорМиттал Кривой Рог" и карьера ЧАО "Южный горно-обогатительный комбинат", что свидетельствует об их пространственном соединении в ближайшие годы. Выявлено, что ликвидация породного целика между карьерами осложняется как пространственно, так и технологически, особенно в результате сейсмических ограничений, но предложенные решения и меры максимально упрощают и защищают данный этап. Установленная проблема снижения загрузки обогатительных фабрик пропорциональна падению добычи руд. Технико-экономические расчеты доказывают, что соответствующее указанному последовательное выведение обогатительных секций рудообогатительных фабрик является целесообразным на одном из взаимодействующих ГОК.

Научная новизна. Усовершенствован комплексный подход к эволюции горно-обогатительных комбинатов на стадии приближения их карьеров до предельных глубин и конечных контуров за счет учета смежных рудников как единой сложной динамической системы. Адаптировано аналитические обоснования технологии буровзрывного разрушения скальных пород к конкретным условиям ликвидации междукарьерного целика.

Практическая значимость определяется высоким уровнем пригодности их к внедрению и использованию в проектировании развития горных работ карьеров ЧАО "АрселорМиттал Кривой Рог" и ЧАО "Южный горно-обогатительный комбинат".

Ключевые слова: *карьер, породный массив, подрыв, рудообогатительная фабрика, концентрат, содержание железа*

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