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Substantiation of mining systems for steeply dipping low-thickness ore bodies with controlled continuous stope extraction

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Abstract

Purpose. The solution to one of the important problems of the underground mining method is to substantiate cost-effective, technologically feasible and safe variants for mining steeply dipping low-thickness ore bodies.

Methods. Mining systems are substantiated on the basis of a detailed analysis of the developed and existing experiential variants for mining steeply dipping ore bodies, identifying production and economic disadvantages, as well as their causes.

Findings. As a result of the research, the pillar raise performance in the mining system with ore shrinkage has been substantiated. The main parameters of the proposed variants for mining systems with ore shrinkage, intended for expansion-type supports and borehole breaking, have been substantiated. A design has been developed of fastening the material-running raises (MRR) and ventilating raises (VR) on the working and ventilation horizons to ensure their performance in the mining system with ore shrinkage.

Originality. For the first time, dependences of dilution and labour productivity on the ore body thickness and the type of ore breaking for blast-hole stoping and borehole breaking for a single and “twinned block” have been obtained. In addition, a certain dependence of the loading and delivery performance on the average fractional composition, as well as on the delivery distance, has been obtained.

Practical implications. The research is characterized by scientific innovations created for the first time, which are able to ensure the efficiency and safety of mining operations, while creating the ability to manage the loss of minerals and dilution in the block, as well as reaching their calculated optimal ratio in order to achieve the most cost-effective production rate.

Keywords: *ore, ore body, production, mining operations, mining practice, stope extraction*

1. Introduction

The use of one or another mining system that meets the requirements of safety, efficiency, productivity of a labour unit [1]-[3] and an extraction site is the most important factor in the successful operation of the entire enterprise [4]-[6].

The transition to innovative technologies of the 21st century, which should also take into consideration new challenges related to the need to maintain natural balance and ensure the minimization of quantitative and qualitative losses, requires time to create these technologies [7], [8]. Therefore, in parallel with this main research activity, it is necessary to work on improving the currently used technologies [9]-[13]. At the same time, it is necessary to pay attention to technologies that provide backfilling of cavities in the mined-out space [14]-[17], safe blasting operations [18], [19], as well as detailed production processes planning [20]-[22].

The most in need of improvement of technological schemes, structural elements and organization of production processes are variants of the mining system with ore shrinkage, due to the use of which the main share of ore is mined from steeply dipping low-thickness ore bodies [23]-[25]. When implementing such types of technological schemes influence on the environment and prediction of groundwater inflow must be considered [26]-[29] as well as geological conditions [30].

The mining systems with ore shrinkage are widely used in mining of vein deposits of rare metals and gold [31], [32]. It should be noted that in recent years the scope of these systems has expanded significantly due to the creation of new types of fastening elements [33]-[35]. A distinctive peculiarity of mining systems with ore shrinkage is that the mined-out area is backfilled with broken ore, which serves to support the host rocks or is used as a kind of platform for workers [36]-[38]. In all cases, after the completion of the block mining, the broken ore is completely drawn out [39], [40]. When using these systems, it should be taken into account that the broken ore occupies a larger volume than it has in the mass [41], [42]. This should be taken into consideration when determining the required value of compensation area [43], [44].

The main disadvantages of the used mining system variants with ore shrinkage with blast-hole stoping [45]-[49] are:

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– additional driving of cut-out raises parallel to the material-running and ventilating raises, leaving between them of columned pillars with "windows" between the pillars along these raises. These pillars remain in losses, since these pillars cannot be mined (if they are broken out for mining along with ore breaking in the shrink stope when the front of stoping operations is advanced from the bottom up, then the rock from the previously mined-out and collapsed block will freely flow into the working block and increase the dilution many times); these operations increase the volume of development work, ore losses and/or dilution by almost 2 times;

– the problem of ore mining from the entry pillars, access to which is impossible for drilling due to their length along the entire block strike. Proposed in the literature, breaking of the entry pillars by drilling vertical rod blast-holes from the surface of the shrinked ore is far from safe and inefficient;

– in variants with the use of self-propelled equipment for loading with end drawing from the inclines, the issue of maintaining the performance of the raises leaving the working block to the previously mined-out collapsed block on the upper horizon has not been resolved;

– in variants with scraper delivery, there are no design solutions for breaking ore in the stump pillar and in the pillar between the scraper drift and the undercutting horizon.

When using the proposed mining system variants with ore shrinkage with borehole breaking [47]-[50], the main disadvantages are as follows:

– pillars are not left during the period of breaking between the working and mined-out blocks. Therefore, the rock from the mined-out block will be constantly mixed with the ore at each cycle of drawing the broken ore from the shrink stope of the working block. In this regard, the volume of commercial ore mined will increase sharply, the mineral content in it will sharply decrease and the production profitability will become negative;

– breaking with paired cuts also does not allow to achieve controlled ore drawing due to the connection of the working block stope space with caving in the mined-out block;

– design issues of mining the entry pillars and stump pillars have not been resolved.

A common disadvantage inherent in the variants with blast-hole stoping and borehole breaking is the inability to continuously perform ore drawing, control losses, dilution and productivity of the extraction site.

