ГИАБ. Горный информационно-аналитический бюллетень /
MIAB. Mining Informational and Analytical Bulletin, 2025;(3):54-63
ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

УДК 622.28:519.87 DOI: 10.25018/0236_1493_2025_3_0_54

МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ПРОГНОЗИРОВАНИЯ НАГРУЗКИ НА КРЕПЬ ГОРИЗОНТАЛЬНОЙ ГОРНОЙ ВЫРАБОТКИ

В.А. Евстратов[1], Э.Ю. Воронова[1], Б.Б. Луганцев[2], В.С. Исаков[3], Л.А. Холодова[1]

[1] Шахтинский автодорожный институт (филиал) Южно-Российского государственного политехнического университета (НПИ) имени М.И. Платова, Шахты, Россия,
e-mail: vae602@yandex.ru

[2] ООО «Шахтинский научно-исследовательский и проектно-конструкторский угольный институт», Шахты, Россия

[3] Южно-Российский государственный политехнический университет (НПИ) имени М.И. Платова, Новочеркасск, Россия

Аннотация: Рассмотрена проблема определения объема горной массы, оказывающего давление на крепь горизонтальной выработки с учетом коэффициента внутреннего трения в массиве и величин сопротивления отрыву и сдвигу (сцепления). Предложена новая математическая модель определения наиболее вероятной формы поверхности разрушения горного массива над горизонтальной выработкой при условии однородности физико-механических свойств породы в окрестностях выработки. В настоящее время при определении расчетной нагрузки на крепь горизонтальной горной выработки за основу принимаются приближенные математические модели, разработанные в первой половине прошлого столетия, имеющие различные допущения и упрощения, дополненные уточнениями, отражающими особенности горно-геологических условий в районе конкретной выработки и особенностями технологического процесса при ее проходке. Принятое за основу математическое описание процесса сводообразования в горном массиве над выработкой приводит к необоснованному принятию расчетной нагрузки при определении несущей способности крепи и, следовательно, к необоснованному выбору прочностных параметров крепи. Целью исследования является разработка математической модели напряженно-деформированного состояния горного массива над горизонтальной горной выработкой с учитывающей влияние физико-механических свойств горной массы и геометрических параметров выработки и позволяющей определить наиболее вероятную нагрузку на крепь выработки. Полученные аналитические зависимости позволяют более точно определить форму поверхности разрушения в горном массиве над горизонтальной горной выработкой, чем существующие методики, при условии однородности физико-механических свойств массива над выработкой.

Ключевые слова: горизонтальная горная выработка, нагрузка на крепь, коэффициент внутреннего трения, сцепление, несущая способность крепи, форма поверхности разрушения, горный массив, свод естественного равновесия.

Для цитирования: *Евстратов В. А., Воронова Э. Ю., Луганцев Б. Б., Исаков В. С., Холодова Л. А.* Математическая модель прогнозирования нагрузки на крепь горизонтальной горной выработки // Горный информационно-аналитический бюллетень. – 2025. – № 3. – С. 54–63. DOI: 10.25018/0236_1493_2025_3_0_54.

Mathematical model of load prediction on horizontal mine tunnel support

V.A. Evstratov[1], **E.Yu. Voronova**[1], **B.B. Lugantsev**[2], **V.S. Isakov**[3], **L.A. Kholodova**[1]
[1] Shakhty Automobile and Road Construction Institute—Branch of the Platov South Russian State Polytechnic University, Shakhty, Russia, e-mail: vae602@yandex.ru
[2] Shakhty Scientific Research and Design Coal Institute, Shakhty, Russia
[3] Platov South Russian State Polytechnic University, Novocherkassk, Russia

Abstract: This paper focuses on determination of rock mass volume that exerts pressure on roof support in horizontal mine tunnels with regard to the internal friction coefficient as well as the shear and tear resistance (cohesion). The authors propose a new mathematical model to find the most probable shape of the failure surface in rock mass above a horizontal mine tunnel in case of the uniform physical and mechanical properties of rock mass in neighborhood of the mine tunnel. At the present time, the load on horizontal mine tunnel support is estimated using approximate mathematical models built in the first half of the previous century, with many various assumptions and simplifications, and updated with the data on geological conditions and heading technologies in a certain underground opening. The adopted mathematical description of arch formation in rock mass above a mine tunnel leads to the unfounded acceptance of an estimated load in determination of a load-bearing capacity of mine support and, consequently, to an invalid strength design of the support. This study aims to develop a mathematical model for the stress–strain behavior of rock mass above a horizontal mine tunnel, with regard to the physical and mechanical parameters of rocks and geometrical parameters of the mine tunnel, to find the most probable load applied to the mine tunnel support. The obtained analytical relations enable more accurate assessment of the shape of the failure surface in rock mass above a horizontal mine tunnel as against the current procedures, given that the physical and mechanical properties of rock mass above the tunnel are uniform.

