

# ГЕОТЕХНОЛОГИЯ: ПОДЗЕМНАЯ, ОТКРЫТАЯ, СТРОИТЕЛЬНАЯ

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## Mining factors effect on the technical and economic indicators of mining the upper sublevel under the rock cushion at iron ore deposits

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### Abstract

**Relevance.** At present, during the transition from open pit to underground mining at iron ore deposits, the most widespread technology is the sublevel caving with frontal ore drawing. This technology has significant drawbacks, namely low ore extraction indicators and increased operating costs for preparatory work and stoping. The development of an alternative technology for the upper sublevel mining, which ensures high extraction indicators, active ore drawing, and lower prime cost of the main flow processes in the presence of an internal dump used as a rock cushion on the quarry floor, is an urgent scientific and technical task.

**Research objective** is to study the mining factors effect on the technical and economic indicators of differing technologies for mining the upper sublevel under the rock cushion at the iron ore deposits.

**Research methods.** The work uses a comprehensive research method, including the search and design of a rational version of technology, economic and mathematical modeling, and technical and economic comparison.

**Analysis of the results.** The dependences of the main technical and economic indicators (losses and dilution, the specific volume of preparatory development works, labor productivity and specific operating costs for flow processes) on the height of the upper sublevel between 40 and 100 m and mine capacity between 0.8 and 2.4 million tonnes of ore per year. It has been determined that the operating costs for ore mining have a minimum value under a height of the upper sublevel of 80 m and a production capacity of 1.6 million tonnes of ore per year, which is optimal for an enterprise during the transition period.

**Conclusions.** The technology of sublevel open stoping with the subsequent rib pillar development by a system of induced block caving has been substantiated, which far more efficient as compared to the traditional version of sublevel caving.

**Keywords:** iron ore deposit; transition zone; rock cushion; mining system; mining factors; extraction indicators; technical and economic indicators.

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**Introduction.** Efficient combined mining of main underground reserves in deep-lying ore deposits greatly depends on efficient organizational, technical, and technological measures in the zone of open-pit-to-underground transition (transition zone, referred to below as TZ) [1]. In turn, efficient TZ mining is conditioned by the mining factors, namely mine production capacity, open-pit depth, and the height of the upper sublevel, as well as mining-geological conditions and technology.

The open-pit depth at many iron ore deposits in Russia is currently close to the designed one [2–4]. Beyond the designed pit limits, there are reserves to be further

