ГИАБ. Горный информационно-аналитический бюллетень /
MIAB. Mining Informational and Analytical Bulletin, 2026;(8):31-40
ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

УДК 622.28:519.87 DOI: 10.25018/0236_1493_2026_8_0_31

МОДЕЛИРОВАНИЕ ПРОЦЕССА СВОДООБРАЗОВАНИЯ НАД ГОРИЗОНТАЛЬНОЙ ВЫРАБОТКОЙ В СКАЛЬНЫХ СЛОИСТЫХ ПОРОДАХ ПРИ РАЗЛИЧНЫХ УГЛАХ ПАДЕНИЯ ПЛАСТА

В.А. Евстратов[1], Э.Ю. Воронова[1], Б.Б. Луганцев[2], 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

Аннотация: Прогнозирование величины нагрузки на крепь выработки и определение ее влияния на структуру и параметры крепи является необходимым для внедрения современных технологий проведения горных выработок. Рассмотрено прогнозирование нагрузки на крепь горизонтальной горной выработки, проведенной в скальных слоистых породах, с учетом величины угла падения породы относительно поперечного сечения выработки и величины сопротивления отрыву породы в направлении, перпендикулярном слоям. В настоящее время объем породы, давящий на крепь горизонтальной горной выработки, определяется по методикам, разработанным на основе теории естественного сводообразования. Предполагается, что порода состоит из раздробленных частиц, между которыми существует внутреннее трение, сцепление и сопротивление отрыву, то есть идентифицируется как среда Шведова-Бингама. Разработанные на основе данной теории модели и методики определения нагрузки на крепь отличаются различными коэффициентами и уточнениями, введение которых направлено на учет физико-механических свойств породы в окрестностях выработки, способов проходки, срока эксплуатации выработки и других факторов. Целью данной работы является исследование напряженно-деформированного состояния хрупких слоистых пород над горизонтальной выработкой при различных углах падения слоев породы и физико-механических свойствах породы. Установлено их влияние на величину предельно допустимых размеров пролетов выработок из условия реализации остаточной несущей способности пород. Получена зависимость величины угла отрыва части породы над выработкой от угла падения пласта породы. Установлено, что с увеличением угла падения пласта породы угол отрыва части породы над выработкой уменьшается.

Ключевые слова: горизонтальная горная выработка, нагрузка на крепь, угол падения пласта породы, несущая способность крепи, слоистая порода, поверхность разрушения, объем породы, крепь выработки, угол отрыва части породы.

Для цитирования: *Евстратов В. А., Воронова Э. Ю., Луганцев Б. Б., Холодова Л. А.* Моделирование процесса сводообразования над горизонтальной выработкой в скальных слоистых породах при различных углах падения пласта // Горный информационно-аналитический бюллетень. – 2026. – № 8. – С. 31–40. DOI: 10.25018/0236_1493_2026_8_0_31.

Modeling arching process in bedded rock mass above a mine tunnel at different dip angles of bedding

V.A. Evstratov[1], **E.Yu. Voronova**[1], **B.B. Lugantsev**[2], **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

Abstract: Advanced mining technologies require prediction of loads exerted on mine support systems and need estimation of influence of loading on the support design. This article focuses on prediction of loads applied to support systems in horizontal mine tunnels in hard and bedded rock masses with regard to the dip angle of bedding relative to the cross-section of the tunnel, and in view of the tear resistance of rocks in perpendicular to the bedding. Currently, the volume of rock mass that exerts pressure on a support system in a mine tunnel is determined using the theory of natural arch. It is assumed that rocks represent granular particles with internal friction, cohesion and tear resistance between them, which conforms with a Shvedov–Bengham's model. The related models and procedures of load assessment on mine supports involve various coefficients and amendments aimed to take into account the physical and mechanical properties of adjacent rock mass, methods of heading, service life of mine tunnels and other factors. The objective of this study is the stress–strain assessment of brittle and bedded rock mass above a mine tunnel at different angles of bedding and physical and mechanical properties of rocks. Their influence on the maximum permissible sizes of spans of the tunnels is determined on the assumption of the remaining load-bearing capacity of rocks. The value of the detachment angle of rocks above the tunnel is correlated with the bedding angle in rock mass. It is found that the rock detachment angle above the tunnel decreases with the increasing angle of bedding.

Key words: mine tunnel, load on mine support, bedding dip angle, load-bearing capacity of support system, bedded rock mass, failure surface, rock volume, mine support system, rock detachment angle.

For citation: Evstratov V. A., Voronova E. Yu., Lugantsev B. B., Kholodova L. A. Modeling arching process in bedded rock mass above a mine tunnel at different dip angles of bedding. *MIAB. Mining Inf. Anal. Bull.* 2026;(8):31-40. DOI: 10.25018/0236_1493_2026_8_0_31.

Introduction

Assessment of ground pressure in the vicinity of openings in underground mines is a subject of many studies. Different theories are either based on a researcher's perception of the nature and mechanism of the phenomena and processes that can occur in surrounding rock mass, or on the generalization and systematization of experimental results.