The paper purpose is to familiarize the scientific community, employees of design organizations, specialists of production structures and management of mining companies with the created mining system variants with shrinkage, the use of which eliminates the above disadvantages of the currently used variants and creates a controlled flow production process. The task set is based on the formulated purpose, therefore, it takes into account all the negative problems created by both natural (objective) and technogenic causes.

2. Methods

An innovative peculiarity of all the proposed variants is the creation of "twinned block", which ensures the continuity and controllability of the process. The following mining system variants with ore shrinkage, accepted for implementation on an industrial scale, have been developed [51], [52]:

– with blast-hole stoping with blast-holes rising from a "twinned block" with material-running raises, fastened in two compartments;

– with blast-hole stoping with blast-holes rising from a "twinned block" with material-running raises, equipped with mechanized monorail complexes;

– with borehole breaking from a "twinned block" with material-running raises, equipped with mechanized monorail complexes.

"Double blocks" on the two extreme sides along the strike are bordered by ventilating raises (VR), along which pillars are left along the rise, alternating with "windows" – exit opening to the stope space.

At the same time, in the proposed variants, the working conditions are organized in such a way that these pillars may not be left, depending on the impact of excessive dilution on the final economy.

The structure and sequence of the conducted research are based on the study and analysis of mining systems with shrinkage used in practice (Corporation Kazakhmys LLP, JSC Kazakhaltyn MMC) and those proposed in scientific works [45]-[48]. This methodology for solving the set task makes it possible to concretize the problems and helps to obtain the initial information used for comparative analysis, as well as to determine the directions to eliminate the negative impact of these problems.

The disadvantages of the commonly used mining system variants with shrinkage have been eliminated in the designs of the proposed variants. In addition, the possibilities for managing technological processes have been created, which make it possible to vary the value of losses and dilution depending on technical-and-economic indicators and the final profitability achieved, taking into account labour productivity:

– massive, almost continuous ore breaking is provided with telescopic blast-holes with a constant ore drawing for shipment on the transport horizon by self-propelled equipment;

– the need of arranging the spiral declines for the entire height of the block in the footwall rock, as in the case of sublevel caving, is eliminated. This provides significant savings from reducing the development work, from reducing the cost for expensive self-propelled equipment;

– the safety of stoping operations is ensured and the possibility of maneuvering is created in the event of emergencies associated with the disturbance of the host rock stability in the footwall and hanging wall of the ore body;

– a practical opportunity is created to conduct stoping operations with the maximum consideration of geological disturbances and, thereby, to reduce dilution when the ore body is displaced.

The pillars along the ventilating raises temporarily remain in losses, because, firstly, there is no access to them for their drilling and blasting; secondly, it is necessary with their use to prevent the ingress of ore and rock into adjacent prepared block.

Dilution reduction is also achieved by the following design peculiarities and organizational measures:

– massive blast-hole stoping with telescopic rising blast-holes contributes not only to an increase in labour productivity and an increase in the block thickness for ore mining per unit time, but also to a constant bearing to the rocks in the hanging wall and footwall of the ore in the shrink stope along the entire strike and the possibility of fastening unstable, capable of collapsing weakened areas of the block. While with the existing methods of breaking with horizontal blast-holes, both from one bench and from an overhead stope, there is no possibility of absolute control;

– massive and one-time breaking with a calculated deceleration and order of breaking the pillars, along and above the material-running and ventilating raises, accelerated drawing of ore from the block can reduce dilution both from the collapse of rocks in the hanging and footwall of the block itself, as well as from the rock outflow from upper, previously mined-out block.

The proposed mining system variants with ore shrinkage have their own distinctive technological peculiarities and the procedure for organizing preparation and mining [51], [52].

2.1. Mining system with ore shrinkage and blast-hole stoping during mining with fastening of material-running raises in two compartments

The order of development and organization of technological operations that allow realizing all the advantages of the proposed variant (Fig. 1) is as follows. From the ore drift *1*, drilling is conducted with the help of a telescopic perforator and blasting of the blast-holes drilled along the roof from the side of the cut-out raise *6* along the entire length of the drift. In this case, ventilation is performed through a mine ventilating pressure drop, that is, clean air is supplied from the side of the fringe drift *2* through the inclines and is released through the ventilating raise *10* to the upper horizon.

