Rock pressure control methods based on detected regularities of stress formation in mining structures

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Abstract

Relevance. Subsurface mining at the Gaysky ore mine is intensifying because of the growing need in raw material. It leads to rapid increase in the depth of mining and to problems connected with the stability of mining system constructive elements. The efficiency of the Gaysky deposit underground development is largely determined by mining system constructive elements stability. Ore cave-in in the chambers of the first and second stages causes the growth of load in the interchamber pillars leading to their collapse, loss of boreholes and development headings. Mining productivity in the chambers of the first, second, etc. stages falls, oversize yield grows, which also impairs the effectiveness of mining. Hanging wall and footwall cave-in in the deposit under consideration may be explained not only by host rock poor stability, but also by the presence of high compressive tectonic stresses, that were determined by the authors. Stress measurements in the rock mass have shown that the east-west stresses have doubled the north-south stresses and have been 1.5 times as high as the vertical ones.

The purpose of the research is to reduce stresses in stopes ore in place when excavating steeply dipping ore bodies using a sublevel stoping method with a hardening backfill.

Research methodology includes full-scale experimental measurements of the stress state of the rock mass and ore in place at accessible depths and horizons of the deposit. A comprehensive scientific research method was used, including the analysis and theoretical generalization of stress distribution regularities in the arrays of the extracted chamber reserves and mathematical modeling of the behavior of the research object; theoretical results were compared with the results of instrumental observations.

The analysis of the research results made it possible to establish the stress-strained state behavior in the course of mining. It was revealed that when mining a deposit using sublevel stoping, the most loaded elements are the hanging wall and footwall exposed parts, ceiling, interchamber pillars and bottom. Therefore, it is necessary to take measures to increase ore in place stability in order to guarantee the safety and efficiency of the mineral extraction technology.

Conclusions. Relieve slots method is among the most effective and frequently used active method of rock mass pressure control. The method has come into common use because it is easy to apply. Main labor inputs of a relieve slot creation are only reduced to extra drilling and blasting which do not require additional tunnel driving. The aim of the relieve slot is to create additional free surfaces for deformation, to redistribute rock mass stress-strain state, and remove stress from the protected element of the mining system.

Key words: stress state of rock mass; rock pressure control; hanging wall; footwall; stress state; mining sequence; stress concentration near mine workings and worked-out spaces; technogenic stresses.

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Introduction. The main difficulties of sublevel stoping nowadays are associated with stoping safety problems in the course of mineral extraction and the deterioration of engineering and economic indicators. The reason for this is that subsurface mining is intensifying because of the growing need in raw material. It leads to rapid increase in the depth of mining and to problems connected with the stability of mining system constructive elements [1].
Most common forms of rock pressure manifestation in the course of stoping are the following: destruction of crosscuts and drifts junctions at the bottom of chambers; collapse of the backfill from the overlaying formations; chamber walls and ore in place caving.

The indicated negative events mostly affect the stability of pillars and exposures, so the issue of mining system constructive elements stability is so pressing.

The analysis and experimental-analytical calculation of rock mass initial stress-strain state (SSS) are important when selecting permanent mines’ location and stoping sequence [2, 3].

Chamber stability study at the Gaysky ore mine, which uses the sublevel stoping mining method with backfill, has determined that the hanging wall caving reached 20% of the chamber length, and the apex of cave reached 8 m.

In case of roof rock and hanging wall cave-in, ore loss and dilution increase causing additional complications with enrichment, consequently increasing the cost of production and significantly deteriorating enterprise engineering and economic indicators [4–7].

Hanging wall and footwall cave-in in the deposit under consideration may be explained not only by host rock poor stability, but also by the presence of high compressive tectonic stresses. Stress measurements in the rock mass have shown that the east-west stresses have doubled the north-south stresses and have been 1.5 times as high as the vertical ones [8–11].

Another significant problem of mining enterprises that use the sublevel stoping mining method is mining system constructive elements stability. Ore cave-in in the chambers of the first and second stages causes the growth of load in the interchamber pillars leading to their collapse, loss of boreholes and development headings. Mining
productivity in the chambers of the first and second stages falls, oversize yield grows, which also impairs the effectiveness of mining. For that reason, it is important to be aware of the regularities of stress state development and distribution within the rock mass. This knowledge will make it possible to more effectively develop and hold activities for ore in place stability in order to ensure safe and efficient technology of mineral extraction.

