

Choosing the method of excavating vein reserves and mineralized zones on the basis of simulation modeling

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Abstract For the effective involvement of off-balance ores into development, a simulation modeling of gross and selective mining variants at "Kochkar" deposit reserves has been carried out by the Monte Carlo method, provided that a new type of geological resource – mineralized rocks has been involved in mining, and an economic evaluation of competing options has been made. **Keywords:** "Kochkar" deposit, underground mining, excavation method, selective and gross mining technologies, Monte Carlo method, ore veins, mineralization zones, poor ore raw stock.

1 Introduction

An analysis of negative trends in the state of the mineral wealth sector of Russia shows that their main reason is the wide use in the mining sector of the concept on extensive subsoil use, which led to a significant deterioration in the quality and primary specifications of the mineral wealth of most mineral deposits. To the full, this refers to the development of veined gold ore deposits in the South Urals, for which the uneven nature of the distribution of minerals in the solid mass of the deposit predetermined the initial selective excavation of rich sites and the abandonment of ore reserves with low quality characteristics.

According to current forecasts, given the existing scale of production, the availability of gold reserves for underground mining in the region is 20-30 years, open - 30-40 years [1]. However, taking into account the increase in the production capacity of mines and the retirement of the facilities of existing enterprises, the supply of the sector will drop sharply, which will bring the region closer to the critical level of the state of the ore gold resource portfolio.

The generalization of the experience of exploitation of gold deposits, developed by "Yuzhuralzoloto Group of Companies", OJSC ("YuGK", OJSC), specializing in the extraction and treatment of gold-bearing ores and metallurgical manufacturing of commercial gold, allowed justifying the concept and identify the principles of preserving the production potential of the mining engineering system in the conditions of reducing volume of reproduction of the resource portfolio and falling quality specifications of the mined ore, as well as increasing mining depth. In order to prevent the liquidation of the

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enterprise and, as a consequence, the emergence of a set of socioeconomic and environmental problems, fundamentally new geotechnological solutions have been adopted aimed at changing the technology of mining and treatment of gold-bearing ores with subsequent disposal of waste in the developed subsoil area [2-6]. That will ensure the stabilization of not only the economic, but also the geomechanical and ecological situation [7].

One of the principles of the new concept is full disclosure of the potential of the resource portfolio, rejecting of the initial selective testing of the richest sites of deposits and transition to joint development of gold ore veins and adjacent mineralized zones. The fulfillment of this condition allows, by increasing the vertical capacity of ore deposits, to increase the intensity of the cleaning works, to apply more productive development systems with mass breaking of ore, to involve hard sites of deposits, with a small and highly variable gold content in the ore, and also to move to deeper horizons, where "traditional", previously used technologies become less profitable, or unprofitable.

To date, the reserves of vein deposits and mineralized host rocks that were previously abandoned during the initial development due to the economic inexpediency of mining have not been considered as promising for involvement in the development.

Analysis of the gold content in veins and in host rocks, applied to the conditions of development of the "Kochkar" deposit, showed that on the worked out horizons there are promising sections of veins and mineralized rocks, in terms of size and techno-economic conditions suitable for development. These reserves include mineralization zones in the hanging and lying sides of gold ore veins (*tabashka*), as well as in quartz-flooded granites. The thickness of such ores reaches 10-14 m, with an average gold content of 3 g / t. In connection with the growth of prices for precious metals, the cleaning-up of these mineralization has become profitable. For their work out, a system has been introduced for the development of sub-floor drifts with borehole breaks, which has made it possible to increase labor productivity at the stoped excavation and to reduce the prime cost of the extracted ore mass [8-10].

In turn, the need to take into account the specifics of the technological schemes for processing ore raw materials of rich veins and mineralized rocks required a set of research works aimed at justifying the parameters of high-performance development systems, choosing the preferred option for mining rich ore reserves and cutting mineralized zones and identifying the economic feasibility of applying various methods of excavating ore veins and mineralized zones: a comparison of the selective working of the vein with gross simultaneous extraction of all the stocks of the mineralized zones and veins included in the chamber contour.

2 Methodology

To select the best option for excavating ore in areas including veins and mineralization zones, a simulated Monte Carlo modeling of gross and selective excavation was performed. The comparative evaluation was carried out according to two criteria: the mass of extracted gold and the resulting specific profit per 1 ton of recoverable reserves for the options considered.