To a great extent, such state of things is governed by a wide variety of the physical and mechanical properties of rocks. Some researchers identify rock mass as an elastic continuum, other — as a granular and incoherent medium. There are theories of natural arch formation, pillar subsidence with friction, detachment of a rock volume from rock mass, and many other [1 — 3].

For finding loads exerted on mine support systems in bedded rock mass, there is a model where each layer (bed) is considered as a single bending beam with fully fixed ends [4]. The studies aimed at improvement of the efficiency of the up-to-date support technologies, stability of mine openings and cost-saving of heading and support emphasize the need of the comprehensive stress—strain analysis in surrounding rock mass of development openings in underground mines [5, 6].

Modeling of fracture propagation in surrounding rock mass provided dependences of the fracture depth and the maximal shear stresses on the dip angles of rock bedding [7]. From the theoretical and experimental research findings, models were developed to predict displacements in surrounding rock mass susceptible to creep for the whole period of service life of mine excavations, with regard to actual rheological properties of rocks [8—10].

The stress—strain behavior of a coal bed in the vicinity of an underground roadway was modeled with regard to the cross-section configuration of the roadway and to the coal bed dip [11]. Design and updating of support technologies during heading operations should take into account specific geological conditions of adjacent rock mass. This enables accurate loading prediction and efficient design of mine support systems to ensure safe and cost effective support of surrounding rock mass [12].

Another study focused on influence exerted by a dip angle of a coal seam on the stress—strain behavior of coal—rock mass [13]. The author carried out the stress—strain assessment of rock mass surrounding a roadway at different dips of the coal seam and at different orientations of the roadway relative to the direction of the seam dip angle. The modeling results show that the load exerted on the support systems during extraction of pitch coal is much higher than the support system loading in mining of horizontal seams. Many studies address design of mine support systems that can ensure the required sustaining capacity and stability of roadways with regard to their service life [14—16].

The influence of the bedding dip angle and nonuniform physical and mechanical properties of rocks on the stability of a horizontal roadway was analyzed in [17—19]. The impact of the specific ground conditions on mine support system during heading in the karst zone in the Tahe area in the northwest of China was described in [20].

One of the main complications of advanced technologies of support system design and installation is the lack of knowledge on the stress—strain behavior of enclosing rock mass surrounding underground mines, which prohibits an accurate prediction of the value of pressure applied to a mine roof support by adjacent rock mass.

The present authors earlier presented the mathematical model of the most probable failure surface in rock mass above a mine tunnel took into account friction, cohesion and tear resistance on the assumption of uniform physical and mechanical conditions of enclosing rock mass surrounding the tunnel [21].

Methods

This study focuses on arch formation above a horizontal opening—mine tunnel—in bedded rock mass at different dip angles of bedding. It is assumed that there are no confining forces between the beds. Each bed represents an overhanging beam that occurs at an angle α relative to the

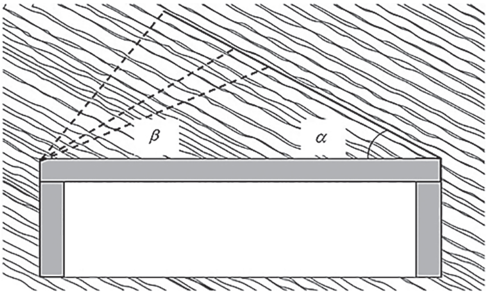

Рис. 1. Поперечное сечение выработки в породе с углом падения α и линии возможных поверхностей отрыва части породы

Fig. 1. Cross-section of mine tunnel in rock mass with bedding angle α and lines of possible failure surfaces

horizon and in perpendicular relative to the longitudinal axis of the mine tunnel (Fig. 1). The grey-color rectangles in the figure depict the support system.

In case of mining along the strike of the coal bed, the angle α is equal to the coal bed dip. If we neglect the tensile strength along the layers, which is much less than the tensile strength across the layers, than a failure surface above the mine tunnel is a plane oriented at the angle α relative to the horizon and leaned on the edge of the pillar. The most probable form of the projection of rock detachment on the cross-section of the mine tunnel is a triangle with its angles at the edges of the cross-section of the mine tunnel roof (Fig. 1). The value of an angle β (Fig. 1), which defines the area of the triangle and, consequently, the load applied to the mine support, depends in a general case on the width of the mine tunnel, dip angle of the coal bed and on the tensile strength of rocks.

According to the assumed calculation model, detached rock volume represents an overhanging beam of a triangular cross-section. Any projection of the failure surface AC on the cross-section of the mine tunnel, oriented at the angle β relative to the horizon (Fig. 2), experiences the joint action of tension and bending. In this case, the strength condition can be given by:

$$\sigma = \frac{M_{\max}}{W_y} + \frac{F_n}{A} \le [\sigma], \tag{1}$$

where σ is the normal stress of rocks in the failure plane, Pa; $[\sigma]$ is the tensile strength of rocks, Pa; $M_{\max}$ is the maximum bending moment in the failure plane, Nm; W_y is the section modulus of the failure surface, m^3; F_n is the projection of gravity force of the detached rock volume along the normal to the failure surface, N; A is the area of the failure surface AC (Fig. 2).