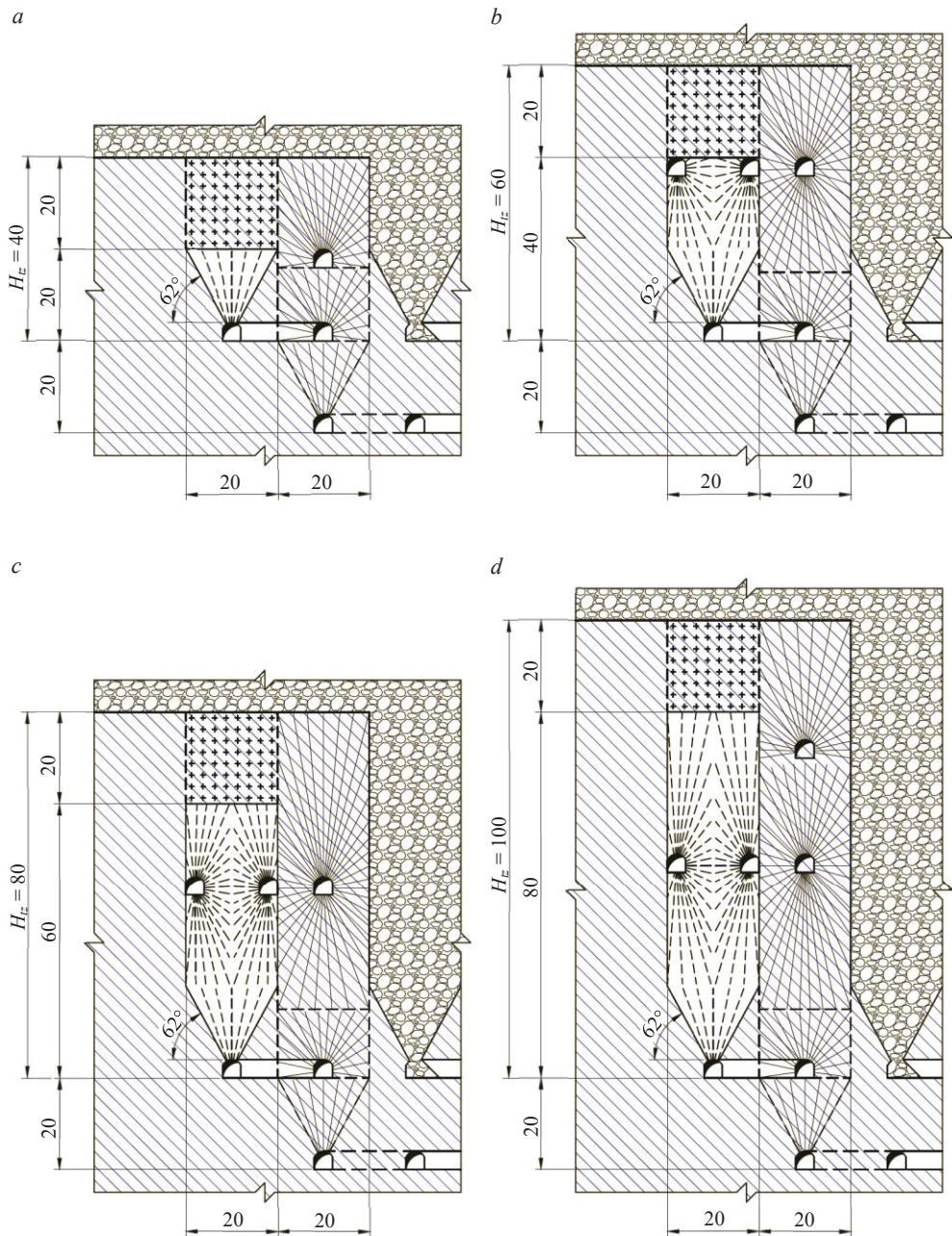


Figure 1. Technology of level open stoping with subsequent caving of the rib pillar at the height of the upper sublevel:

*a – 40 m; b – 60 m; c – 80 m; d – 100 m*

Рисунок 1. Технология этажно-камерной выемки с последующей отработкой МКЦ при высоте подкарьерного этажа:

*a – 40 м; б – 60 м; в – 80 м; г – 100 м*

developed via an underground method. One of the features of underground reserves development at iron ore deposits is an internal dump on the quarry floor [5]. Internal dumping serves as a rock cushion to isolate underground mine workings and the quarry [6]. Existing methods of extracting reserves below the quarry floor provide for a system of sublevel caving with slicing and frontal ore drawing. The system's advantages are well-known. However, it also has significant disadvantages, namely low extraction indicators and relatively high operating costs for the preparatory development work (PDW) and stoping [7–14]. Stoping periodicity with a minimum volume of ore breaking and drawing involves the presence of many panels in the developing entry and large ore areas with a corresponding amount of main equipment operated simultaneously to ensure the productive capacity of the mine [15, 16]. It is possible to remove the disadvantages of the traditional technology by moving from one-stage to two-stage extraction of a block with the development of larger chambers at the first stage.

So, mining factors effect on the technical and economic indicators of differing technologies for mining the upper sublevel under the rock cushion at iron ore deposits is an urgent scientific and technical problem.

**Alternative technology development.** An efficient version was found and designed for the technology of upper sublevel mining at thick (20–70 m) steeply pitching (more than 70°) iron ore deposits.

The version combines sublevel stoping and a system with ore caving and requires a room-pillar sequence of reserves mining at a level (Figure 1). Chamber reserves are extracted by two faces directed from the center towards the sides. A floor pillar forms concurrently to prevent the penetration of the cushion's diluting rocks from the quarry floor, thereby ensuring optimal conditions and high extraction indicators when extracting chamber reserves. Ore drawing and haulage are carried out by the LHD (load, haul, dump) loaders from the crosscuts on the trench floor. After that, bulk caving of the floor pillar is carried out; and the floor pillar is drawn under the caved ground through the chamber's trench floor. A rib pillar (RP) is extracted with a compensation chamber formed in its lower part; into the compensation chamber, main RP reserves are broken down and drawn via LHD from the crosscuts on the trench floor.

This technology is novel. It makes it possible to improve ore extraction indicators, stoping safety, and the intensity of ore drawing from the block (an approval has been received to grant an invention patent of the Russian Federation, application no. 2021110457 of 14 April 2021).

**The effect of mining factors on technical and economic indicators.** For economic mathematical modeling (EMM), in order to determine the level of the main technical and economic indicators (TEI) when developing an upper sublevel under the rock cushion in the conditions of iron ore deposits, two versions have been adopted:

– the technology of sublevel caving with slicing and frontal ore discharge (version 1);

– the technology of sublevel stoping with the subsequent floor pillar caving and RP development by a system of induced block caving with undercutting (version 2).