During the simulation, variants of the stepwise selective excavation of rich ores with their separate extrusion onto the surface for self-processing of the extracted ore mass by cyanidation with different gold contents were considered. Also, the options with gross development of ore veins and mineralized zones with varying gold content in veins and mineralized rocks were considered.

As initial data for the construction of the probability model, the gold extraction parameters were used depending on the base gold content in the ore, provided that the

extracted ore mass was processed by cyanidation at the Artem completed enrichment cycle factory. Economic indicators of ore mass redistribution at this factory were adopted during the modeling. A general view of the probabilistic model, which reflects the dependence of the recovery index on the gold content, is shown in Fig. 1 and is described by the expression:

$$\varepsilon = 100 \cdot \left(\frac{\alpha}{|\alpha| + d} + \delta \right), \tag{1}$$

where ε – extraction parameter, %; α – gold content, g / t; δ – sporadic error of the model; d – model’s parameter.

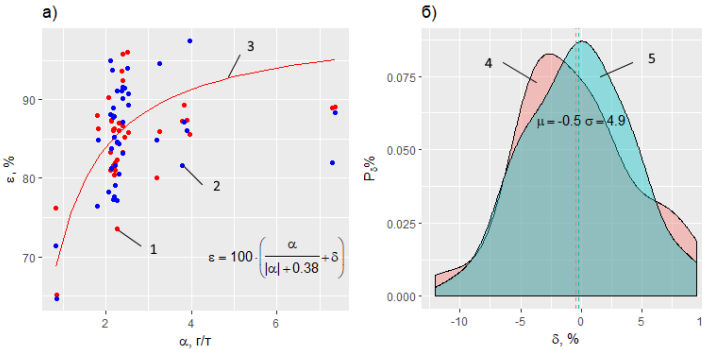


Fig. 1: a - Regression model of the dependence of gold recovery in leaching on the gold content in ore: 1 - observational data; 2 - model-generated data; 3 - graph of the regression model; b - error distribution density of the regression model: 4 - according to observation data; 5 – software-generated results

In Fig. 1, position 1 shows the points obtained from the data of actual observations, position 3 - the results of model processing obtained by regression analysis. Fig. 1b shows the error distribution density for the actual data (4), the values of its mathematical expectation (μ) and standard deviation (σ) are presented, on the basis of which the sporadic error was programmed (5). Based on the regression model (3) and the error distribution density (5), recovery indices were generated depending on the gold content (2).

In the future, the regression model of gold recovery from the extracted ore mass was used to programmatically generate the gold recovery parameter from the extracted ore mass by cyanidation taking into account the error, which included the identification of the mass of recovered gold per 1 ton of extracted ore mass for the options of selective and gross working of veins and mineralized rocks .

This experiment assumed the generation of initial values of gold content in veins and mineralized rocks, their combination, the generation of the recovery index for each combination according to the formula (1), the calculation of the specific gravity of extracted gold for two options of working out (Me_{gr} and Me_{sel}) according to formulas (2) and (3), as well as their difference (ΔMe),calculated according to (4). This algorithm was implemented in the model 100 times, and for each combination of gold content in the vein and mineralized rocks, the probability P_{me} was calculated that the mass of extracted gold for the selective production option would be higher than the mass for the gross extraction.

$$Me_{sel} = \frac{1 - P_{\kappa AM}}{1 + P_{\kappa AM}} \cdot \bar{\alpha} \cdot \varepsilon_{\alpha}^{-}, \text{ g / t}; \tag{2}$$

$$Me_{gr} = 1 - L_{cham} / 1 + D_{cham} * \bar{\alpha} * \varepsilon_{\alpha}^{-} / \text{ g / t};$$

$$Me_{сел} = \frac{V_{жсшл} \cdot \alpha_{жсшл} \cdot \varepsilon_{\alpha_{жсшл}} \cdot \frac{1 - P_{пшш}}{1 + P_{пшш}} + V_{мпш} \cdot \alpha_{мпш} \cdot \varepsilon_{\alpha_{мпш}} \cdot \frac{1 - P_{кам}}{1 + P_{кам}}}{V_{жсшл} + V_{мпш}}, \text{ g / t; } \quad (3)$$