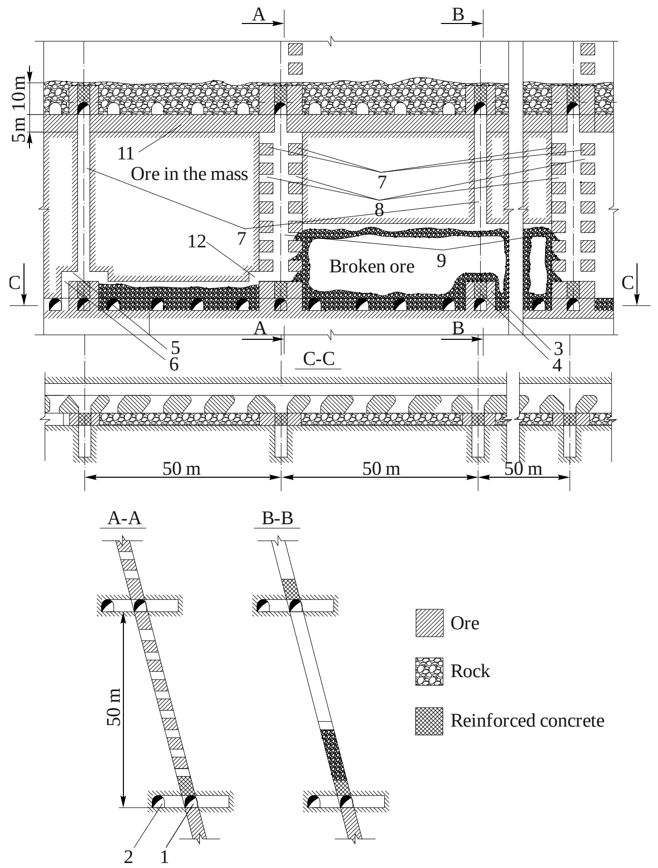

***Figure 1.** Mining system with ore shrinkage and blast-hole stoping with blast-holes rising from a "twinned block" with fastening of material-running raises in two compartments: 1 – shrink (ore) drift; 2 – haulage (fringe) drift; 3 – pillars above raises; 4 – reinforced concrete "plugs"; 5 – cut-out "window"; 6 – cut-out raise; 7 – support pillars along the material-running raises; 8 – "windows" along the material-running raises; 9 – material-running raises; 10 – material-running raises; 11 – entry pillar; 12 – running raise*

The broken rock mass will be something like a cushion for the next roof drilling cycle. As the face advances along the rise, the broken ore will be drawn out through the inclines from the fringe drift *2*. The driller enters the working face through the material-running raise No. 2 from the upper horizon along the running compartment through the "windows" into the face and performs drilling and blasting. Drilling is conducted with a telescopic perforator, depending on the project of work organization (on the number of simultaneously working drillers), for the entire length of the block along the strike or for part of the block. As the ore is broken, up to 30% of the ore cushion is drawn out with loading from the inclines to the fringe drift *2*. If the stope extraction is performed from material-running raises, fastened in two compartments, an entry pillars is left under the upper (ventilation) horizon. The ore from this horizon, in the presence of a collapsed stope space above the rock horizon, can be mined out lastly by drilling and breaking with downward wells from the ventilation horizon. On the one hand, this will increase dilution due to the rock ingress from the upper collapsed space, but will reduce losses.

The technologically necessary through driving of material-running and ventilating raises with maintaining their performance for the period of the stoping operations is an obstacle to the extraction of entry pillars and stump pillars, as well as the use of material-running and ventilating raises until the completion of stoping operations without ingress of collapsed rock from the upper mined-out block into the block working space. This problem can be solved by a special design for the construction of reinforced concrete plugs *4*. The construction of reinforced concrete plugs *4* makes it possible to organize safe and productive drilling and blasting of ore reserves left in the pillars along the material-running and ventilating raises *9* and *10*. The creation of a "twinned block" on both sides of the material-running raise creates conditions for increasing the block productivity, creating safe working conditions, controlled and continuous mining. The use of the ore drift *1* as an exposed plane for ore breaking significantly reduces losses and dilution along with the other advantages of the invention mentioned above.

2.2. Mining system with ore shrinkage and blast-hole stoping with material-running raises, equipped with mechanized monorail complexes

The practical application of the "twinned block" principle creates conditions under which pillars are not left on both sides along the material-running raises, located in the centre of the "twinned block", and thus irretrievable losses during the stope extraction are reduced. Along the ventilating raises, also driven with the use of mechanized complexes, the pillars are left only on one side, elongated and increased in height compared to the size of generally accepted ones, which contributes both to reducing losses and increasing the load-bearing capacity of the pillars. These pillars can also be repeatedly broken down, depending on the results of the financial and economic model when assessing losses and dilution. Figure 2 shows mining system with ore shrinkage and blast-hole stoping with rising blast-holes from a "twinned block" with material-running raises, equipped with mechanized monorail complexes. The columned pillars left along the ventilating raises from one side will not allow the rock from the twinned mine-out block No. 0 to penetrate into the shrink stope of block No. 1 and the rock from the twinned mined-out block No. 1, after its mining and breaking of the entry pillars, to penetrate into block No. 2.

