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Environmental assessment of backfill-based mining technologies for sustainable development of pit-wall zones

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ABSTRACT
The article provides an environmental assessment of the use of technologies for backfilling mined-out areas in the contour zones of quarries from the perspective of sustainable development of mining territories. The relevance of the study is due to the need to reduce the negative impact of mining operations on the environment and to improve environmental safety in the development of mineral resources. The main focus is on the analysis of backfilling technologies as a tool for minimising man-made disturbances, stabilising the geological environment and reducing deformation processes in the contour zones. The research methodology is based on the assessment of a set of environmental and geotechnical indicators characterising the stability of the rock mass, the level of ground surface disturbances and the degree of environmental risk. The results of the study show that the use of backfill technologies contributes to reducing the impact of mining operations on the environment and increasing the stability of mining facilities. The conclusions confirm the feasibility of introducing environmentally oriented mining technologies as one of the directions for ensuring sustainable development and implementing the principles of environmentally responsible nature management
Keywords: environmental assessment; sustainable development; backfill technology; environmental impact; mining sustainability; pit-wall stability

INTRODUCTION:

The intensive development of the mining industry plays an important role in ensuring economic growth and resource security for countries, but at the same time it is accompanied by a significant anthropogenic impact on the environment. The contour zones of quarries are particularly vulnerable in ecological and geotechnical terms, where the disruption of the natural balance manifests itself in the form of deformation of the sides, intensification of landslide processes, changes in hydrogeological conditions, and degradation of land resources. In these conditions, ensuring the sustainable development of mining areas requires the implementation of technological solutions aimed at minimizing the negative consequences of mineral resource development [1–2].

One promising way to reduce the environmental impact of open-pit and combined mining is to use backfill technologies. The use of backfill materials not only allows for the disposal of mining waste, but also increases the stability of the rock mass, reduces the intensity of deformation processes, and limits the spread of man-made disturbances beyond the boundaries of the mining area. In the context of modern concepts of environmentally oriented subsoil use, these technologies are considered an effective tool for creating a safe and sustainable mining system.

The relevance of environmental assessment of backfill technologies is determined by the need for a comprehensive analysis of their impact on the state of the geological environment and adjacent ecosystems [3]. In particular, issues related to the interaction of the backfill massif with surrounding rocks in the contour zones of quarries, as well as their role in reducing environmental risks and ensuring the long-term stability of mining structures, remain insufficiently studied [4]. With the increasing requirements for environmental responsibility of mining enterprises, there is a growing need for scientifically based approaches to assessing the effectiveness of the technologies used from the perspective of sustainable development.

The purpose of this study is to conduct an environmental assessment of backfill technologies in the contour zones of quarries from the point of view of ensuring the sustainable development of mining areas. The paper examines the impact of backfilling solutions on the stability of quarry walls, the level of disturbance to the earth's surface, and the environmental safety of the surrounding area. The results obtained justify the feasibility of introducing environmentally oriented mining technologies as one of the key areas of rational and responsible nature management.

Materials and methods of research

The research materials consisted of data from engineering-geological and environmental surveys conducted within the contour zones of existing and planned quarries. The analysis included characteristics of the geological structure, physical and mechanical properties of rocks, parameters of the deformation state of the rock mass, as well as indicators of ground surface disturbance and anthropogenic transformation of the natural environment. In addition, the results of production observations of the condition of quarry walls and backfill masses formed using various technologies for backfilling mined-out spaces were used.

The methodological basis of the study is based on a comprehensive approach combining ecological and geotechnical assessment of the stability of mining systems. The assessment of the environmental condition of the contour zones of quarries was carried out on the basis of an analysis of a set of indicators characterising the degree of anthropogenic impact on the geological environment, the level of deformation of the sides and potential environmental risks. The key parameters considered were the stability of the rock mass, the intensity of deformation processes, the nature of the spread of man-made disturbances, and the degree of their impact on adjacent natural components.

To assess the effectiveness of backfilling technologies, a comparative analysis of development options with and without backfilling was performed. The comparison was based on indicators of quarry wall stability, the extent of ground surface deformation, and the level of environmental safety of mining operations. The geotechnical stability of the rock mass was assessed using calculation schemes based on the limit state of the rock and analysis of the stress-strain state in the zone affected by mining operations.

The environmental assessment of backfilling solutions was carried out taking into account the principles of sustainable development and rational nature management [5]. The impact of backfilling the mined-out space on reducing the volume of man-made voids, decreasing the area of disturbed land, and stabilising the geological environment in the contour zones of quarries was analysed. The data obtained was processed using methods of generalisation and systematisation, which made it possible to identify patterns in the impact of backfilling technologies on the environmental and geotechnical stability of mining facilities.

