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PHYSICAL GEOTECHNOLOGY AND GEOTECHNICAL ENGINEERING TOWARD ORIGINATIVE SUBSOIL USE IN CONTROLLABLE UNDERGROUND MINING

The history of the Earth's subsoil use associated with extraction of minerals was created by the development of mining, which is reasonably based on the accumulation and generalization of knowledge, i.e., on the advancement of mining sciences. The diversity of mining sciences is generated depending on the conditions of formation of the geological environment, which must be met by a mining technology aimed at the anthropogenic transformation of the subsoil.

Mining technologies come from physical geotechnology and geotechnical engineering for the humanity to provide itself with mineral raw materials, which means extraction of minerals with structural alteration of the subsoil through its disintegration (destruction).

The methods of physical geotechnologies and geotechnical engineering, in their practical implementation, must be scientifically transformed in accordance with the needs of increasing and improving the quantitative and qualitative indicators of production.

The article presents process designs that form a new framework of the physical geotechnologies and geotechnical engineering for the controllable originative subsoil development in the mode of resource reproduction, resource saving and preservation of high-quality natural environment.

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Introduction

The optimal effect of the subsoil use should be achieved in the anthropogenically altered subsoil upon condition of the obligatory preservation of the historical flora and fauna ensemble in a given area, with its air and water flows on ground surface and underground, capable of self-recovery after removal of man-made load. In real life, the natural-and-technical systems used in physical geotechnologies and geotechnical engineering (PGGE) should attend any geological environment being a mineral deposit at the same final performance indicators (PI) described by zero losses and minimized dilution. Therefore, it is for the first turn required to create viable variants of mining systems, stoping advance and ground control [1, 2].

The overall incidence of new man-made systems capable of solving these problems in a continuous operating mode should be considered in terms of two geometrical peculiarities of ore body morphology—isometric ore bodies of great thickness and 'two-dimensional ore bodies of small thickness and steep dip' [3–5]. Such approach to a natural–geotechnical problem drastically reduces the scope of the required theoretical and applied research, and allows varying structural parameters of a created mining system within a wide range of geological conditions, geotechnical factors and technology requirements which should be taken into account at economic efficiency.

In conventional PGGE in ore production, the mining systems structurally arranged in extraction blocks along the strike of an ore body sequentially and in-parallel implement the main and auxiliary technological processes which are mutually interconnected and interdependent. In this succession, the final productiveness and efficiency depend on the performance of stoping operations in the first turn.

In the present-day situation, creation and transition to innovative technologies, which ensure materialization of the originative subsoil use principles, takes much time for carrying out scientific investigations and operational testing in the production environment. On the basis of this objective necessity, the technological revolution should develop concurrently in two directions:

1) Improvement of the existing variants of mining systems for the above-identified two morphological variations of mineralization, which can embrace all ore formations in the subsoil;

2) Development of new process solutions [6] conditioned by three special features of mining organization:

- mining in downward and upward directions;
- getting access to a deposit (or an individual ore body) using, along with vertical skip, cage and ventilation shafts, a haulage and ventilation decline from the top downward to the lower boundary of mineralization;
- overhand cutting from the lower boundary of mineralization by stopes arranged horizontally or in parallel to the haulage declines, with complete backfill using thixotropic materials.

Improvement of flowsheets, structure and organization of technological processes should necessarily embrace the mining systems with shrinkage and ore breaking, and with controllable caving and/or paste cemented backfill. These two mining systems, in different variants, can encompass many ore deposits, including artificially created conditions for their beneficial application in the space of mineralization [7]. Beneficial application can be created, for instance, by stoping at such angles relative to horizon, which are not necessarily agree with the ore body dip.

These mining systems are selected on the ground of their relevance and application range, as well as impact on technical and economic indexes and safety.

Within the discussed paradigm of theoretical and methodological prerequisites which govern specific research materialized in practice at this stage, i.e., using PGGE, the critical initial component is the obligatory development and justification of process flowsheets in hybrID open pit/underground and underground/underground methods of mining [8, 9].