Two most significant mining factors have been identified to establish the nature and rate of TEI change:

– the height of the upper sublevel ( $H_{tz}$ ), which determines reserves amount and development period, extraction indicators, specific scope of PDW, scope of drilling, haulage distance, and therefore the recoverable value and prime cost of mined ore. We considered the following variation range for  $H_{tz} = 40; 60; 80; 100$  m (taking into account the international practice of ore deposits combined mining [17–22]);

– mine's production capacity  $A_{mine}$ , which determines the cross section of underground excavations, volume and intensity of tunneling and stoping, labor

productivity and therefore capital and operating costs. We considered the following variation range for  $A_{\text{mine}} = 0.8; 1.6; 2.4$  million t/year (depending on mine's productivity). For EMM, a corresponding fleet of main and accessory process equipment was specified for each  $A_{\text{mine}}$ .

The first stage of EMM established the dependencies between the loss and dilution indicators variation and  $H_{\text{Tz}}$  (Figure 2). It can be seen from the graph that with the growth of  $H_{\text{Tz}}$  from 40 to 100 m, loss and dilution in version 1 do not change (25 and 30%, respectively); in version 2 they decrease by 1.7 times (from 26.2 to 15.1%) and by 1.9 times (from 30.5 to 16.2%), respectively. So, the upper sublevel height increase makes it possible to increase extraction indicators, and therefore the recoverable value of ore.

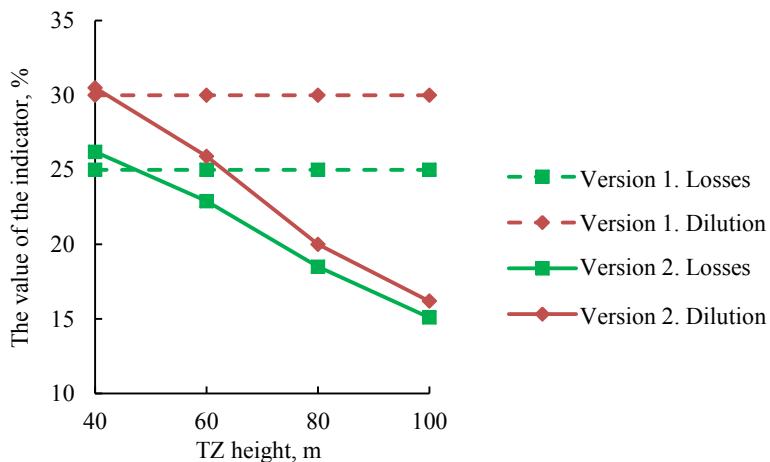


Figure 2. Dependences of ore losses and dilution on the height of the upper sublevel

Рисунок 2. Зависимости потерь и разубоживания руды от высоты подкарьера этажа

The performance criteria of the technology versions were subsequently studied depending on  $H_{\text{Tz}}$  and  $A_{\text{mine}}$ , namely the specific scope of PDW per 1000 tonnes of mined ore, labor productivity for PDW, stoping and the entire mining system (Figure 3).

In version 1, the specific scope of PDW per 1000 tonnes of mined ore (Figure 3, a) does not change as  $H_{\text{Tz}}$  increases and ranges from 55.3 to 87.2 m<sup>3</sup>/1000 tonnes under  $A_{\text{mine}}$  from 0.8 to 2.4 million t/year. The indicator increases with the growth of  $A_{\text{mine}}$  due to an increased cross section of workings when using more productive (large-sized) equipment. In version 2, with  $H_{\text{Tz}}$  growth from 40 to 100 m, the indicator decreases by 11.1–11.9% due to incremental operational reserves of the block and increases proportionally as  $A_{\text{mine}}$  grows from 0.8 to 2.4 million t/year due to the increased cross section of workings. Besides, the specific scope of PDW in version 2 is 2.2–2.9 times lower than in version 1.

Labor productivity at the PDW stage (Figure 3, b) in version 1 does not depend on  $H_{\text{Tz}}$  due to the constant volume of PDW in the block and increases with the growth of  $A_{\text{mine}}$  from 14.0 to 17.5 m<sup>3</sup>/man shift within the studied range due to the reduced volume of sinking and the increased efficiency of drilling rigs for tunneling. In version 2, labor productivity in the PDW stage decreases with the growth of  $H_{\text{Tz}}$  by 6.5–6.9% due to the increased volume of sinking in the block and increases by an average of 25.5% under  $A_{\text{mine}}$  growing from 0.8 to 2.4 million t/year due to the more efficient drilling

rigs for tunneling. Besides, in the entire range of factors under investigation, labor productivity at the PDW stage in version 2 is 1.2–8.7% lower than in version 1 due to a larger volume of sinking.