Table 1. Mine stresses

| Depth, m | Calculation | Measurement |
|----------|-------------|-------------|
|          | $\gamma H$, MPa | Stresses $\sigma$, MPa | $\gamma H$, MPa | Stresses $\sigma$, MPa |
|          | $\sigma_1$ | $\sigma_2$ | $\sigma_z$ | $\sigma_1$ | $\sigma_2$ | $\sigma_z$ |
| 830      | $-22.41$   | $-22.41$   | $-44.82$   | $-22.41$   | $-22.7$   | $-17.6$   | $-39.4$   | $-22.7$   |
| 910      | $-24.57$   | $-24.57$   | $-49.14$   | $-24.57$   | $-24.8$   | $-19.8$   | $-41.6$   | $-24.8$   |
| 990      | $-26.73$   | $-26.73$   | $-53.46$   | $-26.73$   | $-$       | $-$       | $-$       | $-$       |
| 1,070    | $-28.89$   | $-28.89$   | $-57.78$   | $-28.89$   | $-29.2$   | $-32$     | $-48.7$   | $-33.3$   |
| 1,150    | $-31.05$   | $-31.05$   | $-62.1$    | $-31.05$   | $-$       | $-$       | $-$       | $-$       |
| 1,230    | $-33.21$   | $-33.21$   | $-66.42$   | $-33.21$   | $-$       | $-$       | $-$       | $-$       |
| 1,310    | $-35.37$   | $-35.37$   | $-70.74$   | $-35.37$   | $-$       | $-$       | $-$       | $-$       |
| 1,390    | $-37.53$   | $-37.53$   | $-75.06$   | $-37.53$   | $-$       | $-$       | $-$       | $-$       |
| 1,470    | $-39.69$   | $-39.69$   | $-79.38$   | $-39.69$   | $-$       | $-$       | $-$       | $-$       |
| 1,550    | $-41.85$   | $-41.85$   | $-83.7$    | $-41.85$   | $-$       | $-$       | $-$       | $-$       |
| 1,630    | $-44.01$   | $-44.01$   | $-88.02$   | $-44.01$   | $-$       | $-$       | $-$       | $-$       |
| 1,790    | $-48.33$   | $-48.33$   | $-96.66$   | $-48.33$   | $-$       | $-$       | $-$       | $-$       |

$\sigma_1$ – north-south stresses; $\sigma_2$ – east-west stresses; $\sigma_z$ – vertical stresses.

With the development of rock mass and ore in place SSS computer simulation, the optimal sequence of mining has been substantiated.

**Mining sequence substantiation methodology.** The optimal sequence of mining in levels $–830/–1070$ m and $–1070/–1310$ m was substantiated based on rock mass and ore in place stress-strain state computer simulation with Fem software resting upon the finite element method (FEM). The software was developed in IM RAS and has become a rather frequent practice in Russia (IM FEB RAS, Chita State...
University, Irkutsk State Technical University, and Nosov Magnitogorsk State Technical University).

By way of boundary conditions, the results of undisturbed rock mass maximum stress tensor definition were used in calculations (table 1). Mean strength of ore in place was accepted equal to 100 MPa. Calculated parameters of massif’s SSS were set as boundary conditions.

![Fig. 3. Changes in stresses in the ore in place of the third stage chamber on the left flank by sublevels](image)

The computer model had the following parameters: the chambers height \( H = 80 \) m; the chamber width \( b = 20 \) m; chamber length \( m = 80 \) m; orebody angle of dip \( \alpha = 60^\circ \).

The main mining options were simulated in a volumetric setting. After obtaining volumetric solutions, boundary conditions were selected for a particular mining sequence, under which plane problem solution in a horizontal plane satisfactorily converged with the volumetric solution. Additional solutions allowing to elaborate the proposed mining sequences were produced with these boundary conditions.

| Types of media   | \( \gamma \), g/cm\(^3\) | \( E \cdot 10^4 \), MPa | \( \mu \) | \( \rho \), degrees | \( C \), MPa |
|------------------|---------------------------|------------------------|---------|-----------------|-------------|
| Rock mass        | 2.8                       | 7.0                    | 0.28    | 34              | 9.0         |
| Ore in place     | 3.9                       | 9.9                    | 0.15    | 37              | 11.0        |
| Backfill         | 2.1                       | 0.5                    | 0.21    | 36              | 1.5         |

**Stress-strain state calculation results.** Fig. 2 and 3 provide calculation results for the mean value of compressive stresses in the ore pillars dividing the mined-out chambers. The numbers indicate the sequence of chambers mining along the strike within a block.