Thus, the application of PGGE can ensure the *originative subsoil use*—a new scientific notion which is a generalization of the concept of mining development in modern conditions. Concerning rock fracture (blasting, hydraulic fracturing or disintegration) [10], this trend has a science-based right to evolve and take its well-defined place in the present-day mining art. The implementation of the concept becomes a policy of the controllable natural-and-geotechnical process in project preparation for each specific mineral deposit with the complete cycle of development [11, 12].

Methods

Controllable PGGE for the *originative subsoil use* can and should follow the science-based decision-making and conclusion on the basis of the analysis of modern condition of mining at ore deposits distinguished by a variety of geological and geotechnical factors.

It is typical of PGGE to divide produced ore into two types of georesources. Regarding modern conventional deposits, georesources can be primary, i.e., proven reserves which are the basis for the mine design, and secondary, which are produced during mining and processing (concentration and metallurgical treatment) of primary resources, or lost in various-purpose pillars in open pit and underground mines, or in production waste of concentration and metallurgical treatment (tailings, slag, low-grade ore piles, slime, clinker etc.). The concept of novel PGGE and accompanying process designing along the above-discussed directions should ensure the *originative subsoil use* based on the 'resource reproduction, resource saving and preservation of high-quality natural environment'.

Results and discussion

For the implementation of the *originative subsoil use* principles in the framework of PGGE, the science-based procedure is set forth below.

1. Determination of a method of mining for ore deposits with large geometrical dimensions along the strike, thickness and vertical extension with regard to the mineralization boundary depth below ground surface.

Either open pit or underground method of mining requires determining an optimal depth of an open pit. Currently, as an economically efficient variant of safe combination of open pit and underground operations, PGGE consider arrangement of minimum three levels within a single ore cluster to be extracted [13]:

• an open pit, with conventional process flowsheets of access and mining;

• an underground mine, with the same approach as above;

• an intermediate level separating the mine fields of the open pit and underground mine vertically. The height of this level between the open pit bottom and the upper boundary of the mine should enable primary mining and secondary working composed of elements both of open pit and underground mining. This process flowsheet was additionally developed through division of underground reserves into two and more cascades with levels arranged in-between [11].

2. Optimization of mining operations, which are carried out concurrently or sequentially by the open pit and underground methods, on the basis of the proposed classification. It takes into account the variety of mutual occurrence of ore bodies, opening-up of mineral reserves, as well as preparatory and stoping flowsheets (**Fig. 1**). The classification is a framework for the production procedures and performance specifications for the hybrid-type mining design.

3. PGGE meeting the *originative subsoil use* requirements in case of conventional deposits aim to eliminate the shortages in structure of stoping blocks and in organization of process flows. These shortages include:

• no control of the current process flows and their interaction during stoping; as a consequence, the productivity of labor and productive capacity of an extraction block are far from theoretically possible, and the cost exceeds the level of commercial viability;

• uncontrollable dilution which is rated in projects but often exceeds the preset values by 3–5 times in practice;

• no precision and continuity of production because of interruptions in drilling and blasting.

The proposed variants of mining systems with shrinkage at vein deposits and with blasting at isometric ore bodies possess well-thought-out structures and process flows, such that their influence on geological environment proceeds without the listed above shortages [14–17].

Ore bodies thicker than 15 m can be extracted using blasting and different process flowsheets: by blocks consisting of stopes of the first and second order, arranged both along and across the strike. In this process flow, the first order stopes (chequerwise along the strike, up-dip and across the strike) are filled with cemented paste backfill with thixotropic properties. The second order stopes are filled with rocks after their controllable caving and partial bypass from the upper levels.

4. The next step of PGGE in the *originative subsoil use* is creation of natural–manmade systems. These systems include organization of the complete cycle of conversion of secondary georesources to marketable products [18].

5. An important direction of development of manmade systems in PGGE is heap leaching of metals from primary and secondary georesources with obtaining a marketable product. The main obstacles between this technology and the *originative subsoils use* are the low extraction of metal and the seasonal nature of work, while the key process—twelve-month spraying of a heap with a leaching solution—requires continuity.

The solution is found as intra-heap all-round spraying in vertical and horizontal planes via perforated pipes (metal or cheaper polyethylene) laID as a reinforcement grID inside the heap. The leaching solution is fed to the grID from a preparation plant [19]. This way of spraying eliminates harmful mudding and leach solution channeling. The leach solution is fed through the required number of units, under design pressure and from different sides of the heap (**Fig 2.**).