Key words: horizontal mine tunnel, support loading, internal friction coefficient, cohesion, load-bearing capacity of support, failure surface shape, rock mass, natural arch.

For citation: Evstratov V. A., Voronova E. Yu., Lugantsev B. B., Isakov V. S., Kholodova L. A. Mathematical model of load prediction on horizontal mine tunnel support. *MIAB. Mining Inf. Anal. Bull.* 2025;(3):54-63. DOI: 10.25018/0236_1493_2025_3_0_54.

Introduction

Underground construction, tunneling or roadheading in solid mineral mining always include installation of support systems in order to ensure safety of people and operations in underground space.

Design and engineering of structural units or machine parts invariably begins with the strength, stiffness and stability analyses. The first step, indispensable in such analyses, is the determination and assignment of rated loads which govern stresses and strains in units of structures and in parts of machines.

This phase of industrial and civil construction and machine building involves no difficulties, as a rule, and uses the known methods and procedures.

As compared with industrial and civil construction and machine building, in construction of mines and underground structures, as well as in roadheading and tunneling, determination and prediction of mine support loading is a challenge and a multi-factor problem. There are many reasons for such situation: different geological conditions in different regions, different occurrence depths, nonuniform physical and mechanical conditions of rocks in neighborhood of underground openings, different technologies of roadheading, low temperatures, etc. [1].

The most analytical techniques of determining mine support loads in mine tunnels rest upon a hypothesis which assumes formation of a natural arch in the roof of a mine tunnel. The majority of basic theoretical and experimental studies on loads on mine roof support were performed in the late 19th–early 20th centuries by M.M. Protodyakonov, P.M. Tsimbarevich, N.P. Pokrovsky, V.D. Slesarev, V.V. Orlov, R. Kvapil, W. Ritter and other scientists. They differed by the hypotheses and assumptions made about the shape of the natural arch, physical and mechanical conditions of surrounding rocks enclosing mine roadways, and by the approaches to nonuniformity of geological conditions [2].

Various theories on loads on mine roof support contain assumptions, simplifications and inaccuracies which can be avoided.

W. Ritter [3] analyzed the arching action in rocks composed of coupled particles. The coupling counteracts detachment of rocks between the arching surface and roof support. Resistance to shear — friction and cohesion — is neglected.

Also, in decomposing the normal force to the arch surface to two projections (vertical and tangential), the tangential projection is equal not to the product but to the ratio of the force and the cosine of an angle.

It appears that the force projection is larger than the force itself. As a result, the length of the curve representing the arch surface is given by:

$$Z = \int_0^{2a} k\gamma\left(1 - y'^2\right)dx .$$

Here, the integrand lacks a square root, which contradicts the common relation of a curve length:

$$Z = \int_0^{2a} k\gamma\sqrt{1 - y'^2}\,dx .$$

Then, after the variational calculation, the author obtained that “the arch curve is a parabola” [3].

Protodyakonov’s theory of rock pressure [4] enjoyed the widest application. This theory states that failure of rock mass above a mine opening follows a curvilinear surface generated by progressive advance of a parabola along the longitudinal axis of a mine opening with its maximal height and width obeying a direct proportion.

Accordingly, mine roof support experiences the weight of a rock mass volume which lies between the failure surface and the support [4].

In this theory, the shape of the curve representing an arch above a mine opening is governed by such physical and mechanical properties of rocks as the internal friction coefficient and cohesion. Both parameters are integrated into the apparent friction coefficient or the factor of hardness of rocks — f:

$$f = \eta + \frac{c}{\sigma},$$

where η — internal friction coefficient of rocks; c — cohesion (value of shear stress in case of zero normal stress in rocks); σ — normal stresses in rocks.

The shortages of this theory is the fusion of two parameters (friction coefficient and cohesion) and the neglect of the coupling which prevents detachment of rocks between the arching surface and the mine roof support.

The argumentation in favor of a parabolic curve (Fig. 100 in [4]) gives rise to doubts. The parabolic shape of a curve only ensures equality of pressure values at all points the curve. This formula only suits to the description of the free surface of fluid in a cylindrical vessel which is rotated around the vertical axis. And how can zero torque at any point of an arch surface ensure the equilibrium of the latter?