Based on the quoted results analysis, it is possible to assert that none of the considered schemes can be accepted as totally satisfactory: as the depth of mining grows, bed outcrop stress in the lower levels exceeds ore uniaxial compressive strength (100 MPa) (fig. 1 and 2) [12–16].

Elasticity problem in a plane setting was being solved. Stresses presented in table 1 were used in calculation as boundary conditions. The accepted stresses acting in the undisturbed rock mass are presented in table 2.

Calculated parameters of massif’s SSS were set as boundary conditions in the models. Main dimensions and parameters of the applied calculation model were...
Fig. 4. Distribution of stresses in the array in level 990–1070 m when developing the chambers of:

a – the 1st stage; b – the 2nd stage; c – the 3rd stage.

Рис. 4. Распределение напряжений в массиве на этаже 990–1070 м при отработке камер:

а – 1-й очередь; б – 2-й очеред; в – 3-й очеред
Fig. 5. Distribution of stresses in the array in level 990–1070 m when developing the chambers of:

- the 4th stage;  
- the 5th stage.
accepted in accordance with the actual dimensions of the orebody within the level under consideration.

Physical and mechanical properties of the rock mass and the backfill material applied in the simulation are presented in table 2.

Under hor. –830 m the reserves are developed in accordance with the feasibility study. In order to extract the reserves from levels –830/–910 m and –910/–990 m, a method of sublevel stoping with room-driving in a block was provided, as per the scheme I – II – III – I – IV – V (ore pillars are temporarily left at the site of chambers III, IV and V, they are extracted later with due attention to protective measures).

In order to identify the regularities of stress distribution in ore in place and substantiate the optimal sequence of stoping at level 910–990 m, at different stages of the Gaysky mine development in accordance with the established schedule of mining, mathematical modeling was carried out for the depth of 935 m at the upper sublevel because block simulation in the volumetric setting recorded maximum compressive stress in this level. The calculation accounted for the effect made by the backfilled chambers of stages I–II because the collapse of the backfill or its excessive deformation due to fragility may lead to additional concentration of stresses in ore in place (pillars) and create a number of technological problems.

Pillars in the chambers of stages III, IV and V with the total thickness of 40 m under the acting stress state in level 910–990 m will be in a stable condition. Stress growth in the pillars was most starkly illustrated in graphs of stress behavior in ore in place by sublevels (fig. 3). They show stresses distribution over the center of the pillar at the level of sublevels along the whole length of the future chamber starting from the footwall. It can therefore be concluded from these graphs analysis that the use of the three-stage scheme of mining at the depth of more than 910 m may be considered ineffective without stress state reduction precautions in the inter-block pillars.

**Rock pressure control methods.** In case of organized systematic extraction of chamber reserves in a level by a general expansion of the extraction front in the chambers of stages I–III, there will be no problems of great concern (fig. 4). However,
for the chambers of stages IV and V as well as ore inter-block pillars it is necessary to provide for some measure for their protection (fig. 5).

Pillars should be mined “from the center to the flanks”. In case of using this stoping scheme, after the first pillar is extracted, as a result of stresses redistribution, compressive stresses values in the next pillar will grow by 35%, and its excessive deformation will begin. After that, ore in place broken condition will result in drilling difficulties and increased dilution due to backfill collapse near the chambers contours (fig. 6).

For that reason, active methods of rock mass pressure control should be used as inter-block pillars protective measures. The active method involve direct change of stresses in local sites of the rock mass by means of reducing or redistributing the stresses.

Relieve slots method is among the most effective and frequently used active method of rock mass pressure control. The method has come into common use because it is easy to apply. Main labor inputs of a relieve slot creation are only reduced to extra drilling and blasting which do not require additional tunnel driving. The aim of the relieve slot is to create additional free surfaces for deformation, to redistribute rock mass stress-strain state, and remove stress from the protected element of the mining system.

Relieve slot plane should be at right angles to maximum stresses direction in the rock mass.