The proposed process flowsheet enables total and year-round spraying of the whole heap irrespective of weather conditions and eliminates formation of 'dead zones'. The reinforcement grID has its both ends let out of the heap, which allows more than 92–95% of metal to be recycled after removal and tear-down of the pipes.

For the complete utilization of the mining area at operational economy, complete recovery of metal in pregnant solution and use of heat of exothermal reaction, the continuous layout chart of the leach heaps is proposed. The heaps are arranged side to side and one-by-one (**Fig. 3**).

6. The need to optimize the natural-and-manmade system simultaneously by ecological, economic and technological criteria dictates introduction of a dual control. With such approach, the control actions are aimed at both studying the control object (geological environment) and optimizing its condition. This optimized condition should balance the interaction of geological and geotechnical factors in PGGE. The dual control, as the basic of complex system optimization, is proposed to be applied in integrated solution of problems connected with the subsoil use and preservation, which ensures sustainable social development [20].

7. In the conditions of underground–underground multi-level parallel–sequential mining, two variants of mining advance are discussed: underhand (top-down) cutting and overhand bottom-up) cutting.

The proposed process flowsheet efficiently interacts with the geological environment, and ensures operational exploration, complete adjustment of the morphology of ore body, rock interfaces, as well as detection of faults. This becomes possible owing to getting access to the ore body along its total vertical extension by means of a preventive haulage decline (or declines) driven down to the bottom boundary of the ore body, which is rimmed with the horizontal drifts driven up to the extent of both end (**Fig. 4**).

The access to the ore body via vertical skip and cage shafts is got to the depth which is economically effective in combination with capital and operating costs connected with the haulage decline heading, and the number of the entry crosscut reduces to the number of levels between cascades.

Ventilation shafts are sunk to the floor of the lower horizontal drift. Crosscuts connect the vertical shafts with the horizontal drifts headed on the floor of the levels between cascades to the next to last cascade. The crosscuts are arranged for dump trucks (load–haul–dumpers) to be unloaded in ore passes at the skip shaft.

8. The proposed overhand stoping flowsheet is the most safely and efficiently used in combination with the cut-and-fill method, with stopes arranged horizontally or in parallel to the haulage declines.

This process flowsheet is highly economically efficient, eliminates ore losses, allows dilution not more than 4–6% and preserves the rock mass being mined, without destructive effect on the subsoil and ground surface—owing to application of backfill with thixotropic properties.

Classification of mineral reserves extracted by the hybrid-type geotechnology, relative to the open pit (Level 1)				
Group 1 At the same level or above the pit bottom, beyond the open pit influence	**Group 2** Offshoots or other-type ore bodies adjacent to pitwall or pit bottom	**Group 3** Extension of the ore body, extracted by open pit mining method beneath the designed pit bottom	**Group 4** Beneath the designed pit bottom, not the extension of the ore body extracted by the open pit; other ore bodies	**Group 5** Beneath the designed pit bottom, all the rest reserves of the extension of the ore body extracted by the open pit

Fig. 1. Classification of ore reserves extracted by hybrID geotechnology in the space between the open pit and underground mine, on the same level and beyond it relative to the open pit reserves.