Numerous studies focus on the improvement and adjustment of analytical methods and empirical relations available for determining loads on mine tunnel support with regard to difference in geological conditions and roadheading technologies. The relevance of such research is defined by the essentiality of the maximally accurate prediction of a possible load on roof support in order to determine the support capacity to bear loading.

Many researches necessitate inclusion of physical and mechanical properties of rocks in prediction of loads on roof supports in mines at specific mineral deposits.

Yu. Zaslavsky analyzed features of rock pressure at great depths in the Donbas [5]. Specifics of calculations of loads on roof support in the Yakovlevsky Mine is addressed by the authors in [6, 7]. The works [8, 9] describe inclusion of specific geological conditions in mine support design at a dolomite deposit in South Africa and in a karst zone in Tahe area, NW China, respectively.

Geomechanical processes at the Zhdanov deposit are modeled numerically in [10]. An approach to taking into account physical and mechanical properties of rocks at junctions of underground openings in mines of APATIT is described in [11]. The studies [12, 13] validate load-bearing capacity of roof support for the mines at the Upper Kama Potash Deposit and for the tunnels in the Himalayas, respectively.

The authors of the work [14] determined safe and stable designs for the roof support in roadways with a large cross-section for the whole period of their service life in the Vedugin Mine.

The works [15, 16] describe research findings on the influence of mine opening inclination and arch shape on the value of load on roof support.

The influence of nonuniformity and anisotropy of physical and mechanical properties of rocks in the vicinity of underground openings on the value of load on roof support is addressed by the authors of [17–19].

This review shows that a lot of research aim at inclusion of nuances, peculiarities and deviations of both geological conditions and roadheading technologies into a calculation procedure for loads on roof support in mines. However, all these details are included in the base procedures, with many assumptions and simplifications. There is yet no procedures to determine the failure surface shape in rock mass above a mine tunnel on the basis of adequate mathematical description of the arching action process in rock mass with uniform strength properties, with regard to the joint effect exerted by tear resistance, shear resistance and internal friction coefficient on the arch shape.

Methods

In the context of the aforesaid, it seems to be expedient to create initially an adequate mathematical model of interaction between mine support and rock mass with uniform properties, i.e. with everywhere constant values of tear resistance, shear resistance and internal friction coefficient.

This paper proposes an analytical method of determining load on mine tunnel support through finding the most probable shape of a curve which is advanced progressively along the longitudinal axis of a mine tunnel and forms a natural arch in roof rocks.

Let us discuss the stress–strain behavior of rock mass above a mine tunnel (Fig. 1).

It is assumed that properties of rock mass are uniform in neighborhood of the mine tunnel.

Failure of rock mass will take place along a curved surface between the ends of the tunnel (Fig. 1), and the shape of this surface will depend on the values of the tear resistance, shear resistance and inter-

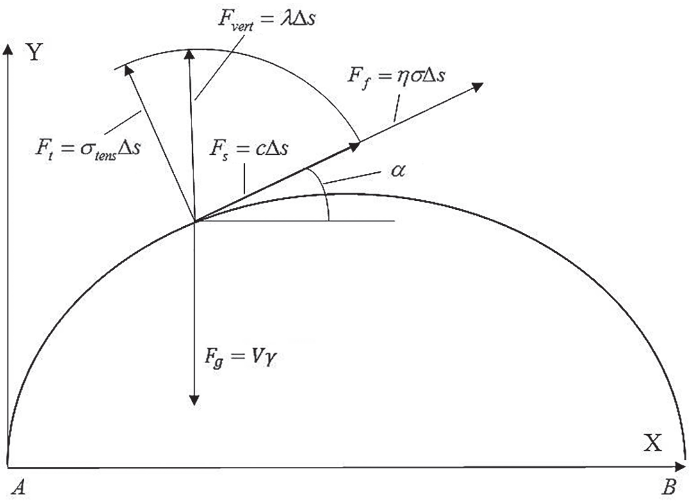

Fig. 1. Failure surface in rock mass above mine tunnel support
Рис. 1. Поверхность разрушения массива над крепью выработки

nal friction angle of rock mass [20]. In return, the shape of the failure surface will govern the volume of rock mass which applies load on the tunnel support.

We assume that the length of the tunnel is larger than its width by an order of magnitude or more, i.e., we solve a plane problem on a mass element with the thickness $\Delta b = 1$.

The forces at any point of the adopted failure surface (Fig. 1) include:

- the gravity force $F_g = mg$ directed downward;
- the friction force $F_f = \eta\sigma\Delta s$ along the tangent to the failure surface;
- the tear resistance $F_t = \sigma_{tens}\Delta s$ along the normal to the failure surface;
- the shear resistance $F_s = c\Delta s$ along the tangent to the failure surface,

where Δs is the unit area equal to the product of the length of a unit segment of the failure surface curve and the length element Δb of the mine tunnel.