Results of the study

The analysis showed that in deposits with complex geological structures, ore bodies outside the planned contour of the open pit are characterised by significant variability in shape and thickness, uneven distribution, high fracturing and, in some cases, a tendency to spontaneous combustion. These features significantly complicate the use of traditional mining methods and increase environmental and geotechnical risks when developing areas outside the quarry boundaries. It has been established that issues related to the extraction of reserves outside the contours of quarries in conditions of complex ore body structure remain insufficiently systematised and require comprehensive scientific justification [6-7]. The results of the study show that when developing reserves located in berm zones and under the bottom of the quarry, priority is given to technologies that ensure the safety of mining operations, preserve the stability of the quarry walls, and minimise losses and dilution of ore. Analysis of practical experience has shown that the most stable and environmentally safe mining conditions are achieved when using mining systems with backfilling of the mined space [8]. The use of such systems makes it possible to abandon technologies based on the collapse of ore and host rocks, which in the contour zones can lead to deformation of the sides and disruption of the ecological balance. It has been established that backfilling of mined underground workings, especially using hardening materials, contributes to the stabilisation of the rock mass, reduction of stresses in the contour zones and preservation of the design parameters of the quarry [9]. In complex-structured deposits, where ore bodies often extend beyond the calculated contours both below and above the quarry floor, the use of backfilling technologies ensures more complete and rational use of mineral resources, which is particularly important when developing deposits with high-value ores.

The results of the comparative analysis showed that in cases where the use of a single mining system does not allow the required level of stability and environmental safety to be achieved, it is advisable to use combined mining technologies. Such technologies represent a structurally unified system within which different methods of mining complement each other within a single block or section of the deposit. At the same time, the geomechanical state of the rock mass is managed taking into account the alternation of backfill and collapse zones, which reduces the man-made load on the contour zones of the quarries [10]. Based on the example of complex ore deposits, it has been established that combining systems with backfilling of mined-out areas and local application of caving systems reduces the risk of spontaneous combustion of ores, increases the stability of mine workings, and minimises environmental impact. Alternating backfilled and caving zones contributes to the formation of a stable geotechnical structure that limits the development of deformation processes and ensures the environmental safety of mining operations. The summary of the results showed that the main factors driving the transition to combined and backfill technologies are increased reserve recovery, management of the stress-strain state of the rock mass, reduced production and environmental risks, and the possibility of utilising mining waste as backfill material. The use of low-grade ores and tailings for backfilling mined areas makes it possible to simultaneously reduce the cost of forming the backfill mass and reduce the area of external dumps, which contributes to a reduction in the negative impact on the environment. An analysis of existing mining systems has shown that, in some cases, inclined layer mining systems are used when mining reserves in the contour areas of open pits. These systems can be characterised by increased production efficiency due to the use of gravity in the transportation of both ore and backfill material [11]. At the same time, it has been established that their practical application is limited due to the increased level of production risks associated with mining operations on inclined backfill surfaces, which reduces the overall safety and environmental sustainability of the mining system.

Based on the analysis of the use of backfill systems as part of combined mining technologies, a method for extracting minerals has been developed based on horizontal layer mining of ore bodies followed by backfilling of the mined-out space. The proposed method is focused on the development of deposits with high-value ore reserves and is aimed at increasing the stability of the contour zones of the quarry and reducing the negative impact on the environment (Fig. 1). After the quarry has been brought to its final design position and open-pit mining operations have been completed, the sides and benches of the quarry are filled with internal overburden spoil. Access to the ore body located in the contour zone is provided by a horizontal transport tunnel along the strike of the ore body at the level of the transport berm. This solution ensures minimal interference with the stability of the quarry sides and allows their design parameters to be maintained. Preparatory mining operations include the construction of transport, excavation and ventilation workings. In addition, a ventilation shaft and ore chute are constructed, after which the mining block is prepared. A horizontal transport tunnel is constructed to the boundary of the ore body, parallel to which an excavation tunnel is formed. From the excavation tunnel towards the side of the quarry, mining drifts are constructed to ensure layer-by-layer ore extraction [12]. Cleaning excavation is carried out by sequentially mining the layers of the ore body, with the faces located at an angle to the strike of the ore body and mined in a staggered order. This alternation ensures the redistribution of stresses in the rock mass and increases the stability of the contour zone. Ore extraction within the layer is carried out by drilling and blasting using drilling equipment, after which the broken ore is transported to the surface through the ore chute and transport workings.