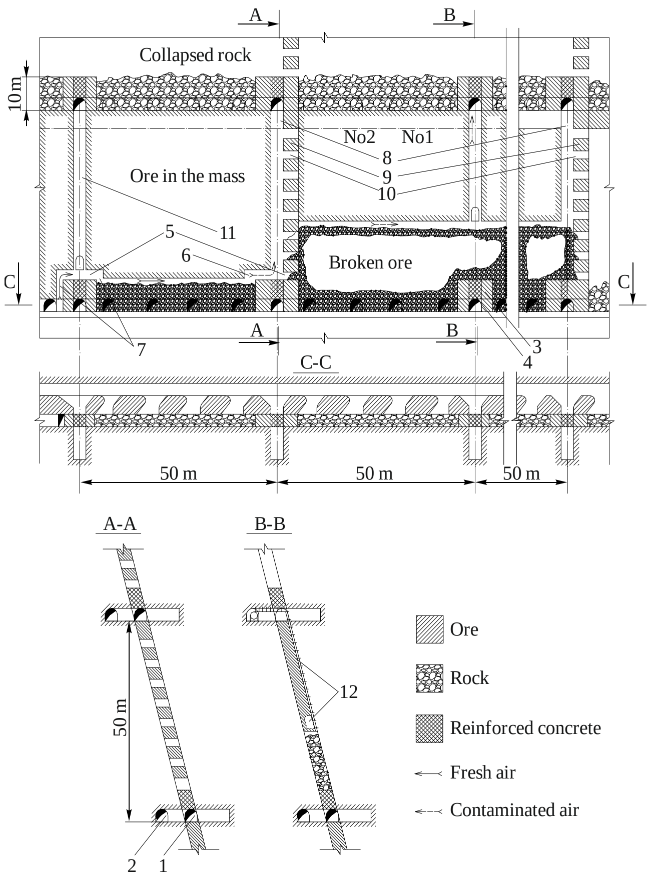

Figure 2. ***Mining system with ore shrinkage and blast-hole stoping with rising blast-holes from a "twinned block" with material-running raises, equipped with mechanized monorail complexes: 1 – shrink (ore) drift; 2 – haulage (fringe) drift; 3 – pillars above raises; 4 – reinforced concrete "plugs"; 5 – cut-out "window"; 6 – cut-out raise; 7 – running raise; 8 – ventilating raise; 9 – support pillars along the ventilating raises; 10 – "windows" along the ventilating raises; 11 – material-running raises; 12 – mechanized monorail complexes***

Therefore, the ore mined in blocks No. 1 and 2 can also be minimally diluted. Breaking with telescopic blast-holes can make it possible to most accurately consider the displacement of the veins along the plane of faults and thus, even within the same shrink stope (twinned block), prevent excessive dilution, which previously was considered impossible in the technology of using mining systems with shrinkage.

Thus, the stope unit, which is at the stage of ore breaking, starting from the creation of a compensation area, is a "twinned" standard block, bordered by ventilating raises on both sides of the block boundaries along the strike, with the material-running raise located in the centre of the "twinned" block, in which, after driving, a mechanized monorail complex (MMC) is left, which serves in the upper area to deliver people and materials to the stope space for shrinked ore in order to continue the complex of technological processes for ore breaking.

In the lower area, material-running raise serves as a slot, which, together with the lower exposed plane created by breaking the ore onto the shrink (ore) drift of the lower horizon, after it reaches the upper level of the pillar above the material-running raise along the vertical, creates a compensation area with two exposed planes.

2.3. Mining system with ore shrinkage and borehole breaking from a "twinned block" with material-running raises, equipped with mechanized monorail complexes

The mining system design, outwardly similar to the well-known variants of the traditional stope block, along the strike length depends on the optimal depth of horizontal wells. The latter are drilled from the cabin BPO-20 (BPO-1.5) or other similar mechanized monorail complexes, which provide the drilling rig setting for drilling in both directions from the material-running raise (Fig. 3).

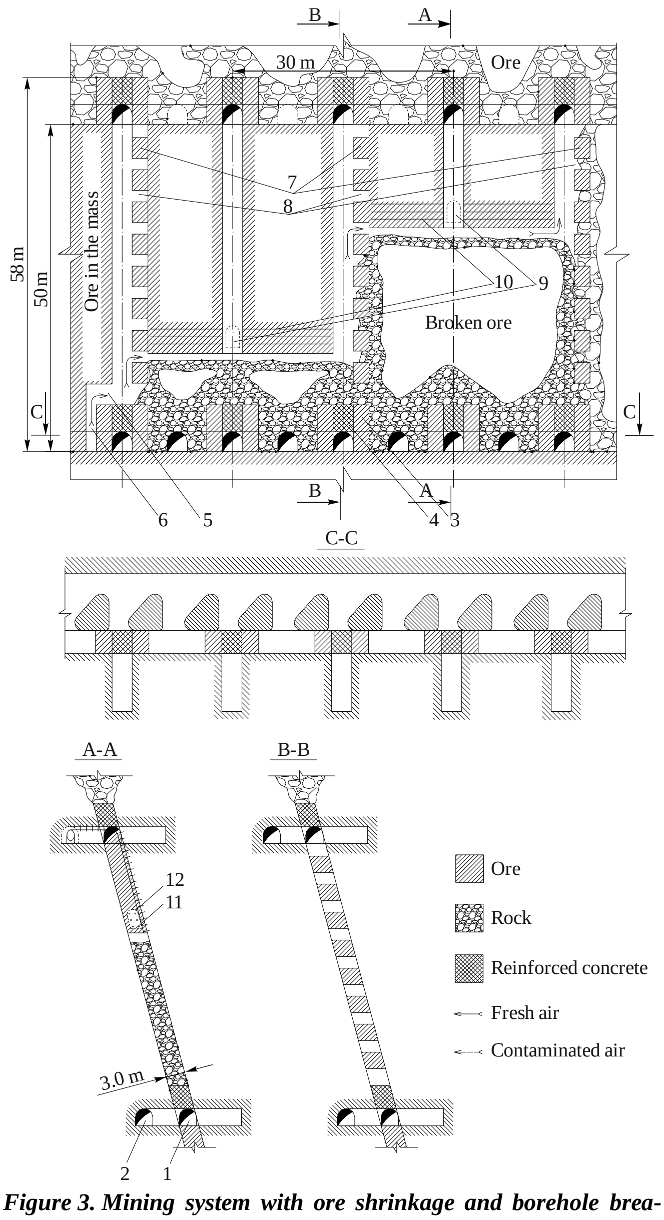

Figure 3. ***Mining system with ore shrinkage and borehole breaking from a "twinned block" with material-running raises, equipped with mechanized monorail complexes: 1 – shrink (ore) drift; 2 – haulage (fringe) drift; 3 – pillars above raises; 4 – reinforced concrete "plugs"; 5 – cut-out "window"; 6 – cut-out raise; 7 – support pillars along the ventilating raises; 8 – "windows" along the ventilating raises; 9 – mechanized monorail complexes; 10 – wells for the broken ore; 11 – drilling rig; 12 – monorails***