$$Me_{сел} = V_{vein} * \alpha_{vein} * \varepsilon_{\alpha_{vein}} * I - L_{sfl} / I + D_{sfl} + V_{mr} * \alpha_{mr} * \varepsilon_{\alpha_{mr}} * I - L_{cham} / I + D_{cham}$$

$$\Delta Me = Me_{сел} - Me_{gr}, \text{ g / t, } \quad (4)$$

where $\bar{\alpha}$ – weighted average content of gold in the ore block, g / t; α_{vein} and α_{mr} – gold content in vein and mineralized rocks, g / t; $V_{vein} = l * h * m_{vein}$ and $V_{mr} = l * h * m_{mr}$ – volume of vein and mineralized rocks in the block, respectively, m³; h and l – height and width of the block, m; ε_{α} – extraction of gold from ores in gross mining, unit fraction; $\varepsilon_{\alpha_{vein}}$ and $\varepsilon_{\alpha_{mr}}$ – extraction of gold from vein and mineralized rocks in selective mining, unit fraction; L_{cham} , D_{cham} , L_{sfl} and D_{sfl} – loss and dilution of ore under systems of chamber and sub-floor drifts, unit fraction.

Weighted average content of gold in the ore block:

$$\bar{\alpha} = \frac{V_{жсшл} \cdot \alpha_{жсшл} + V_{мпш} \cdot \alpha_{мпш}}{V_{жсшл} + V_{мпш}}. \quad (5)$$

$$\bar{\alpha} = V_{vein} * \alpha_{vein} + V_{mr} * \alpha_{mr} / V_{vein} + V_{mr}$$

Similarly, the probability (P_{pr}) was calculated that, with the selective extraction option, the profit would be higher than with the gross mining, respectively. The profit for selective and gross options of mining was found by the formulae:

$$Pr_{yд\ сел} = Me_{сел} \cdot II_{золота} - (C_{пшп\ пшш\ сел} + C_{пшп\ кам\ сел} + C_{закл\ сел} + C_{обог\ сел}), \quad (6)$$

$$Pr_{sp\ сел} = Me_{сел} * P_{gold} - (C_{POD\ sfl\ сел} + C_{POD\ cham\ сел} + C_{fill\ сел} + C_{enr\ сел})$$

$$Pr_{yд\ вал} = Me_{вал} \cdot II_{золота} - (C_{пшп\ кам\ вал} + C_{закл\ вал} + C_{обог\ вал}), \quad (7)$$

$$Pr_{sp\ gr} = Me_{gr} * P_{gold} - (C_{POD\ cham\ gr} + C_{fill\ gr} + C_{enr\ gr})$$

$$\Delta Pr = \Delta Pr_{sp\ сел} - \Delta Pr_{sp\ gr} \quad (8)$$

The cost of preparatory-development operations (PDO) for a system of sub-floor drifts in selective mining was defined as:

$$C_{пшп\ пшш\ сел} = \frac{C_{пшп\ пшш} \cdot V_{жсшл}}{V_{жсшл} + V_{мпш}} \cdot \frac{1 - P_{пшш}}{1 + P_{пшш}}, \quad (9)$$

$$C_{POD\ sfl\ сел} = C_{POD\ sfl} * V_{vein} / V_{vein} + V_{mr} * I - L_{sfl} / I + D_{sfl}$$

where $C_{POD\ sfl}$ – cost of PDO for a system of sub-floor drifts per 1 ton of mined ore mass, rubles/t.

Cost of PDO for a chamber system in selective mining was defined as:

$$C_{пшп\ кам\ сел} = \frac{C_{пшп\ кам} \cdot V_{мпш}}{V_{жсшл} + V_{мпш}} \cdot \frac{1 - P_{кам}}{1 + P_{кам}}, \quad (10)$$

$$C_{POD\ cham\ сел} = C_{POD\ cham} * V_{mr} / V_{vein} + V_{mr} * I - L_{cham} / I + D_{cham}$$

where $C_{POD\ cham}$ – cost of PDO for a chamber system, per 1 ton of mined ore mass, rubles/t.

Cost of filling operations accounting for underfilling factor and loss/dilution in gross mining option is assessed as:

$$C_{fill\ sel} = (1 - L_{cham}) * (1 + D_{cham}) * (1 - L_{sfl}) * (1 + D_{sfl}) * k_{uf} * C_{fill} \tag{11}$$

where C_{fill} – cost of filling operations per 1 ton of mined ore mass, rubles/t.