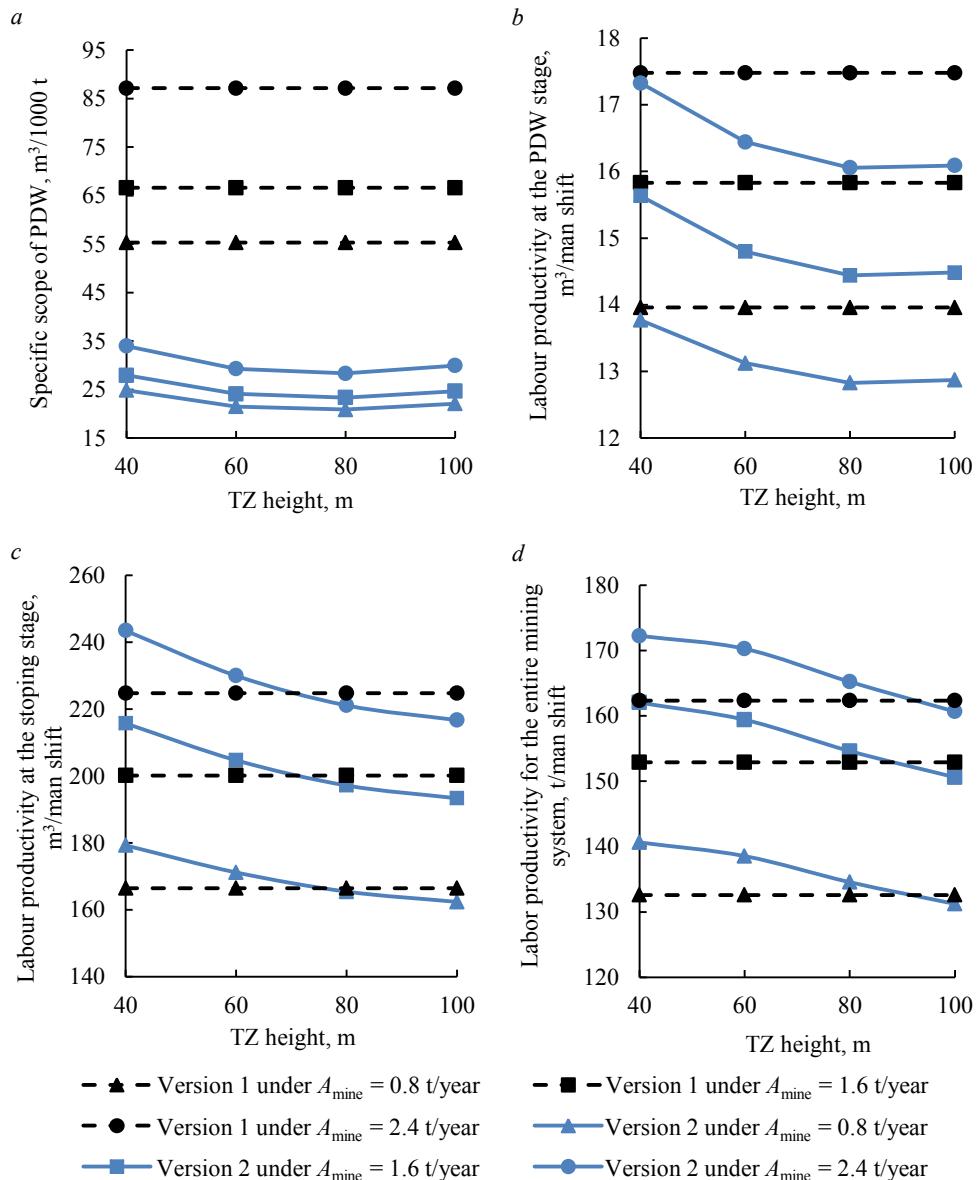


Figure 3. Dependences between the main indicators, the height of the upper sublevel mining, and the production capacity of the underground mine:  
 a – the specific scope of PDW; b – labor productivity at the PDW stage; c – labor productivity at the stoping stage;  
 d – labor productivity for the entire mining system

Рисунок 3. Зависимости основных показателей от высоты подкарьерного этажа и производственной мощности шахты:  
 a – удельный объем ПНР; b – производительность труда на ПНР; c – производительность труда на очистной выемке; d – производительность труда по системе разработки

Labor productivity at the stage of stoping (Figure 3, c) in version 1 does not depend on  $H_{\text{Tz}}$  due to the constant productivity of flow processes (ore breaking, handling, and haulage) and increases with the growth of  $A_{\text{mine}}$  from 166 to 225 t/man shift by

reducing the scope of drilling and using more efficient equipment for handling and haulage. In case of version 2, the productivity at the stage of stoping reduces by 9.4–11.0% with the growth of  $H_{tz}$  due to the increased scope of downhole drilling and the increased distance of ore haulage, and it increases by an average of 34.6% with the growth of  $A_{mine}$  due to the reduced scope of drilling and the use of more efficient equipment for ore handling and haulage. Besides, in version 2, labor productivity at the stage of stoping is 7.7–8.3% higher within  $H_{tz}$  40–60 m due to higher productivity of ore haulage, and 2.5–3.6% lower under  $H_{tz}$  80–100 m due to lower productivity of ore breaking and haulage.