In some cases, blasthole rings may be used without blasting. It may be sufficient to relieve and protect the chamber from compressive stresses. If one ring is insufficient, 2 or 3 rings may be required. Parameters and required number of the rings in the relieve slot may be accurately identified only from pilot testing. Also, blasthole rings with camouflet blasting of the next but one well are used to create tension joints. This method is used to relieve the rock mass and protect it from tensile stresses at the contour of the chambers.

Ore in place must be relieved by means of creating advance relieve (cutoff) slot at full pillar width or making a blasthole ring in the hanging wall which will reduce stress.
in the pillar as a result of deformation. When extracting a pillar in the chambers of stages VI, VII and VIII, it is necessary to produce one tensile joint per blast (fig. 6). Otherwise, there will be overload of ore unrelieved part up to incredible values inevitably resulting in rock mass collapse (fig. 7).

Maximum stresses $\sigma_{\text{max}}$ acting from chambers hanging wall and footwall have also been calculated for different angles $\beta$ in the base of the triangle mass left. It has been determined that it is most reasonable to leave this mass with angle $\beta$ equal to $70^\circ$ (fig. 8).

**Summary.** The quoted results of the rock mass SSS calculation allow stating that it is impossible to extract all the reserves in a level using the sublevel stoping method without taking the special measures. So, the sequence of mining is as follows:

1. When extracting level 830–910 m, almost any scheme can be applied.
2. Reserves of levels 910–990 m are extracted according to scheme I – II – III – I – IV – V.
3. At levels 990–1,070, 1,150–1,230 and 1,230–1,310 m, sublevel stoping is used with backfilling and longwall mining with 160 m goaf and 60 m inter-block pillar.
4. Protective belts at levels 910–990 and 990–1,070 m are pointless due to the low thickness of orebodies and thick rock intercalations.
5. As a special measure, it is recommended to relieve ore in place in the intervening pillars by means of producing advance relieve (cutoff) slot at full pillar width or making blasthole ring in the hanging wall which will reduce stress in the pillar as a result of deformation.

REFERENCES

1. Zubkov A. V. Geomechanics and geotechnology. Ekaterinburg: IM UB RAS Publishing; 2001. (In Russ.)

2. Sidorov D. V., Potapchuk M. I., Sidliar A. V. Prediction of rock burst hazard of tectonically disturbed ore massif on deep horizons of the Nikolaev polymetallic deposit. Zapiski Gornogo instituta = Journal of Mining Institute. 2018; 234: 604–611. (In Russ.)

3. Eremenko V. A., Gakhova L. N., Semeniakin E. N. Formation of higher stress zones and clusters of seismic events in deep mining in Tashtagol. Fiziko-tekhnicheskie problemy razrabotki poleznykh iskopaemykh = Journal of Mining Science. 2012; 2: 80–87. (In Russ.)

4. Miaskov A. V. Methodological foundations of ecological and economic substantiation of the preservation of natural ecosystems in mining regions. Gornyi informatsionno-analiticheskiy biulleten (nauchno-tekhnicheskoe zhurnal) = Mining Informational and Analytical Bulletin (scientific and technical journal). 2011; 1: 399–401. (In Russ.)

5. Miaskov A. V. Modern ecological and economic issues of subsoil use. Gornyi informatsionno-analiticheskiy biulleten (nauchno-tekhnicheskoe zhurnal) = Mining Informational and Analytical Bulletin (scientific and technical journal). 2014; 2: 157–160. (In Russ.)

6. Timonin V. V., Kondratenko A. S. Process and measuring equipment transport in uncased boreholes. J. Min. Sci. 2015; 51 (5): 1056–1061.

7. Jianju Du, Xiang hui Qin, Qingli Zeng, Luqing Zhang, Qunce Chen, Jian Zhou, Wen Meng. Estimation of the present-day stress field using in-situ stress measurements in the Alxa area, Inner Mongolia for China's HLW disposal. Engineering Geology. Vol. 30; March 2017: 76–84.

8. Sentyabov S., Zubkov A. Investigation of stress field parameters at deep horizons of the Gayskoye field. In: E3S Web of Conferences: VIII International Scientific Conference “Problems of Complex Development of Georesources” (PCDG 2020), Khabarovsk, Russia Federation, September 8–10, 2020. 2020; 192: 01028. Available from: https://doi.org/10.1051/e3sconf/202019201028.