The tear and shear resistances are conditioned by the interaction of rock particles and are determined by pulling tests in rheology of dispersions, as a rule.

For this reason, it is possible to assume, at an error on the safe side, that the failure resistance forces at any point of the presumptive surface of arching are equal in all directions:

$$F_{vert} = F_t = F_s = \lambda\Delta s\,,$$

where λ — the least stress in resistance to tear and shear.

The volume of rock mass between the assumable surface of failure and the tunnel support (Fig. 2) is affected by the gravity force $F_g = V\gamma$ and by the upward vertical confining force:

$$F_{vert} = \eta\sigma\Delta b\sum l_i \sin\alpha_i + \Delta b l_{arch}\lambda\,,$$

where V — the volume of rock mass between the failure surface and support; l_{arch} — the length of the curve AB of the failure surface (Fig. 1); $\Sigma l_i \sin\alpha_i$ — the sum of products of the lengths of the curve segments by the sine guiding lines.

Failure of rock mass takes place if $F_g > F_{vert}$ on the surface for which the condition below holds true:

$$F_g - F_{vert} = \max. \qquad (1)$$

The failure surface curve AB (Fig. 1) represents a graph of the function $Y = f(x)$.

Let us express F_g and F_{vert} in terms of $f(x)$ and insert it in equation (1).

The volume of rock mass between the failure surface and mine tunnel support:

$$V = \Delta b \int_a^b f(x)dx\ . \qquad (2)$$

The length of the failure surface curve is given by:

$$l_{arch} = \int_0^b \sqrt{1 + (f'(x))^2}\,dx\ . \qquad (3)$$

The sum of products given as the length of segments in the curve *AB* multiplied by the sine guiding lines is

$$\sum l_i \sin\alpha_i = 2\varsigma_0\ , \qquad (4)$$

where y_0 — the maximal ordinate of the curve *AB*.

Placement of the values obtained from (2)–(4) in (1) yields:

$$\gamma\int_a^b f(x)dx - 2y_0\eta\sigma - \\ -\lambda\int_0^b \sqrt{1 + (f'(x))^2}\,dx = \max \qquad (5)$$

Results

Relation (5) allows determining the most probable shape for a curve that represents a failure surface in rock mass above a mine tunnel, and consequently, enables finding an estimated load on the tunnel support as function of:

- the normal stresses σ (rock pressure);
- the overlying rock weight γ;
- the internal friction coefficient η;
- the tunnel span *AB*;
- the tear or shear resistance λ.

Furthermore, for a surface of failure to appear, it is required that the left-hand side of relation (2) is positive:

$$\gamma\int_a^b f(x)dx - 2y_0\eta\sigma - \\ -\lambda\int_0^b \sqrt{1 + \left(f'(x)\right)^2}\,dx > 0 \qquad (6)$$

The first member in inequality (6) conforms with the load applied on the unit length of a tunnel support by rock mass between the natural arch and the support, N/m.

The second member takes into account the force of friction between rock particles per unit length of the failure surface, N/m.

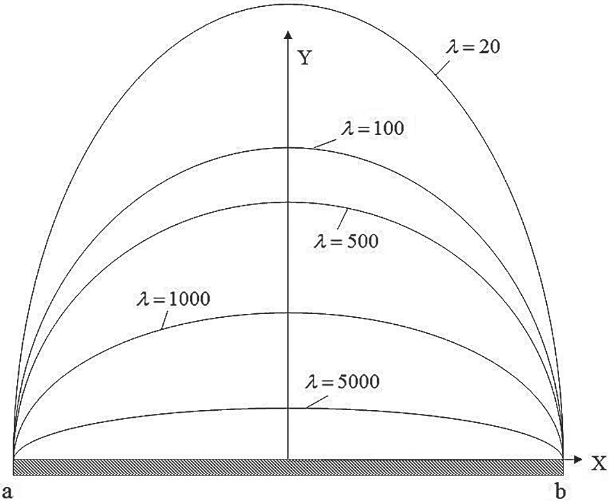

Fig. 2. Profiles of failure surfaces in rock mass above mine tunnel at different values of tear or shear resistance λ, kPa

Рис. 2. Профили поверхностей разрушения горного массива над горизонтальной выработкой при различных значениях величины сопротивления отрыву и сдвигу λ, кПа

The third member is the product of the tear or shear resistance and the length of a curve which forms the surface of failure in rocks when is advanced progressively along the longitudinal axis of an underground opening.