After completing the excavation of the next layer, the excavated space is filled with backfill material, which ensures the formation of a supporting medium that stabilises the rock mass. The results of the study show that the sequential alternation of excavation and backfilling processes contributes to a reduction in deformation processes, limits the spread of man-made disturbances, and increases the environmental safety of reserve development in the contour zones of quarries.

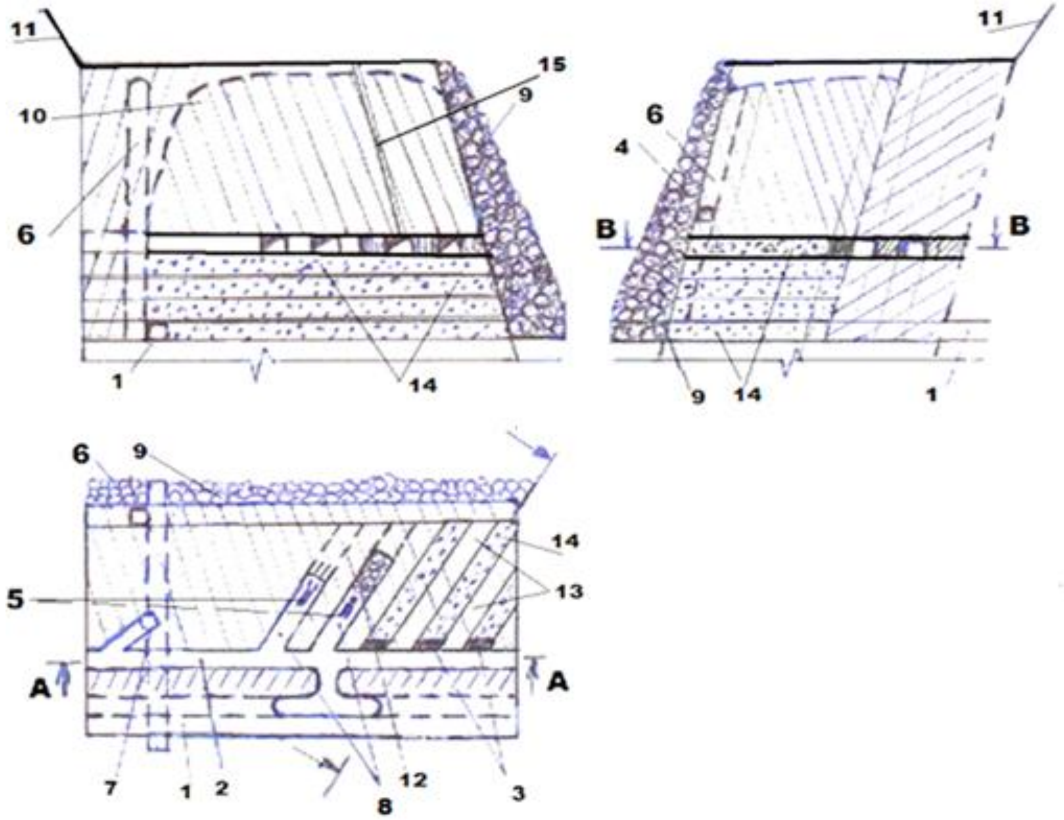

Fig. 1. Method for extracting pit-wall reserves with backfilling in combined mining of deposits: 1 – haulage drift, 2 – slicing drift, 3 – concrete bulkheads, 4 – backfill-ventilation drift,

5 – drilling and loading-hauling equipment, 6 – backfill-ventilation raise, 7 – ore chute, 8 – stope entries, 9 – internal waste dump of subeconomic ore, 11 – pit bench, 12 – caved ore, 13 – ore pillar between stope entries, 14 – backfill mass, 15 – boreholes for backfill material delivery.

Backfilling operations begin after the blasting and extraction of the ore from the layer. The mined-out void is filled with backfill materials (14), moving from the pit toward the rock mass. As backfilling progresses, the entrances of the stope entries are sealed with concrete bulkheads (3). Once the backfill has hardened in the entries, the remaining ore pillars (12) between them are extracted.

In cases where the ore thickness allows for multiple layers in height, the stope entries are mined in a staggered (checkerboard) pattern, with the ore reserves extracted from bottom to top. The broken ore from the upper layers is discharged into the horizontal workings through the ore passes. The results showed that this sequence of operations contributes to the effective redistribution of stresses in the contour zone and reduces the impact of underground mining operations on the stability of the quarry wall. The formation of a backfill mass prevents the development of loosening zones and limits the spread of deformations towards the surface, which is of fundamental importance for environmentally oriented subsoil use. With the ore body's capacity allowing for mining in several layers vertically, the cleaning passes are worked out in a staggered order, with reserves being extracted from the bottom up. It has been established that this scheme provides additional stability to the rock mass due to the phased formation of the backfill mass and the preservation of temporary support elements. The ore broken from the upper layers is transported to horizontal workings through ore chutes, which eliminates the impact of mining operations on the surface and reduces the area of disturbed land.