**Table 1. Total costs for the entire mining system, rub/t**  
**Таблица 1. Суммарные затраты по системе разработки, р./т**

Version of the technology	Mine capacity, mln t/year											
	0.8				1.6				2.4			
	Height of the upper sublevel (transition zone), m											
	40	60	80	100	40	60	80	100	40	60	80	100
1	520	520	520	520	516	516	516	516	583	583	583	583
2	320	311	316	333	310	300	303	321	315	305	309	327

Labor productivity of the entire mining system (Figure 3, d) in version 1 does not change with the growth of  $H_{tz}$  and increases the growth of  $A_{mine}$  from 132.6 to 152.9 t/man shift due to the increased productivity at the stages of PDW and stoping. In case of version 2, with the growth of  $H_{tz}$ , productivity decreases by an average of 6.8% as a result of the increased volume of sinking and the decreased productivity of ore breaking and haulage, and it increases by 22.5% in the considered range of  $A_{mine}$  due to the reduced volume of sinking and more efficient equipment. Besides, in version 2, the productivity indicator is 5.6–5.7% higher under  $H_{tz}$  ranging from 40 to 80 m due to the higher productivity at the stage of ore breaking and haulage, and by 1.0–1.5% lower under  $H_{tz} = 100$  m due to the increased volume of sinking and the decreased productivity at the stage of ore breaking and haulage.

It has been found that the technology level of the considered versions, including the effect of  $H_{tz}$  and  $A_{mine}$  on the main TEI of TZ development, complies with the best analogs used in Russia [7–11] and other leading mining countries [12–14, 16–22].

**Choosing the optimal version.** Production cost of 1 tonne of ore and profit per unit of recovered reserves are the main economic indicators to be determined to assess and make the final decision about the type of the upper sublevel mining technology.

The prime cost includes the costs of PDW, breaking, drawing, haulage, and stoping of ore. The calculation results for changing  $H_{tz}$  and  $A_{mine}$  are presented in Table 1.

It can be seen from the data in the table that the production cost of 1 tonne of ore, expressed through the total costs of the system of mining, under various  $H_{tz}$  and  $A_{mine}$  for versions 1 and 2, has a minimum value under  $A_{mine} = 1.6$  million t/year. So, this  $A_{mine}$  is optimal for the conditions under consideration.

The technology for TZ reserves mining is assessed and finally chosen under the established  $A_{mine}$  according to the profit criterion, rub/t, per unit of recovered reserves [1]:

$$Pr = P_c \left( \frac{\varepsilon_c c}{\beta_c} \right) (1 - L) - C_{m.d} \frac{(1 - L)}{(1 - D)},$$

where  $P_c$  is the price of 1 tonne of iron concentrate, rub/t;  $\varepsilon_c$  is the coefficient of iron recovery into concentrate, unit fraction;  $c$  is the content of iron in reserves, unit fraction;

$\beta_c$  is the content of iron in concentrate, %;  $C_{m,d}$  is the cost of ore mining and dressing, rub/t;  $L$  is loss, unit fraction;  $D$  is dilution, unit fraction.

The recoverable value of mined and dressed ore, ore production and dressing cost, and profit are the economic efficiency indicators, the calculation results of which are given in Table 2.

**Table 2. Economic indicators of the mining technology under the mine capacity of 1.6 million tonnes per year**

**Таблица 2. Экономические показатели технологии при производственной мощности шахты 1,6 млн т**

Indicator	Version on the technology	Height of the upper sublevel (transition zone), m			
		40	60	80	100
Recoverable value of mined and dressed ore, rub/t	1	2537	2537	2537	2537
	2	2496	2608	2756	2871
Cost of ore production and dressing, rub/t	1	2160	2160	2160	2160
	2	1569	1511	1487	1527
Profit, rub/t	1	377	377	377	377
	2	927	1097	1269	1344

It was found that the recoverable value of ore in version 2 is 2.8–13.2% higher (under  $H_{tz}$  from 60 to 100 m), and ore production and dressing cost is 27.4–31.2% lower. As a result, the profit is 2.5–3.6 times higher (under  $H_{tz}$  from 40 to 100 m) as compared to option 1.

**Conclusion.** EMM and assessment of mining factors effect on the TEI of differing technologies for mining the upper sublevel under the rock cushion at iron ore deposits, revealed that the technology of sublevel stoping with the subsequent RP development by a system of induced block caving is the most efficient, while the operating costs for ore extraction have a minimum value under  $H_{tz} = 80$  m and  $A_{mine} = 1.6$  million t/year, which are optimal for an enterprise during the transition period. Considering changes in  $H_{tz}$  and  $A_{mine}$ , the level of TEI is high and can be compared to the world's best analogs.