When $\eta = 0$ and $\lambda = 0$, which fits in with fluids, condition (2) is fulfilled at $f(x) = H$, where H is the height of the rock mass layer above the mine tunnel support:

$$F_g = \gamma\Delta b\int_a^b H dx = \gamma\Delta bHL = \max .$$

This means that the support of a mine tunnel experiences the weight of a water wedge above the tunnel (Pascal's law).

When $\lambda = 0$ and $\eta \neq 0$ (absolutely dry sand), the third member in relation (2) is equal to zero:

$$\gamma\int_a^b f(x)dx - 2y_0\eta\sigma = \max .$$

In this case, the force on the support is equal to the difference between the rock mass wedge above the support and the friction force between the wedge and surrounding rock mass:

$$F_g = \gamma\Delta bHL - 2\Delta bH\eta\sigma = \max$$

$$\text{or } \gamma L - 2\eta\sigma = \max > 0 .$$

As $\lambda\to\infty$ (strong rocks), the area of the failure surface tends to a minimum and the volume of rock mass, which generates pressure on the tunnel support, tends to zero.

In a general case, at non-zero η and λ, equation (5) was solved on computer. The function $y = f(x)$ was investigated in the form of an exponential function $y = a - dx^n$, where a, d and n were the positive real numbers.

Integrals of wide-range exponential functions were calculated using the Gaussian method, with the subsequent determination of a maximum, which made it possible to determine the influence exerted on the shape of a failure surface in rock mass by the values of rock pressure, tear resistance, cohesion and internal friction coefficient of rock mass, and by the width of a mine tunnel.

Fig. 2 shows the profiles of the failure surfaces in rock mass above a horizontal mine tunnel at different values of the tear or shear resistance λ, kPa, at the following values included in equation (1): the tunnel span width l_{span} = 3m; the normal stresses in rock mass above the tunnel (pressure) σ = 2 MPa; the overlying rock weight γ = 25 000 N/m^3; the internal friction coefficient η = 0,7.

Conclusions

The analysis of the obtained results shows that the shape of an arching curve greatly depends on the values of tear or shear resistance in rock mass. As these values get lower, the larger volume of rock mass exerts influence on roof support in mine tunnels, and vice versa.

Furthermore, the function which forms the surface of failure in rock mass is not a parabola but has an exponent that changes in a fairly wide range, subject to the physical and mechanical properties of rocks, and the width of a mine tunnel.

СПИСОК ЛИТЕРАТУРЫ

1. *Петренко В. Д., Тютькин А. Л., Петренко В. И.* Обзор аналитических и экспериментальных методов исследования взаимодействия массива и крепи // Мосты и тоннели: теория, исследования, практика. — 2012. — № 1. — С. 75—81.

2. *Решетников А. А.* Совершенствование технологии разработки скальных урановых руд Стрельцовской группы месторождений: Автореф. дис. ... канд. техн. наук: 25.00.22. — Чита, 2006. — 21 с. РГБ ОД, 61:06-5/2374.

3. *Ritter W.* Die Static der Tunnel-Gewölbe. Berlin, 1879. p. 347.

4. *Протодьяконов М. М.* Давление горных пород и рудничное крепление. Ч. 2 / Рудничное крепление. — М.; Ленинград; Новосибирск: Госгориздат, 1933. — 222 с.

5. *Заславский Ю. З.* Исследование проявлений горного давления в капитальных выработках глубоких шахт Донбасса. — М.: Недра, 1966. — 267 с.

6. *Огородников Ю. Н., Очкуров В. И., Максимов А. Б.* Расчет нагрузок на арочную крепь КМП-А3 выработок, пройденных по рудному массиву Яковлевского железорудного месторождения // Записки Горного института. — 2007. — Т. 172. — С. 33—38.

7. *Куранов А. Д., Багаутдинов И. И., Котиков Д. А., Зуев Б. Ю.* Комплексный подход к прогнозу устойчивости предохранительного целика при слоевой системе разработки запасов Яковлевского месторождения // Горный журнал. — 2020. — № 1. — С. 115—119. DOI: 10.17580/gzh.2020.01.23.

8. *Dippenaar M. A., Louis van Rooy J., Diamond R. E.* Engineering, hydrogeological and vadose zone hydrological aspects of Proterozoic dolomites (South Africa) // Journal of African Earth Sciences. 2019, vol. 150, pp. 511—521. DOI: 10.1016/j.jafrearsci.2018.07.024.