A comprehensive assessment has shown that the use of internal dumps of substandard ore and mining waste as backfill material allows both technological and environmental issues to be addressed simultaneously. Reducing the volume of external waste storage reduces the man-made impact on the environment, while filling underground voids helps to stabilise the rock mass in the areas adjacent to the quarry. Thus, the results of the study confirm that the proposed method of extracting reserves in contour areas using horizontal layer excavation and backfilling of the mined space ensures increased stability of quarry walls, reduced environmental risks, and implementation of sustainable development principles in the development of mineral deposits.

DISCUSSION

The results obtained in the course of the study are consistent with and develop the conclusions of previously published works devoted to the problems of developing reserves in the peripheral areas of quarries in conditions of combined deposit development. A number of studies emphasise the need to introduce innovative and integrated approaches to subsoil use aimed at increasing the completeness of mineral extraction while reducing the negative impact on the environment. These provisions confirm the advisability of using backfill technologies, which are considered in this paper as a key element of environmentally oriented mining solutions.

The results of studies on the use of combined mining systems have shown that the integration of various technologies, such as sublevel caving and ore storage systems, can significantly increase the recovery rate of reserves in conditions of complex ore body morphology. These conclusions are confirmed by the results of this study, which shows that the use of horizontal layer mining with backfilling of the mined space provides technological flexibility and adaptation of the mining system to changing geological conditions.

Analysis of literature data also indicates the advantages of combined underground systems, including improved control of the geomechanical condition of the rock mass, reduced dilution, and the possibility of utilising mining waste as backfill material. The results obtained in the study confirm these statements, especially in terms of combining economic and environmental benefits when using substandard ores and tailings to fill underground voids.

Practical experience in the application of phased extraction of reserves with backfilling in complex and fire-hazardous deposits has shown that alternating between cleaning and backfilling operations helps to reduce the risk of spontaneous combustion of ores and improve the overall safety of mining operations. These provisions are also reflected in the technological scheme proposed in this study, which is focused on the phased mining of ore bodies with the mandatory formation of a stable backfilling massif.

The results of studies devoted to changes in the physical and mechanical properties of rocks during mining operations are of additional importance, as they emphasise the need for constant monitoring and adaptation of engineering solutions. The inclusion of backfill materials in the structure of the mining system, as shown in this work, makes it possible to compensate for negative geomechanical effects and ensure the long-term stability of the contour zones of the quarry.

Overall, discussion of the results of previous studies confirms that the proposed method of horizontal layer mining with backfilling of the mined-out space is consistent with modern theoretical concepts and practical experience in deposit development. At the same time, this technology is a structurally integrated solution that ensures increased reserve recovery, mining safety and minimisation of environmental damage, which is fully consistent with the principles of sustainable development of mining areas.

CONCLUSIONS

The assessment of the environmental and geomechanical consequences of using backfill technologies in the combined development of deposits in the near-contour zones of quarries has shown their high efficiency in terms of the sustainable development of mining areas. The use of backfilling of mined-out areas is considered a technologically and environmentally sound solution aimed at stabilising the geological environment, reducing the scale of man-made disturbances and improving the environmental safety of mining operations.

The following main conclusions were drawn from the research:

It has been established that the use of backfilling technologies in combined deposit development significantly reduces the negative man-made impact on the geological environment and adjacent natural ecosystems in the areas surrounding quarries. It has been shown that the use of horizontal-layer extraction of reserves with mandatory backfilling of mined-out spaces increases the stability of quarry walls by redistributing the stress-strain state of the rock mass and limiting the development of deformation processes. It has been established that the formation of a backfill mass contributes to a reduction in the volume of man-made voids, a reduction in the area of disturbed land and the localisation of the zone of influence of mining operations, which increases the level of environmental and geomechanical safety of reserve development. The feasibility of using substandard ores and mining waste as backfill material has been substantiated, which makes it possible to simultaneously solve the problems of waste disposal, reduction of external dumps, and rational use of mineral resources. The results obtained confirm the effectiveness of introducing environmentally oriented backfill and combined mining technologies as a tool for the sustainable development of mining areas, ensuring a reduction in environmental risks and the implementation of the principles of responsible subsoil use.

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