The block is prepared structurally in the same way as the previously described variants. Along the ventilating raises, along the height on one side of the ventilating raises, namely, from the side opposite to the broken block or in the process of preparation for breaking, support pillars are left. Their dimensions in height and length are determined based on the largest dimensions calculated according to 2 variants – geomechanical characteristics and mining-geological conditions, as well as ensuring a guaranteed exclusion of rock outflow from a previously mined-out block into a working block, ore during blasting of a shrink stope and rock from a possible collapse of a footwall and hanging wall of the mined-out block after breaking of the entry pillars and pillars above the material-running and ventilating raises when flowing at a repose angle into the "window" between the pillars.

The order of stoping operations is based on the formation of a "twinned block", for which the stope space is created from two adjacent blocks simultaneously, when the stope space moves upwards as the horizontal wells are broken on both sides of the material-running raise. For borehole breaking, a compensation area is formed with three exposed planes on the side closest to the previously mined-out block, and two exposed planes on the side of material-running raise, opposite to the first side.

Breaking of ore in the shrink stope by boreholes is ensured by the fact that the stope space is first created by blast-hole stoping with telescopic blast-holes of 3-4 ore layers, starting from the roof of the shrink (ore) drift to the upper level of the pillars above the material-running and ventilating raises. To do this, on both sides of the pillars above the material-running and ventilating raises of the lower working horizon, which is the shrink (ore) drift, cut-out raises are driven to the upper edge of the pillars above the material-running and ventilating raises, which are broken into (connected) with the "windows" that were previously driven during the driving of the raises themselves along the upper edge of the pillars. Cut-out raises along the pillars above the ventilating raises are a slot, along the pillars above the material-running raises they are a passage for people to pass into the created compensation area in order to break the layers before this area reaches the level of well drilling.

The last rows of horizontal wells under the shrink (ore) drift of the upper horizon are drilled and blasted simultaneously with the pillars above the material-running and ventilating raises of the block part adjacent to the previously mined-out block. These pillars are drilled with wells from the inclines connecting ore and fringe (haulage) drifts of the upper horizon, which previously served for loading ore during the end drawing of ore above the upper horizon. Before blasting the pillars above the material-running and ventilating raises, the mechanized monorail complex is completely dismantled through the inclines between the ore and rock drifts of the upper horizon, which served as a chamber for its storage during blasting operations on breaking the shrink stope.

The stope space ventilation is performed by natural draught from the lower horizon through a cut-out raise near the ventilating raise, located closer to the block prepared through the "windows" into the stope space above the shrink stope, and the polluted air outlet upwards through the material-running and ventilating raises.

The entry pillar is drilled along from the cabin of mechanized monorail complex with the similar horizontal wells as the entire block before. The pillars above the material-running and ventilating raises are drilled along with ascending blast-hole fans from the inclines between the fringe (haulage) and shrink (ore) drifts, which previously served for the ore shipment from the upper horizon through the end of the incline. Before blasting the wells drilled to break the entry pillar and pillars above the material-running and ventilating raises, the mechanized monorail complex is lifted to the incline of upper horizon, located in the pillar above the material-running and ventilating raises, and then is dismantled and removed to a new work site.

The use of these changes during the stope extraction makes it possible to:

– replace the manual labour of several stope face miners drilling telescopic blast-holes in the stope space with mechanized labour of 1-2 well drillers located in an enclosed space of the mechanized monorail complex cabin;

– achieve high labour productivity in drilling and breaking (up to 400-600 tons of ore per shift with an ore body thickness of 3.0 m) and reduce the cost of breaking by 30-40%;

– reduce losses and dilution during the stope extraction due to the fact that pillars are not left along the material-running raise and along the ventilating raise; the pillars are left only on one side, entry pillars and pillars above the material-running and ventilating raises are temporary and are also exposed to breaking last;

– ensure a decrease in dilution in comparison with the current standards, due to the constant backing of the footwall and hanging wall of the block, strengthened by the explosion force of the blast-hole charges;

– reduce both dilution and losses due to the calculated length of the support pillars and the height of the "windows" along the ventilating raise, which do not allow the rock from the adjacent, previously broken block, to penetrate into the working block stope space;

– reduce losses and dilution due to mass continuous ore drawing from the working block after blasting entry pillar and pillars above the material-running and ventilating raises with quality control of the ore drawing at the end of inclines near the shrink (ore) drift on the lower horizon and monitoring the state of the drawing funnel in the block;

– at the same time from one block raise (material-running raise) to mine 2 blocks in both directions, due to which the ore drawing productivity (output capacity) is increased by 2 times.