9. *Zhang S., Jin Q., Hu M., Han Q., Sun J., Cheng F., Zhang X.* Differential structure of Ordovician karst zone and hydrocarbon enrichment in paleogeomorphic units in Tahe area, Tarim Basin, NW China // Petroleum Exploration and Development. 2021, vol. 48, no. 5, pp. 1113—1125. DOI: 10.1016/S1876-3804(21)60095-2.

10. *Козырев А. А., Земцовский А. В., Кулькова М. С., Соннов М. А.* Опыт применения CAE Fidesys при разработке численных геомеханических моделей Ждановского месторождения // Горная промышленность. — 2021. — № 6. — С. 94—98. DOI: 10.30686/1609-9192-2021-6-94-98.

11. *Корчак П. А., Карасев М. А.* Геомеханическое обоснование формирования зон хрупкого разрушения пород в окрестности сопряжений горных выработок рудников АО «Апатит» // Устойчивое развитие горных территорий. — 2023. — Т. 15. — № 1. — С. 67—80. DOI: 10.21177/19984502-2023-15-1-67-80.

12. *Кашников Ю. А., Ермашов А. О., Ефимов А. А.* Геолого-геомеханическая модель участка Верхнекамского калийного месторождения // Записки Горного института. — 2019. — Т. 237. — С. 259—267. DOI: 10.31897/PMI.2019.3.259.

13. *Rehman H., Naji A. M., Kim J. J., Yoo H.* Extension of tunneling quality index and rock mass rating systems for tunnel support design through back calculations in highly stressed jointed rock mass: An empirical approach based on tunneling data from Himalaya // Tunnelling and Underground Space Technology. 2019, vol. 85, pp. 29—42. DOI: 10.1016/j.tust.2018.11.050.

14. *Шапошник Ю. Н., Неверов С. А., Неверов А. А., Конурин А. И.* Рейтинговая оценка массива горных пород Ведугинского месторождения // Фундаментальные и прикладные вопросы горных наук. — 2020. — Т. 7. — № 1. — С. 202—208. DOI: 10.15372/FPVGN 2020070131.

15. *Jingyuan W., Xianghui D., Weiping C.* Numerical analysis on the stability of layered surrounding rock tunnel under the conditions of different inclination angle and thickness // American Journal of Traffic and Transportation Engineering. 2019, vol. 4, no. 2, pp. 67—74. DOI: 10.11648/j.ajtte.20190402.14.

16. *Ngoc Anh Do, Daniel Dias, van Diep Dinh, Tien Tung Tran, van Canh Dao, Dao Viet Doan, Phuc Nhan Nguyen* Behavior of noncircular tunnels excavated in stratified rock masses — Case of underground coal mines // Journal of Rock Mechanics and Geotechnical Engineering. 2019, vol. 11, no. 1, pp. 99—110. DOI: 10.1016/j.jrmge.2018.05.005.

17. *Zhang J., Kuang M., Zhang Y., Feng T.* Evaluation and analysis of the causes of a landslide and treatment measures during the excavation of a tunnel through a soil-rock interface // Engineering Failure Analysis. 2021, vol. 130, article 105784. DOI: 10.1016/j.engfailanal.2021.105784.

18. *Fazioa N. L., Perrottia M., Lollinoa P., Pariseb M., Vattanoc M., Madoniac G., Di Maggio C.* A three-dimensional back-analysis of the collapse of an underground cavity in soft rocks // Engineering Geology. 2017, vol. 228, pp. 301—311. DOI: 10.1016/j.enggeo.2017.08.014.

19. *Протосеня А. Г., Алексеев А. В., Вербило П. Э.* Прогноз напряженно-деформированного состояния и устойчивости лба забоя тоннеля при пересечении нарушенных зон грунтового массива // Записки Горного института. — 2022. — Т. 254. — С. 252—260. DOI: 10.31897/PMI.2022.26.

20. *Evstratov V. A., Voronova E. Yu., Linnik Yu. N., Linnik V. Yu., Apachanov A. S., Grigoryev V. I., Suxarnikova V. A.* Designing mining machinery screw modules // IOP Conference Series: Materials Science and Engineering. 2021, vol. 1064, no. 1, article 012010. DOI: 10.1088/1757-899X/1064/1/012010. ГИАБ

REFERENCES

1. Petrenko V. D., Tyutkin A. L., Petrenko V. I. Review of analytical and experimental methods for studying rock–support interaction. *Mosty i tonneli: teoriya, issledovaniya, praktika*. 2012, no. 1, pp. 75 — 81. [In Russ].

2. Reshetnikov A. A. *Sovershenstvovanie tekhnologii razrabotki skal'nykh uranovykh rud Strel'tsovskoy gruppy mestorozhdeniy* [Improvement of mining technology for hard uranium ores of the Streltsovo deposits], Candidate's thesis, Chita, 2006, 21 p.