#### REFERENCES

1. Sokolov I. V., Smirnov A. A., Antipin Yu. G., Nikitin I. V. Scientific aspects of choosing the geotechnical strategy for mining of transition areas while combined mining of ore deposits. *Problemy nedropolzovaniia = The Problems of Subsoil Use*. 2020; 1(24): 11–17. Available from: doi: 10.25635/2313-1586.2020.01.011 (In Russ.)
2. Kaplunov D. R., Leizerovich S. G., Tomaev V. K., Sidorchuk V. V. About further development of mining works in Kursk Magnetic Anomaly basin. *Gornyi zhurnal = Mining Journal*. 2011; 10: 44–49. (In Russ.)
3. Kalmykov V. N., Gavrishev S. E., Burmistrov K. V., Gogotin A. A., Petrova O. V., Tomilina N. G. New underground mining approaches justification for the Mal'iy Kuybas open pit mining operations. *Gornyi informatsionno-analiticheskii biulleten (nauchno-tehnicheskii zhurnal) = Mining Informational and Analytical Bulletin (scientific and technical journal)*. 2013; 4: 132–139. (In Russ.)
4. Golik V. I., Polukhin O. N. Use of the mineral resources of KMA toward ecologization of society. *Problemy regionalnoi ekologii = Regional Environmental Issues*. 2013; 4: 45–49. (In Russ.)
5. Sakantsev G. G. *Internal piling at deep ore pits*. Ekaterinburg: UB RAS Publishing; 2008. (In Russ.)
6. Sokolov I. V., Smirnov A. A., Antipin Yu. G., Nikitin I. V., Tishkov M. V. Substantiation of protective cushion thickness in mining under open pit bottom with the caving methods at Udachnaya pipe. *Fiziko-tehnicheskie problemy razrabotki poleznykh iskopаемых = Journal of Mining Science*. 2018; 2: 52–62. Available from: doi: 10.15372/FTPRPI20180207 (In Russ.)
7. Lobanov E. A., Eremenko A. A. Development of podcarrier ore resources of Oleniy ruchey deposit. *Vestnik Kuzbasskogo gosudarstvennogo tekhnicheskogo universiteta = Bulletin of the Kuzbass State Technical University*. 2021; 4(146): 86–95. Available from: doi: 10.26730/1999-4125-2021-4-86-95 (In Russ.)
8. Neverov S. A., Konurin A. I., Shaposhnik Yu. N. Safety in substopping-and-caving in tectonically stressed rock masses. *Interexp Geo-Sibir = Interexpo GEO-Siberia*. 2021; 2(3): 311–321. Available from: doi: 10.33764/2618-981X-2021-2-3-311-321 (In Russ.)

9. Shamiev Zh. B., Alibaev A. P. The technology of pit reserves combined mining by the sublevel caving system with slicing and frontal ore drawing through the slot. *Sovremennye problemy mehaniki sploshnykh sred = Current Issues of Continuum Mechanics*. 2010; 12: 62–70. (In Russ.)
10. Sokolov I. V., Smirnov A. A., Antipin Yu. G., Nikitin I. V., Baranovskii K. V. Underground geotechnology for thick iron-ore deposit combined mining. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = News of the Higher Institutions. Mining Journal*. 2014; 7: 25–32. (In Russ.)
11. Mazhitov A. M. Assessment of the extent of man-induced transformation of a subsoil block in upward mining using ore and host rock caving. *Gornaia promyshlennost = Mining Industry*. 2021; 4: 113–118. Available from: doi: 10.30686/1609-9192-2021-4-113-118 (In Russ.)
12. Lovitt M. Evolution of sublevel caving – safety improvement through technology. *The AusIMM Bulletin*. 2016; April: 82–85.
13. Quintero C. Design of a new layout for sublevel caving at depth. In: *Proceedings of the Fourth International Symposium on Block and Sublevel Caving. Australian Centre for Geomechanics, Perth. 2018*. P. 433–442. Available from: doi.org/10.36487/ACG\_rep/1815\_33\_Quintero
14. Mijalkovski S., Despodov Z., Mirakovski D., Adjiski V. Methodology for optimization of coefficient for ore recovery in sublevel caving mining method. *Podzemni Radovi*. 2017; 30: 19–27. Available from: doi.org/10.5937/podrad1730019S
15. Savich I. N., Mustafin V. I. Perspectives of use and rationale design solutions of block (level) and sublevel face draw. *Gornyi informatsionno-analiticheskii biulleten (nauchno-tehnicheskii zhurnal) = Mining Informational and Analytical Bulletin (scientific and technical journal)*. 2015; S1: 419–429. (In Russ.)
16. Pourrahimian Y., Askari Nasab H., Tannant D. A multi-step approach for block-cave production scheduling optimization. *International Journal of Mining Science and Technology*. 2013; 23: 739–750. Available from: doi: 10.1016/j.ijmst.2013.08.019
17. Afum B. O., Ben-Awuah E. A review of models and algorithms for surface-underground mining options and transitions optimization: some lessons learnt and the way forward. *Mining*. 2021; 1: 112–134. Available from: doi.org/10.3390/mining1010008
18. MacNeil J. A. L., Dimitrakopoulos R. G. A stochastic optimization formulation for the transition from open pit to underground mining. *Optimization and Engineering*. 2017; 18: 793–813. Available from: doi: 10.1007/s11081-017-9361-6
19. Whittle D., Brazil M., Grossman P., Rubinstein H., Thomas D. Combined optimisation of an open-pit mine outline and the transition depth to underground mining. *European Journal of Operational Research*. 2018; 268(2): 624–634. Available from: doi: 10.1016/j.ejor.2018.02.005
20. King B., Goycoolea M., Newman A. Optimizing the open pit-to-underground mining transition. *European Journal of Operational Research*. 2017; 257(1): 297–309.
21. Dagdelen K., Traore I. Open pit transition depth determination through global analysis of open pit and underground mine production scheduling. *Advances in Applied Strategic Mine Planning*. 2018. P. 287–296. Available from: doi: 10.1007/978-3-319-69320-0\_19
22. Soltani A., Osanloo M. Semi-symmetrical production scheduling of an orebody for optimizing the depth of transitioning from open pit to block caving. *Resources Policy*. 2020; 68. Available from: doi: 10.1016/j.resourpol.2020.101700