Cost of enrichment per 1 ton of ore in block:

$$C_{обогащ\ цел} = \frac{V_{ж\у\ла} \cdot (1 - \Pi_{\text{III}}) \cdot (1 + P_{\text{III}}) \cdot C_{обогащ\ ж\у\ла\ 1\text{т}} + V_{\text{МП}} \cdot (1 - \Pi_{\text{кам}}) \cdot (1 + P_{\text{кам}}) \cdot C_{обогащ\ \text{МП}\ 1\text{т}}}{V_{ж\у\ла} + V_{\text{МП}}}, \tag{12}$$

$$C_{enr\ sel} = V_{vein} * (1 - L_{sfl}) * (1 + L_{sfl}) * C_{enr\ vein\ 1\text{т}} + V_{mr} * (1 - L_{cham}) * (1 + L_{cham}) * C_{enr\ mr\ 1\text{т}} / (V_{vein} + V_{mr})$$

where $C_{enr\ vein\ 1\text{т}}$ – cost of enrichment of 1 ton of ore from vein, rubles/t; $C_{enr\ mr\ 1\text{т}}$ – cost of enrichment of 1 ton of ore from mineralized rocks, rubles/t.

Cost of PDO for chamber system in gross mining:

$$C_{\text{ППР}\ \text{кам}\ \text{вал}} = C_{\text{ППР}\ \text{кам}} \cdot \frac{1 - \Pi_{\text{кам}}}{1 + P_{\text{кам}}}. \tag{13}$$

$$C_{\text{POD}\ \text{cham}\ \text{gr}} = C_{\text{POD}\ \text{cham}} * (1 - L_{cham} / (1 + D_{cham}))$$

Cost of filling operations accounting for underfilling factor and loss/dilution in gross mining option is assessed as:

$$C_{fill\ gr} = (1 - L_{cham}) * (1 + L_{cham}) * k_{uf} + C_{fill} \tag{14}$$

Cost of enrichment per 1 ton of ore in block:

$$C_{enr\ gr} = (1 - L_{cham}) * (1 + L_{cham}) * C_{enr\ vein-mr\ 1\text{т}} \tag{15}$$

where $C_{enr\ vein-mr\ 1\text{т}}$ – cost of enrichment of 1 ton of averaged ore from veins and mineralized rocks, rubles/t.

3 Results and Discussion

As the initial data for geotechnological modeling, the extraction and enrichment indicators achieved at the "Kochkar" underground mine (Table 1) were adopted.

Table 1. Initial data of geotechnological modeling

Parameters	Symbol	Unit	Value
Block length	l	m	60
Block height	h	m	60
Loss in sub-floor drift systems	L_{sfl}	unit fraction	0.11
Dilution in sub-floor drift systems	D_{sfl}	unit fraction	0.10
Loss in chamber systems	L_{cham}	unit fraction	0.15
Dilution in chamber systems	D_{cham}	unit fraction	0.15
Gold price	P_{gold}	rubles	2,480
Underfilling factor	k_{uf}	unit fraction	0.95
Cost of filling mixture per 1 ton of mined ore mass	C_{fill}	rubles/t	382.80
Cost of preparatory-development operations for a system of sub-floor drifts per 1 ton of mined ore mass	$C_{\text{PDO}\ sfl}$	rubles/t	1,121.92
Cost of preparatory-development operations for a chamber system per 1 ton of mined ore mass	$C_{\text{PDO}\ \text{cham}}$	rubles/t	518
Cost of enrichment of 1 ton of averaged ore from veins and mineralized rocks	$C_{enr\ vein-mr\ 1\text{т}}$	rubles/t	700
Cost of enrichment of 1 ton of vein gold	$C_{enr\ vein\ 1\text{т}}$	rubles/t	700

Parameters	Symbol	Unit	Value
Cost of enrichment of 1 ton of mineralized rocks	$C_{enr\ mr\ 1t}$	rubles/t	700

Fig. 2 presents in the form of diagrams the results of calculating the probability of preferred selective extraction based on the maximum profit criteria and the maximum gold extraction for various values of gold content in ore and zones adjacent to the vein as the thickness of veins and mineralized rocks varies. Taking into account the influence of the contrast of the gold content in the ore mass on the factors of maximum profit and maximum extraction of gold, the areas of preference for the use of selective excavation have been identified (dark color selection in the graph).