3. Results and discussion

In order to create conditions for stoping operations when mining the entry pillars and stump pillars, as well as the use of material-running and ventilating raises until the completion of stoping operations without collapsed rock ingress from the upper mined-out block into the working block space, as described in the typical variants, the through driving of these raises from the bottom of the lower (working) horizon to the bottom of the upper (ventilation) horizon, as well as ensuring their safety until the completion of stoping operations, is technologically necessary.

All the mining system variants with ore shrinkage that are in operation at the production site do not solve these problems both in blast-hole stoping and borehole breaking, neither when using raises fastened in two compartments, nor equipped with mechanized monorail complexes, both with scraper ore delivery, and when using self-propelled equipment.

The created constructive design of the material-running raises makes it possible to eliminate the indicated disadvantages and use the raises until the completion of the block's operation, up to breaking off the entry pillars and stump pillars, the pillars above the raises above the ventilation horizon and partially or completely (depending on the variant used) along the raises in height inside the block, thereby ensuring their performance and safety of operations (Fig. 4).

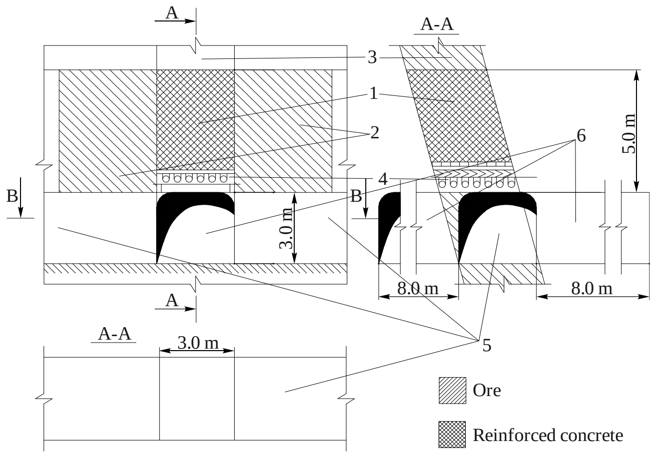

Figure 4. Design of fastening the material-running and ventilating raises on the working and ventilation horizons to ensure their performance in the mining system with ore shrinkage: 1 – reinforced concrete "plug"; 2 – support pillar along the raise; 3 – raise; 4 – wooden cover; 5 – shrink (ore) drift; 6 – inclines (chambers) for sheltering mechanized complexes during the period of mining the raises and ore breaking in the block

The raises in the pillar body, starting from the roof of the shrink (ore) drift to the upper edge of the pillars, are filled with a reinforced concrete "plug", serving together with a completely unified structure that ensures the fulfilment of the above requirements for the constructive design of the pillars and the performance of the raises for their intended purpose. The "plug" is made in the following way. Above the ore drift roof, setting blast-holes for curly brackets are drilled in two rows, on which butt-joints are laid crosswise, on which boards t = 50 mm are also fixed with pins in two rows crosswise. Blast-holes with a depth of 0.5 m are drilled in the body of the raises to the upper edge of the pillars along the perimeter of the raises, and a reinforcing mesh is set in them crosswise one above the other at a vertical distance of 1.0 m throughout the entire section of the raises. The body of the raises is then poured with concrete with the M300 cement consumption in the amount of 200 kg/m^3.

The proposed solution, together with other technological methods, also makes it possible to control losses and dilution in the block, determining their calculated optimal ratio in order to achieve the most cost-effective production rate. The technical parameters and performance indicators of the created designs of mining system variants with ore shrinkage are given in Table 1.

Since the main factors of the advantages of the proposed mining system designs are minimizing dilution and increasing labour productivity, their dependence on the ore body thickness, m (from 0 to 4.0 tons) during blast-hole stoping and borehole breaking have been experimentally determined (with variants of blast-hole stoping with horizontal overhead and vertical blast-holes for a single and "twinned block").

Table 1. The main parameters of the proposed mining system variants (with a standard block length along the strike of 50 m with blast-hole stoping)

No.	Parameter name	Mea. unit	Mining system with ore shrinkage			Mining system with expansion-type support	Mining system with borehole breaking*	
			Ore body thickness, m					
			3.0	2.0	1.0	1.5-2.0	3.0	2.0
1	Length of a twinned block along the strike	m	100	100	100	100	26	26
2	Block height vertically	m	50	50	50	50	50	50
3	Ore body inclination angle (averaged with boundaries from 50 to 90°)	deg.	75	75	75	75	75	75
4	True (inclined) height of the block	m	51.8	51.8	51.8	51.8	51.8	51.8
5	Balance ore reserves in a twinned block	ton	42568	28379	14189	21284-28379	11229	7486
6	Balance ore output	ton	38280	25520	12760	19764-26292	10128	6752
7	Balance ore losses (losses according to mining system)	%	10	10	10	7.2	9.8	9.8
8	Marketable ore total output from a twinned block (p. 6 + p. 9)	ton	43918.7	30755	17997.7	25000.2-31500	12301.9	9333.6
9	Quantity of rock mixed with mined balance ore	ton	5638.7	5235	5237.7	5236.5-5235.0	2173.9	2581.6
10	Total dilution	%	12.84	17.02	29.1	20.95-16.62	17.67	27.7
11	Scope of drifting operations in total, including:	r.m. m^3	403.6 3452	403.6 3452	403.6 3452	403.6 3452	239.6 1976	239.6 1976
12	– by ore	r.m. ton	223.6 4945	223.6 3296	223.6 1649	223.6 2473-3296	149.6 3146.8	149.6 2099
13	– by ore (taking into account the rock ingress when the ore thickness decreases)	r.m. m^3	180 1620	180 3269	180 4916	180 4096-3269	90 810	90 1199
14	Specific consumption of explosives for ore breaking and secondary crushing	kg/t	0.6-0.8 0.06	0.6-0.8 0.06	0.6-0.8 0.06	0.6-0.8 0.06	0.6-0.8 0.06	0.6-0.8 0.06
15	Ore yield from 1 m of wells	ton	–	–	–	–	1.8-2.0	1.8-2.0