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**Влияние горнотехнических факторов на технико-экономические показатели отработки подкарьерного этажа под породной подушкой в условиях железорудных месторождений**

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**Реферат**

**Актуальность темы.** В настоящее время при переходе от открытых горных работ к подземным на железорудных месторождениях наибольшее распространение получил вариант

системы разработки подэтажного обрушения с торцевым выпуском руды. Данная технология имеет существенные недостатки – низкие показатели извлечения руды из недр и увеличенные эксплуатационные затраты на подготовительно-нарезные и очистные работы. Разработка альтернативной технологии отработки подкарьерного этажа, обеспечивающей повышение показателей извлечения и интенсивности выпуска руды из блока и снижение себестоимости основных технологических процессов в условиях наличия внутреннего отвала на дне карьера, используемого в качестве породной подушки, является актуальной научно-технической задачей.

**Цель работы.** Исследование влияния горнотехнических факторов на технико-экономические показатели различных друг от друга технологий отработки подкарьерного этажа под породной подушкой в условиях железорудных месторождений.

**Методы исследований.** В работе использован комплексный метод исследований, включающий изыскание и конструирование рационального варианта технологии, экономико-математическое моделирование и технико-экономическое сравнение.

**Анализ результатов.** Установлены зависимости основных технико-экономических показателей (потери и разубоживание, удельный объем подготовительно-нарезных работ, производительность труда и удельные эксплуатационные затраты по технологическим процессам) от высоты подкарьерного этажа в интервале от 40 до 100 м и производственной мощности шахты в интервале от 0,8 до 2,4 млн т руды в год. Определено, что эксплуатационные затраты на добывчу руды имеют минимальное значение при высоте подкарьерного этажа 80 м и производственной мощности 1,6 млн т руды в год, которые являются оптимальными для предприятия в переходный период.

**Выводы.** Обоснована технология этажно-камерной выемки с последующей отработкой междукамерного целика системой этажного принудительного обрушения, обеспечивающая большую эффективность по сравнению с традиционным вариантом подэтажного обрушения.

**Ключевые слова:** железорудное месторождение; переходная зона; породная подушка; система разработки; горнотехнические факторы; показатели извлечения; технико-экономические показатели.

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#### БИБЛИОГРАФИЧЕСКИЙ СПИСОК