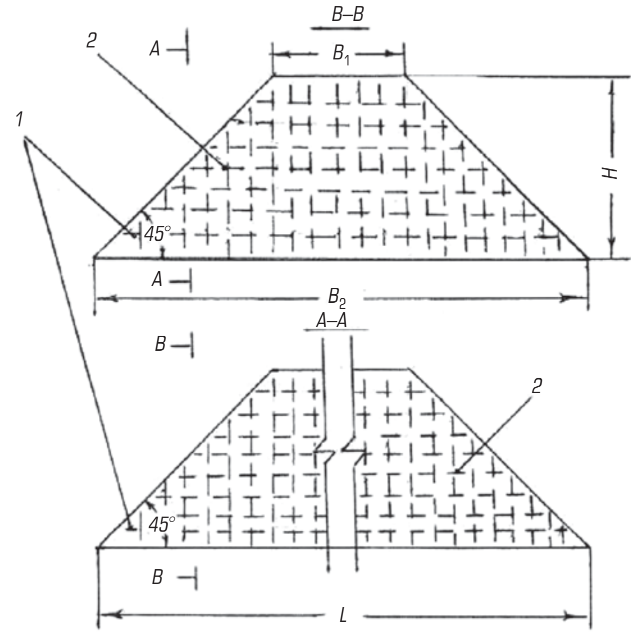

Fig. 2. Process flowsheet of continuous and controllable heap leaching:
1—ore heap (B_1—width of the smaller side of the heap trapezoid; B_2—width of the larger side of the heap trapezoid; *H*—heap height; *L*—heap length); *2*—perforated metal or synthetic pipes to feed leaching solution in vertical and horizontal planes; *A–A*—heap view from its width side; *B–B*—heap view from its length side; B_1—width of the shorter (upper) side of the heap trapezoid; B_2—width of the longer (lower) side of the heap trapezoID

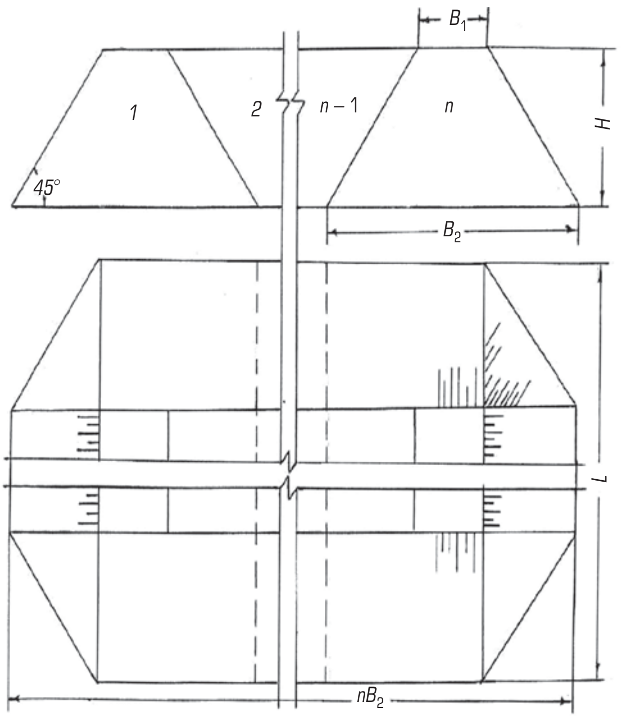

Fig. 3. Process flowsheet of continuous heaping. Odd-numbered and even-numbered heaps are piled with the shorter side of the trapezoID up and down, respectively:
1, *2*, *n*–1, *n*—numbering of heaps; B_1 and B_2—widths of the shorter and longer sides of the heap trapezoids; *H*—heap height; *L*—width of the piled heaps; *n*—final numer of heaps piled end-to-end

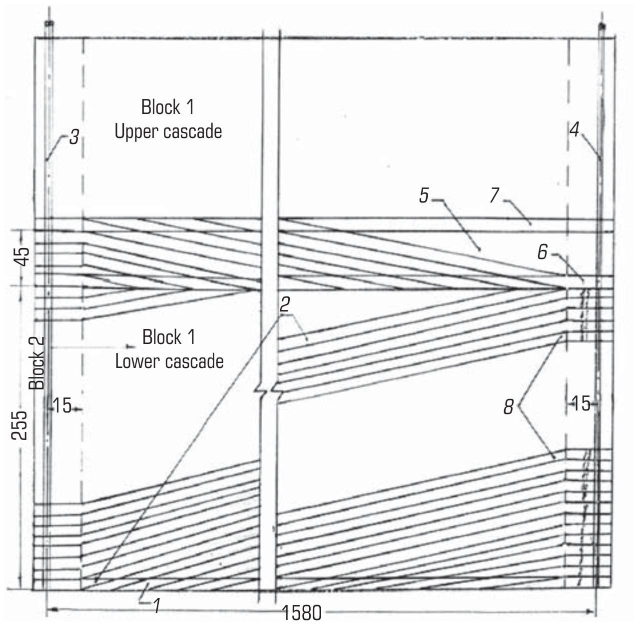

Fig. 4. Overhand stoping with cut-and-fill and complete thixotropic backfill:
1—haulage drift at the bottom of ore body; *2*—haulage decline; *3*—inter-block ventilation raise with mechanized hoisting and backfill pipeline; *4*—side ventilation shaft with mechanized hoisting and backfill pipeline; *5*—inter-cascade level–pillar; *6*—haulage drift of the inter-cascade level–pillar; *7*—haulage drift of the upper cascade; *8*—level stopes in parallel to haulage decline