*Note: The block length along the strike during borehole breaking is taken according to the effective length of blast-holes

Graphs are shown in Figures 5, 6 and 7. Experimental studies and generalizations have been made for the same mining and mechanical conditions. Labour productivity has been determined by the average indicator without taking into account the time spent on waiting (when the loading point is busy, no passage for a dump truck) and the queue (when there is a lack of loading and unloading points).

Labour productivity is indicated by a symbol P_l – the Productivity of Labour, including preparatory works, drilling, blasting, loading and transportation onto a carriage or conveyor.

It should be noted that the calculation is made for the use of one load-haul machine and a complex of one load-haul machine and one dump truck.

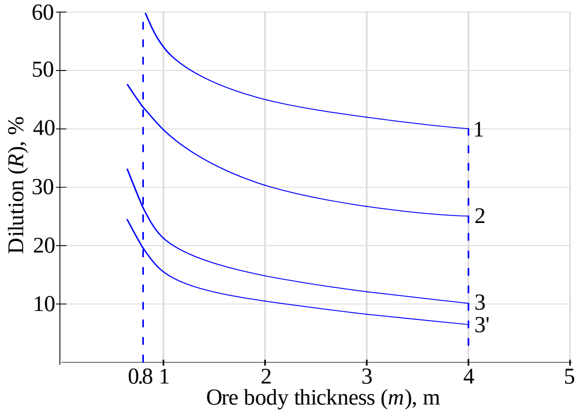

Figure 5. Dependency graph of dilution on the ore body thickness and the type of ore breaking: 1 – borehole breaking; 2 – with horizontal blast-holes; 3 – with vertical blast-holes in a single block; 3' – with vertical blast-holes in a "twinned block"

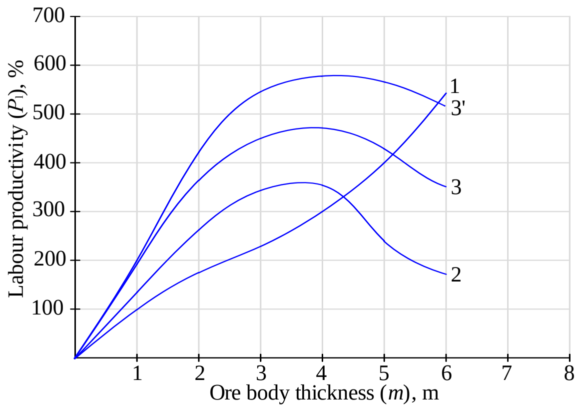

Figure 6. Dependency graph of labour productivity P_l on the ore body thickness and the type of ore breaking: 1 – borehole breaking; 2 – with horizontal blast-holes; 3 – with vertical blast-holes in a single block; 3' – with vertical blast-holes in a "twinned block"

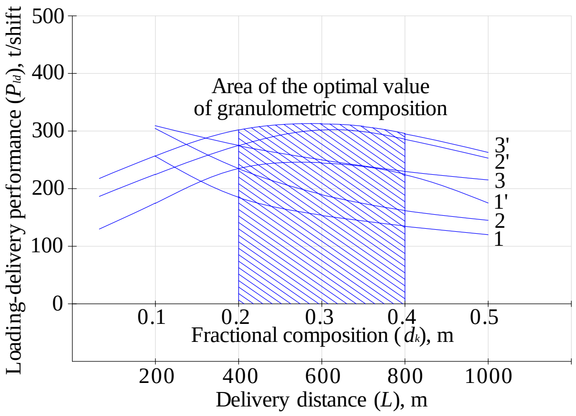

Figure 7. Dependency graph of loading and delivery performance (P_{ld}) on the average fractional composition (d_k) and on the delivery distance (L) with a steeply dipping ore body thickness up to 4.0 m and breaking with vertical blast-holes: 1, 1' – load-haul machine; 2, 2' – complex of load-haul machine and a dump truck (a single block); 3, 3' – complex of load-haul machine and a dump truck (a "twinned block")

The driving velocity of load-haul machine and dump truck (laden and unladen), including unforeseen downtime, is 6 km/h (100 m/min). The duration of loading and unloading of the load-haul machine is 8 minutes and 3 minutes, respectively, and a dump truck with loading on a load-haul machine is 24 minutes, unloading is 9 minutes. The average duration of load-haul operations during a 7-hour shift is 300 minutes from a single block and 360 minutes from a "twinned block". The operating capacity of the load-haul machine bucket is 12.6 tons, the dump truck body is 37.8 tons (the filling factor of the bucket and the body is 0.9). The calculation takes into account Sandvik and Epiroc LH514 and ST14 load-haul machines, Sandvik TH545i and MT42 dump trucks.