9. Zubkov A. V., Sentiabov S. V. Interrelation of physical processes in space, on the sun and their manifestation in the lithosphere. In: Earth and environmental science: international multidisciplinary conference on industrial engineering and modern technologies "FarEastCon" (Vladivostok, Russky Island, October 1–4, 2019). 2020; 459 (3): 042082. (In Russ.)

10. Volkov Iu. V. Systems for the development of underground geotechnology of copper pyrite deposits in the Urals. Ekaterinburg: IM UB RAS Publishing; 2001. (In Russ.)

11. Vlokh N. P. Underground mine pressure management. Moscow: Nedra Publishing; 1994. (In Russ.)

12. Zubkov A. V., Sentiabov S. V. New approaches to the assessment of stability of rock rock arrays. Gornyi informatsionno-analiticheskiy biulleten (nauchno-tekhnicheskoe zhurnal) = Mining Informational and Analytical Bulletin (scientific and technical journal). 2020; 3-1: 68–77. Available from: 25018 / 0236-1493-2020-31-0-68-77. (In Russ.)

13. Kong L., Ostadjhassan M., Li C., Tamimi N. Rock Physics and geomechanics of 3D printed Rocks. ARMA 51st U.S. Rock Mechanics. Geomechanics Symposium, San Francisco, California, USA. 2017, pp. 1–8.

14. Gell E. M., Walley S. M., Braithwaite C. H. Review of the Validity of the Use of Artificial Specimens for Characterizing the Mechanical Properties of Rocks. Rock Mechanics and Rock Engineering. 2019; 3: 1–13.

15. Kartashov Iu. M., Matveev B. V., Mikheev G. M., Fadeev A. B. Strength and deformability of rocks. Moscow: Nedra Publishing; 1979. (In Russ.)

16. Hong K., Han E., Kang K. Determination of geological strength index of jointed rock mass based on image processing. Journal of Rock Mechanics and Geotechnical Engineering. 2017; 9: 702–708.

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Методы управления горным давлением, основанные на выявленных закономерностях формирования напряженного состояния в горных конструкциях

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Реферат

Актуальность темы. Интенсификация подземных горных работ на Гайском руднике, вызванная все возрастающей потребностью в сырье, приводит к быстрому росту глубины разработки месторождений полезных ископаемых и возникновению проблем устойчивости конструктивных элементов системы разработки. Эффективность разработки Гайского месторождения подземным способом в значительной мере определяется устойчивостью конструктивных элементов системы разработки. Обрушение рудных стенок в камерах первой и второй очередей вызывает рост нагрузок на междукамерные целики, что приводит к их разрушению, потере буровых скважин и подготовительных выработок. Падает производительность добычи из камер второй, третьей и др. очередей. При самообрушении пород кровли и висячего бока возрастают потери и засорение руды, выход негабарита. Причины разрушения висячего и лежачего боков на данном месторождении связаны не только с низкой устойчивостью вмещающих пород, но и с наличием высоких сжимающих тектонических напряжений, которые были определены авторами. Измерения напряжений массива горных пород показали, что напряжения, действующие по субширотному направлению, вдвое превысили напряжения меридионального направления и в 1,5 раза больше вертикальных.

Цель исследований – снижение напряжений в рудных массивах очистных камер при ведении крупнодиафрагмных рудных тел камерной системой разработки с твердующей заказкой.

Методика исследований предполагает натурные экспериментальные измерения напряженного состояния массива пород и руд месторождения на доступных глубинах и горизонтах месторождения. Использован комплексный метод научных исследований, включающий анализ и теоретическое обобщение закономерностей распределения напряжений в массивах вынимаемых камерных запасов; математическое моделирование; сопоставление теоретических результатов с результатами инструментальных наблюдений.

Анализ результатов исследований позволил установить закономерности изменения напряженно-деформированного состояния при ведении горных работ. Выявлено, что при отработке месторождения камерными системами разработки наиболее нагруженными элементами являются обнаженная часть висячего и лежачего боков, потолочина, междукамерные целики и днище, поэтому необходимо проводить мероприятия, обеспечивающие повышение устойчивости рудного массива горных пород с целью гарантирования безопасности и эффективности технологии добычи полезного ископаемого.

Выводы. Один из наиболее эффективных и часто применяемых активных методов управления горным давлением массива горных пород – это применение разгрузочных щелей. Широкое применение данный метод получил из-за его простоты в осуществлении. Основные трудозатраты образования разгрузочной щели сводятся только к дополнительным буровзрывным работам, не требующим дополнительной проходки выработок. Сущность разгрузочной щели – в создании дополнительных свободных поверхностей, на которых происходит деформация, перераспределение напряженно-деформированного состояния массива горных пород, снятия напряжения с защищаемого элемента системы разработки.