- Соколов И. В., Смирнов А. А., Антипин Ю. Г., Никитин И. В. Научные аспекты выбора геотехнологической стратегии освоения переходных зон при комбинированной разработке рудных месторождений // Проблемы недропользования. 2020. № 1(24). С. 11–17. DOI 10.25635/2313-1586.2020.01.011
- Каплунов Д. Р., Лейзерович С. Г., Томаев В. К., Сидорчук В. В. О дальнейшем развитии горных работ в бассейне КМА // Горный журнал. 2011. № 10. С. 44–49.
- Калмыков В. Н., Гаврищев С. Е., Бурмистров К. В., Гоготин А. А., Петрова О. В., Томилина Н. Г. Обоснование рациональных вариантов перехода с открытого на подземный способ разработки месторождения «Малый Куйбас» // ГИАБ. 2013. № 4. С. 132–139.
- Голик В. И., Полухин О. Н. Использование минерально-сырьевой базы КМА в условиях экологизации общества // Проблемы региональной экологии. 2013. № 4. С. 45–49.
- Саканцев Г. Г. Внутреннее отвалообразование на глубоких рудных карьерах. Екатеринбург: УрО РАН, 2008. 225 с.
- Соколов И. В., Смирнов А. А., Антипин Ю. Г., Никитин И. В., Тишков М. В. Обоснование толщины предохранительной подушки при отработке подкарьерных запасов трубы «Удачная» системами с обрушением // Физико-технические проблемы разработки полезных ископаемых. 2018. № 2. С. 52–62. DOI: 10.15372/FTPBPRI20180207
- Лобанов Е. А., Еременко А. А. Разработка подкарьерных рудных запасов месторождения Олений ручей // Вестник Кузбасского государственного технического университета. 2021. № 4(146). С. 86–95. DOI: 10.26730/1999-4125-2021-4-86-95
- Неверов С. А., Конурин А. И., Шапошник Ю. Н. Безопасность очистных работ при подэтажной выемке с обрушением в тектонически напряженных массивах // Интерэкспо Гео-Сибирь. 2021. Т. 2. № 3. С. 311–321. DOI: 10.33764/2618-981X-2021-2-3-311-321
- Шамиев Ж. Б., Алибаев А. П. Технология комбинированной разработки подкарьерных запасов системой подэтажного обрушения с секционной отбойкой и торцевым выпуском руды через щель // Современные проблемы механики сплошных сред. 2010. № 12. С. 62–70.
- Соколов И. В., Смирнов А. А., Антипин Ю. Г., Никитин И. В., Бараповский К. В. Подземная геотехнология при комбинированной разработке мощного железорудного месторождения // Известия вузов. Горный журнал. 2014. № 7. С. 25–32.
- Мажитов А. М. Оценка степени техногенного преобразования участка недр при разработке месторождения с обрушением руды и вмещающих пород в восходящем порядке // Горная промышленность. 2021. № 4. С. 113–118. DOI: 10.30686/1609-9192-2021-4-113-118
- Lovitt M. Evolution of sublevel caving – safety improvement through technology // The AusIMM Bulletin. 2016. April. P. 82–85.

13. Quinteiro C. Design of a new layout for sublevel caving at depth // Proceedings of the Fourth International Symposium on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth. 2018. P. 433–442. URL: [https://doi.org/10.36487/ACG\\_rep/1815\\_33\\_Quinteiro](https://doi.org/10.36487/ACG_rep/1815_33_Quinteiro)
14. Mijalkovski S., Despodov Z., Mirakovski D., Adjiski V. Methodology for optimization of coefficient for ore recovery in sublevel caving mining method // Podzemni Radovi. 2017. No. 30. P. 19–27. DOI: 10.5937/podrad1730019S
15. Савич И. Н., Мустафин В. И. Перспективы применения и обоснование проектных решений при этажном и подэтажном торцевом выпуске руды // ГИАБ. 2015. № S1. С. 419–429.
16. Pourrahimian Y., Askari Nasab H., Tannant D. A multi-step approach for block-cave production scheduling optimization // International Journal of Mining Science and Technology. 2013. Vol. 23. P. 739–750. DOI: 10.1016/j.ijmst.2013.08.019
17. Afum B. O., Ben-Awuah E. A review of models and algorithms for surface-underground mining options and transitions optimization: some lessons learnt and the way forward // Mining. 2021. Vol. 1. P. 112–134. <https://doi.org/10.3390/mining1010008>
18. MacNeil J. A. L., Dimitrakopoulos R. G. A stochastic optimization formulation for the transition from open pit to underground mining // Optimization and Engineering. 2017. No. 18. P. 793–813. DOI: 10.1007/s11081-017-9361-6
19. Whittle D., Brazil M., Grossman P., Rubinstein H., Thomas D. Combined optimisation of an open-pit mine outline and the transition depth to underground mining // European Journal of Operational Research. 2018. Vol. 268(2). P. 624–634. DOI: 10.1016/j.ejor.2018.02.005
20. King B., Goycoolea M., Newman A. Optimizing the open pit-to-underground mining transition // European Journal of Operational Research. 2017. Vol. 257. No. 1. P. 297–309.
21. Dagdelen K., Traore I. Open pit transition depth determination through global analysis of open pit and underground mine production scheduling // Advances in Applied Strategic Mine Planning. 2018. P. 287–296. DOI: 10.1007/978-3-319-69320-0\_19
22. Soltani A., Osanloo M. Semi-symmetrical production scheduling of an orebody for optimizing the depth of transitioning from open pit to block caving. Resources Policy. 2020. Vol. 68. DOI: 10.1016/j.resourpol.2020.101700

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