The data obtained from the dependences can be useful when mining steeply dipping ore bodies up to 4.0 m thick under the same (identical) mining-geological and mining-engineering conditions for choosing a set of complexes for load-haul operations and mining system variants with ore shrinkage, providing maximum labour productivity and minimal dilution.

New technological schemes have been developed on the basis of ore body preparation in the form of a "twinned block", in which two standard and generally accepted elements of the stoping operations in the form of blocks are combined by one material-running raise [53], [54]. At the same time, during blast-hole stoping of ore, the material-running raise is equipped with fastening in two compartments (cargo and tail). Otherwise, the functions of delivering people and materials are performed by the monorail mechanized complex left in it after driving the material-running raise. The "twinned block" is bordered on both sides along the strike by ventilating raises, driven in the same way as the material-running raises.

The ore breaking in such a block with vertical (inclined) telescopic blast-holes ensures the constant presence of an unlimited front of stoping operations for ore drawing in one block and for ore breaking in another. In addition, it is possible to perform a through ventilation due to the mine ventilating pressure drop and control the production volumes in real-time, thereby creating broken ore reserves and backing of rocks in the sides of the ore body preventing from collapse.

The presence of a front of work for various purposes in two adjacent blocks, to which miners are constantly provided with free access, allows both to control the stable geomechanical state of the host rocks, taking preventive measures, if necessary, for cable or roof-bolt fastening of host rock unstable areas, as well as to take into account fault-thrust geological disturbances, thereby reducing excessive dilution.

Reinforced concrete cushion, created in the material-running and ventilating raises on the ventilation and working horizons, creates conditions for the safe maintenance of all types of work on the preparation and mining of ore, and also eliminates the "short-circuiting" of the outgoing air ventilation jet.

4. Conclusions

The use of the proposed mining system variants with ore shrinkage can eliminate the existing disadvantages and create the possibility of breaking with vertical blast-holes in the plane of strike and inclined blast-holes parallel to the ore body incidence plane. This, in turn, creates favourable and human-controlled conditions for mass and safe breaking, which makes it possible to regulate the broken ore volumes and its drawing, having the ability to organize breaking along the entire "twinned block" strike. Such a scheme creates incomparable advantages over breaking with horizontal blast-holes with a single-bench breaking. When managing the ore breaking and ore drawing, it is possible to create an ideal opportunity to digitalize ore mining using an algorithm included in the control program, depending on the required block performance.

With such an organization of ore mining from several "twinned blocks", a controlled workable scheme is created for solving the issues of mining the required ore volumes with an average metal content, practical possibility of achieving economically balanced indicators of losses, dilution, cost, labour productivity.

A technological possibility is created for the working scheme operation for the safe breaking of entry pillars and stump pillars, to which constant and safe access is provided due to the design of the proposed mining system variants with ore shrinkage.

The flat bottom of the block with end drawing significantly improves the operating conditions throughout the entire set of production process. The block length along the strike is determined by calculation, depending on the economic and technological efficiency, taking into account factors. This solution is also an advantage, since in most cases it provides economical driving of the raises.

The use on a production scale of the mining system variants with ore shrinkage, created at the level of inventions, makes it possible to mine ore in accordance with calculated indicators, which are 1.2-2 times more efficient than those of currently used designs.

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Обґрунтування систем розробки крутопадаючих малопотужних рудних тіл з керованим безперервним очисним вийманням

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Мета. Вирішення однієї з важливих проблем підземного способу видобутку – обґрунтування економічно ефективних, технологічно здійсненних та безпечних варіантів системи розробки крутопадаючих малопотужних рудних тіл.

Методика. Обґрунтування систем розробки здійснено на основі детального аналізу розроблених та діючих на практиці варіантів розробки крутопадаючих рудних тіл з виявленням виробничо-економічних недоліків та їх причин.

Результати. В результаті дослідження обґрунтовано працездатність підняттєвих при системі розробки з магазинуванням руди. Обґрунтовано основні параметри запропонованих варіантів систем розробки з магазинуванням руди, із розпірним кріпленням та свердловинним відбиванням. Розроблено конструкцію кріплення матеріально-ходових та вентиляційних підняттєвих на робочому та вентиляційному горизонтах для забезпечення їх працездатності при системі розробки з магазинуванням руди.

Наукова новизна. Вперше отримані залежності збіднення та продуктивності праці від потужності рудного тіла та виду відбивання руди при шпуровому та свердловинному відбиванні для одинарного та «зведеного блоку», а також визначена залежність продуктивності вантажно-доставки від середнього фракційного складу та відстані доставки.

Практична значимість. Робота характеризується вперше створеними науковими нововведеннями, які здатні забезпечити ефективність і безпеку гірничих робіт, створивши можливість управляти втратами корисної копалини та збідненням у блоці, досягаючи розрахункового оптимального їх співвідношення з метою максимально рентабельного показника видобутку

Ключові слова: *руда, рудне тіло, видобуток, гірничі роботи, гірнича справа, очисне вилучення*