3. Ritter W. *Die Static der Tunnel-Gewölbe*. Berlin, 1879. p. 347.

4. Protodyakonov M. M. Rock Pressure and Mine Support. Part 2. *Rudnichnoe kreplenie* [Mine Support], Moscow, Leningrad, Novosibirsk, Gosgorizdat, 1933, 222 p.

5. Zaslavskiy Yu. Z. *Issledovanie proyavleniy gornogo davleniya v kapital'nykh vyrabotkakh glubokikh shakht Donbassa* [Study of rock pressure-induced phenomena in permanent roadways in deep mines of the Donbas], Moscow, Nedra, 1966. 267 p.

6. Ogorodnikov Y. N., Ochkurov V. I., Maksimov A. B. Calculation of the loads on the arch support of the KMP-A3 excavations in the ore massif of the Yakovlevskoye iron ore deposit. *Journal of Mining Institute*. 2007, vol. 172, pp. 33 — 38. [In Russ].

7. Kuranov A. D., Bagautdinov I. I., Kotikov D. A., Zuev B. Yu. Integrated approach to safety pillar stability in slice mining in the Yakovlevo deposit. *Gornyi Zhurnal*. 2020, no. 1, pp. 115 — 119. [In Russ]. DOI: 10.17580/gzh.2020.01.23.

8. Dippenaar M. A., Louis van Rooy J., Diamond R. E. Engineering, hydrogeological and vadose zone hydrological aspects of Proterozoic dolomites (South Africa). *Journal of African Earth Sciences*. 2019, vol. 150, pp. 511 — 521. DOI: 10.1016/j.jafrearsci.2018.07.024.

9. Zhang S., Jin Q., Hu M., Han Q., Sun J., Cheng F., Zhang X. Differential structure of Ordovician karst zone and hydrocarbon enrichment in paleogeomorphic units in Tahe area, Tarim Basin, NW China. *Petroleum Exploration and Development*. 2021, vol. 48, no. 5, pp. 1113 — 1125. DOI: 10.1016/S1876-3804(21)60095-2.

10. Kozyrev A. A., Zemtsovskiy A. V., Kulkova M. S., Sonnov M. A. Experience of CAE Fidesys application in numerical geomechanical modelling of Zhdanovskoe deposit. *Russian Mining Industry Journal*. 2021, no. 6, pp. 94 — 98. [In Russ]. DOI: 10.30686/1609-9192-2021-6-94-98.

11. Korchak P. A., Karasev M. A. Geomechanical justification of brittle fracture zones in rocks in the vicinity of excavation junctions in Apatit's mines. *Sustainable Development of Mountain Territories*. 2023, vol. 15, no. 1, pp. 67 — 80. [In Russ]. DOI: 10.21177/19984502-2023-15-1-67-80.

12. Kashnikov Y. A., Ermashov A. O., Efimov A. A. Geological and geomechanical model of the Verkhnekamsk potash deposit site. *Journal of Mining Institute*. 2019, vol. 237, pp. 259 — 267. [In Russ]. DOI: 10.31897/PMI.2019.3.259.

13. Rehman H., Naji A. M., Kim J. J., Yoo H. Extension of tunneling quality index and rock mass rating systems for tunnel support design through back calculations in highly stressed jointed rock mass: An empirical approach based on tunneling data from Himalaya. *Tunnelling and Underground Space Technology*. 2019, vol. 85, pp. 29 — 42. DOI: 10.1016/j.tust.2018.11.050.

14. Shaposhnik Yu.N., Neverov S. A., Neverov A. A., Konurin A. I. Rating evaluation of the rock mass of the Veduginsky deposit. *Mining sciences: fundamental and applied issues*. 2020, vol. 7, no. 1, pp. 202 — 208. [In Russ]. DOI: 10.15372/FPVGN 2020070131.

15. Jingyuan W., Xianghui D., Weiping C. Numerical analysis on the stability of layered surrounding rock tunnel under the conditions of different inclination angle and thickness. *American Journal of Traffic and Transportation Engineering*. 2019, vol. 4, no. 2, pp. 67 — 74. DOI: 10.11648/j.ajtte.20190402.14.

16. Ngoc Anh Do, Daniel Dias, van Diep Dinh, Tien Tung Tran, van Canh Dao, Dao Viet Doan, Phuc Nhan Nguyen Behavior of noncircular tunnels excavated in stratified rock masses — Case of underground coal mines. *Journal of Rock Mechanics and Geotechnical Engineering*. 2019, vol. 11, no. 1, pp. 99 — 110. DOI: 10.1016/j.jrmge.2018.05.005.