Ключевые слова: напряженное состояние массива скальных пород; управление горным давлением; висячий бок; лежачий бок; напряженное состояние; порядок отработки; концентрация напряжений около выработок и выработанных пространств; техногенные напряжения.

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БИБЛИОГРАФИЧЕСКИЙ СПИСОК
1. Зубков А. В. Геомеханика и геотехнология. Екатеринбург: ИГД УрО РАН, 2001. 333 с.
2. Сидоров Д. В., Потапчук М. И., Сидляр А. В. Прогнозирование у daraопасности тектонически нарушенного рудного массива на глубоких горизонтах Николаевского полиметаллического месторождения // Записки Горного института. 2018. Т. 234. С. 604–611.
3. Еременко В. А., Гахова Л. Н., Семенякин Е. Н. Формирование зон концентрации напряжений и динамических явлений при отработке рудных тел Таштагольского месторождения на больших глубинах // ФТПРПИ. 2012. № 2. С. 80–87.
4. Мясков А. В. Методологические основы эколого-экономического обоснования сохранения естественных экосистем в горнопромышленных регионах // ГИАБ. 2011. № 1. С. 399–401.
5. Мясков А. В. Современные эколого-экономические проблемы недропользования // ГИАБ. 2014. № 2. С. 157–160.
6. Timonin V. V., Kondratenko A. S. Process and measuring equipment transport in uncased boreholes // J. Min. Sci. 2015. Vol. 51. No 5. P. 1056–1061.
7. Jianju Du, Xiang hui Qin, Qingli Zeng, Luqing Zhang, Quence Chen, Jian Zhou, Wen Meng. Estimation of the present-day stress field using in-situ stress measurements in the Alxa area, Inner Mongolia for China's HLW disposal // Engineering Geology. Vol. 220. 30 March 2017. P. 76–84.
8. Sentyabov S., Zubkov A. Investigation of stress field parameters at deep horizons of the Gayskyoe field // E3S Web of Conferences : VIII International Scientific Conference “Problems of Complex Development of Georesources” (PCDG 2020), Khabarovsk, Russia Federation, September 8–10, 2020. Vol. 192. P. 01028. DOI: https://doi.org/10.1051/e3sconf/202019201028
9. Zubkov A. V., Sentyabov S. V. Vзаимосвязь физических процессов в космосе, на Солнце и их проявление в литосфере // Земля и наука об окружающей среде: Междунар. мультидисциплин. конф. по промышленному инжинирингу и современным технологиям «FarEastConf» (Владивосток, остров Русский, 1–4 октября 2019 г.). 2020. T. 459, гл. 3. C. 042082. DOI: 10.1088/1755-1315/459/4/042082
10. Волков Ю. В. Системы разработки подземной геотехнологии медноколчеданных месторождений Урала // Екатеринбург: ИИД УрО РАН, 2001. 248 с.
11. Влох Н. П. Управление горным давлением на подземных рудниках. М.: Недра, 1994. 208 с.
12. Зубков А. В., Сентябов С. В. Новые подходы к оценке устойчивости скальных массивов горных пород // ГИАБ. 2020. № 3-1. С. 68–77. DOI: 25018/0236-1493-2020-31-0-68-77
13. Kong L., Ostadhassan M., Li C., Tamimi N. Rock Physics and geomechanics of 3D printed Rocks // ARMA 51st U. S. Rock Mechanics. Geomechanics Symposium, San Francisco, California, USA, 2017. P. 1–8.
14. Gell E. M., Walley S. M., Braithwaite C. H. Review of the validity of the use of artificial specimens for characterizing the mechanical properties of rocks // Rock Mechanics and Rock Engineering. 2019. No. 3. P. 1–13.
15. Карташов Ю. М., Матвеев Б. В., Михеев Г. М., Фадеев А. Б. Прочность и деформируемость горных пород. М.: Недра, 1979. 269 с.
16. Hong K., Han E., Kang K. Determination of geological strength index of jointed rock mass based on image processing // Journal of Rock Mechanics and Geotechnical Engineering. 2017. No 9. P. 702–708.

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