Creation of strong rock mass is also conditioned by the constant presence of two planes of exposure in the layer being broken, which reduces specific and total powder factor, and this, in its turn, improves air quality owing to a decrease in volume of blasting-produced gases [21].

Strength of rock mass is higher and conditions can be created for the trouble-free operation of machines in the upper stope if the backfill in the lower stope is preliminary reinforced with a fiberglass rock bolt grID with additional reinforcement by rounded profiles made of scrap metal.

Dynamics of stoping operations and performance of two mining methods are depicted in Fig. 4 and described in **Table**.

Conclusions

1. The analytical review of the performance of operating mines and scientific achievements in reduction of losses during mining, as well as preservation of stoping and wallrock space reveals the advantages of physical geotechnology and geotechnical engineering which combine open pit and underground mining methods within the same deposit.

2. Complete cycle of ore mining is ensured by geotechnical systems which include treatment of secondary georesources. Such georesources appear both in primary ore mining and in ore processing on ground surface—from dumps, tailings and production waste.

3. The major achievement to ensure the scientific and technical progress, highly productive performance and economic efficiency is the discussed variant of the overhand stoping geotechnolgy. This PGGE variant is proposed for the first time in the history of mining science and ensures complete utilization of geological reserves at the enhanced mining safety.

4. The implemented research, at the preserved key principles of PGGE concerning control of ore body by means of it disintegration, is targeted at:

• total quantitative and qualitative extraction of mineral;

• preservation of natural environment in the subsoil in the area of mineralization;

• great reduction in volume of manmade secondary georesources on ground surface.

Comparative analysis of process flowsheets in different systems of mining

Underhand stoping (top-down)	Overhand stoping (bottom-up)
Standard ore body 1000 m long along the strike, 1000 m high vertically, with a dip of 60° and 8.0 m thick, with an average metal content of 1.0%, overburden thickness is 50 m	
Access along the total depth by vertical skip, cage and vertical shafts, fringe crossdrifts, drifts and ramps between fringe and rift drifts; ore and waste rock storage chambers with skip hoisting are arranged beneath the 20th level (beneath 1050 m below ground surface)	Access by vertical skip and cage shaft sunk to the level below the underlying part of the intermediate underground level, with ore and waste rock storage chambers (beneath 50 below ground surface), and by vertical shafts down to the total depth, with haulage declines
Total volume of rocks per all operations in getting access and in extraction	
Shafts and storage chambers 117 791 m$^{2.}$	Shafts and storage chambers 73 828.5 m²
Fringe crossdrifts, drifts and other mine openings 134 800 m²	Fringe crossdrifts, drifts and other mine openings 19.572 m²
Preproduction mining 0 t of ore	Preproduction mining 450 000 t of ore
Underhand cutting with levels 50 high; sublevel caving with fan blasting. Ore haulage to block ore passes from each sublevel. Separating raise headed by basting to the sublevel height of 15 m. Ore loss 12–15%, ore dilution 8–10%	Overhand cutting with separation of ore body into 2 cascades with vertical length of 450 m and with an intermediate underground level 20 m high in-between the cascades. Slice mining, with blasting, with stopes arranged in parallel and end-to-end with the haulage decline and with complete cemented paste backfill. Depending on geological factors, the level stopes can be arranged horizontally, with bypass of the operating decline. Ore loss 0–2%, ore dilution 5–6%

5. The examples from foreign reference sources, including mapping, digitalization and modeling of mining and processing of primary georesources and production waste, demonstrate the advantages of the proposed procedures of physical geotechnology and geotechnical engineering [22–25].

On the basis of the existing mining practice and using PGGE, the controllable process is developed for the *originative subsoil use* involving preliminary estimation of balance between production of primary georesources and formation of secondary georesources.

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