17. Zhang J., Kuang M., Zhang Y., Feng T. Evaluation and analysis of the causes of a landslide and treatment measures during the excavation of a tunnel through a soil-rock interface. *Engineering Failure Analysis*. 2021, vol. 130, article 105784. DOI: 10.1016/j.engfailanal.2021.105784.

18. Fazioa N. L., Perrottia M., Lollinoa P., Pariseb M., Vattanoc M., Madoniac G., Di Maggio C. A three-dimensional back-analysis of the collapse of an underground cavity in soft rocks. *Engineering Geology*. 2017, vol. 228, pp. 301 — 311. DOI: 10.1016/j.enggeo.2017.08.014.

19. Protosenya A. G., Alekseev A. V., Verbilo P. E. Prediction of the stress–strain state and stability of the front of tunnel face at the intersection of disturbed zones of the soil mass. *Journal of Mining Institute*. 2022, vol. 254, pp. 252—260. [In Russ]. DOI: 10.31897/PMI.2022.26.

20. Evstratov V. A., Voronova E. Yu., Linnik Yu. N., Linnik V. Yu., Apachanov A. S., Grigoryev V. I., Suxarnikova V. A. Designing mining machinery screw modules. *IOP Conference Series: Materials Science and Engineering*. 2021, vol. 1064, no. 1, article 012010. DOI: 10.1088/1757-899X/1064/1/012010.

ИНФОРМАЦИЯ ОБ АВТОРАХ

Евстратов Владимир Александрович[1] — д-р техн. наук,
профессор, профессор, e-mail: vae602@yandex.ru,
ORCID ID: 0000-0001-9531-2557,
Воронова Элеонора Юрьевна[1] — д-р техн. наук, доцент,
зав. кафедрой, e-mail: eleonora_sam_ti@mail.ru,
ORCID ID: 0000-0002-4721-4570,
Луганцев Борис Борисович — д-р техн. наук, профессор,
действительный член Академии горных наук, председатель
совета директоров, ООО «Шахтинский научно-исследовательский
и проектно-конструкторский угольный институт»,
e-mail: boris4721@mail.ru, ORCID ID: 0000-0002-8296-7922,
Исаков Владимир Семенович — д-р техн. наук, профессор, зав. кафедрой,
Южно-Российский государственный политехнический университет (НПИ)
имени М.И. Платова, e-mail: vs.isakov@mail.ru, ORCID ID: 0000-0003-1859-6589,
Холодова Людмила Александровна[1] — старший преподаватель,
e-mail: holodova0420@yandex.ru, ORCID ID: 0009-0003-9726-399X,
[1] Шахтинский автодорожный институт (филиал) Южно-Российского
государственного политехнического университета (НПИ) имени М.И. Платова.
Для контактов: Евстратов В.А., e-mail: vae602@yandex.ru.

INFORMATION ABOUT THE AUTHORS

V.A. Evstratov[1], Dr. Sci. (Eng.), Professor, Professor,
e-mail: vae602@yandex.ru, ORCID ID: 0000-0001-9531-2557,
E.Yu. Voronova[1], Dr. Sci. (Eng.), Assistant Professor,
Head of Chair, e-mail: eleonora_sam_ti@mail.ru,
ORCID ID: 0000-0002-4721-4570,
B.B. Lugantsev, Dr. Sci. (Eng.), Professor, Full Member
of the Academy of Mining Sciences, Chairman of the Board of Directors,
Shakhty Scientific Research and Design Coal Institute,
346500, Shakhty, Russia, e-mail: boris4721@mail.ru,
ORCID ID: 0000-0002-8296-7922,
V.S. Isakov, Dr. Sci. (Eng.), Professor, Head of Chair,
Platov South Russian State Polytechnic University,
346400, Novocherkassk, Russia, e-mail: vs.isakov@mail.ru,
ORCID ID: 0000-0003-1859-6589,
L.A. Kholodova[1], Senior Lecturer, e-mail: holodova0420@yandex.ru,
ORCID ID: 0009-0003-9726-399X,
[1] Shakhty Automobile and Road Construction Institute—
Branch of the Platov South Russian State Polytechnic University, 346500, Shakhty, Russia.
Corresponding author: V.A. Evstratov, e-mail: vae602@yandex.ru.

Получена редакцией 08.07.2024; получена после рецензии 05.11.2024; принята к печати 10.02.2025.
Received by the editors 08.07.2024; received after the review 05.11.2024; accepted for printing 10.02.2025.