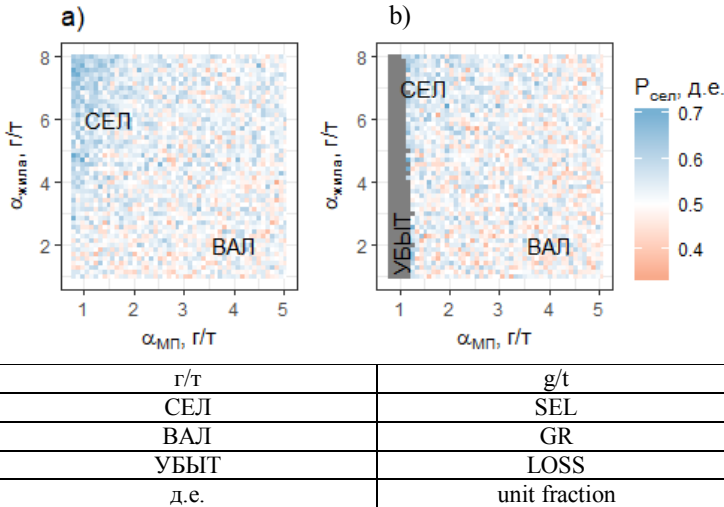


Fig. 2. Diagrams of the probability of preferring the use of selective technology of mining in comparison with the gross method by the criterion: *a* - recoverable gold; *b* - maximizing the corporate profit

An analysis of the data in Fig. 2 allows drawing a conclusion that for ranges of gold content in veins from 1 g/t to 8 g/t and in mineralized rocks from 0.7 g/t to 3 g/t, respectively, the preferred technology is gross extraction, both by the criterion of maximum metal extraction and by the criterion of profit.

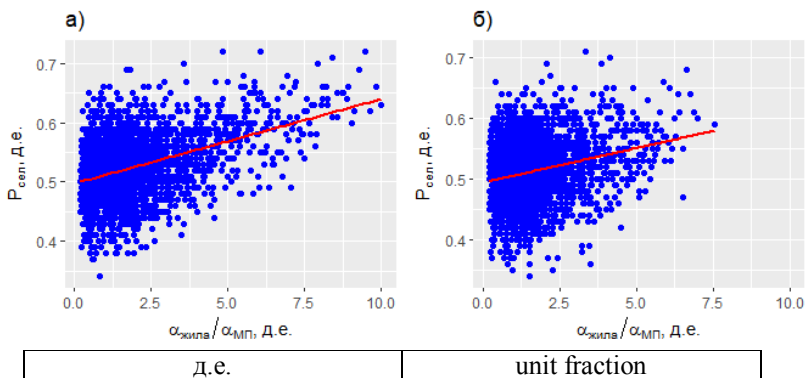


Fig. 3. Probability of the effectiveness of applying selective extraction method depending on the contrast of the contents by the criterion: *a* - recoverable gold; *b* - maximizing the corporate profit

The influence of the contrast of the average gold content in the vein and the adjacent mineralized zone on the area of preferential application of selective extraction for different values of the vein and mineralized rock thickness by these factors is shown in Fig. 3. An analysis of the diagrams presented in Fig. 3, allows concluding that as the contrast of the content of ores increases ($\alpha_{\text{vein}}/\alpha_{\text{mr}}$), the probability of effective application of the selective extraction method also increases.

4 Conclusions

On the example of "Kochkar" deposit, for the first time for the conditions of involving a new kind of geological resource - mineralized rocks of vein gold deposits - at the final stage of exploitation of balance reserves, the efficiency of gross and selective excavation of gold-bearing ore mass was compared on the basis of geological testing of ore veins and mineralized zones. As shown by the comparison of the options performed, with the current level of gold prices and the existing difference in production costs for gross and selective excavation, the difference in the processing of rich and poor ores is not compensated by a change in production costs in the extraction methods under consideration. When the content of gold in veins and adjacent mineralized zones is up to 8 and the thickness of the veins is up to 1 m, gross excavation of ore is preferred at the final stage of underground mining of vein gold deposits in the South Urals. Selective excavation is expedient only at high contrast of gold content in the vein and adjacent mineralized zones - above 8, vein thickness more than 1.5 m and thickness of mineralized zones less than 10 m.

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