Apparently, rock failure will take place along AC when β is such that the normal stresses in this cross-section have the maximum value:

$$\sigma = \frac{M_{\max}}{W_y} + \frac{F_n}{A} = \max. \tag{2}$$

The maximal bending moment in the failure plane AC (Fig. 2) is:

$$M_{\max} = F_\tau h, \text{ Nm}, \tag{3}$$

where F_τ is the projection of gravity force of detached rocks in parallel to the failure surface (Fig. 2):

$$F_\tau = G \sin\beta, \text{ N}, \tag{4}$$

where β is the angle of the failure surface AC relative to the horizon; G is the weight of detached rocks:

$$G_1 = \rho g S \Delta d, \text{ N}, \tag{5}$$

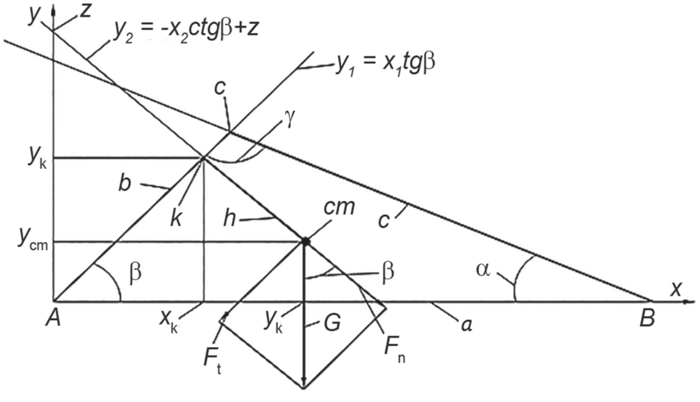

Рис. 2. Схема сил, действующих на отрывающуюся часть породы над выработкой
Fig. 2. Diagram of forces exerted on rock detachment above mine tunnel

where ρ is the rock density, kg/m^3; g is the free fall acceleration, m/s^2; S is the cross-section area of detached rocks (Fig. 2):

$$S = \frac{1}{2} ac \sin\alpha \text{, m}^2, \qquad (6)$$

where a is the width of the mine tunnel, m; c is the length of the line BC (Fig. 2):

$$c = a\frac{\sin\beta}{\sin\gamma} \text{, m}, \qquad (7)$$

where γ is the angle ACB (Fig. 2):

$$\gamma = 180 - \alpha - \beta \text{, deg}, \qquad (8)$$

α is the dip of the bed (Fig. 2), angle; Δd is the unit stretch of the mine tunnel length, m.

The distance h from the gravity center of detached rocks to the plane of failure (Fig. 2) is given by:

$$h = \sqrt{\left(x_{cm} - x_k\right)^2 + \left(y_{cm} - y_k\right)^2} \text{, m}, \qquad (9)$$

where x_{cm} and y_{cm} are the coordinates of the center of mass of the detached rock volume (Fig. 2):

$$x_{cm} = \frac{x_A + x_B + x_C}{3},\ y_{cm} = \frac{y_A + y_B + y_C}{3}, \qquad (10)$$

where $x_B = 0$, $x_C = b\cos\beta$, $y_A = 0$, $y_B = 0$ and $y_C = b\sin\beta$ are the coordinates of the triangle corners at A, B and C (Fig. 2); x_k and y_k are the coordinates of the intersection between the line AC and the normal that passes through the gravity center of the detached rock volume (Fig. 2).

The equation of the failure surface line AC:

$$y_1 = x_1 tg\beta. \qquad (11)$$

The equation of the straight lines oriented along the normal to the line AC:

$$y_2 = -x_2 ctg\beta + z. \qquad (12)$$

For the straight line that passes through the gravity center of the detached rock volume:

$$z = y_c + x_c ctg\beta. \qquad (13)$$

Accordingly:

$$x_k = \frac{y_{cm} + x_{cm} ctg\beta}{tg\beta + ctg\beta},\ y_k = \frac{x_{cm} + y_{cm} ctg\beta}{tg\beta + ctg\beta}. \qquad (14)$$

The section modulus of the failure surface is:

$$W_y = \frac{b^2 \Delta d}{6} \text{, m}^3, \qquad (15)$$

where b is the length of the failure stretch (Fig. 2):

$$b = a\frac{\sin\alpha}{\sin\gamma} \text{, m}. \qquad (16)$$

The area of the failure surface is:

$$A = b\Delta d. \qquad (17)$$

The projection of the gravity force of detached rocks along the normal to the failure surface (Fig. 2):

$$F_n = G\cos\beta \text{, N}. \qquad (18)$$

Failure will take place in the plane of the maximal stresses:

$$\sigma = \frac{M_{\max}}{W_y} + \frac{F_n}{A} = \max. \qquad (19)$$

In this manner, expression (1) of the maximal stresses in rocks above a mine tunnel can be written as a function of a few parameters:

$$\sigma = f\left(\alpha, \beta, a, \rho\right) = \max \geq \left[\sigma_l\right]. \qquad (20)$$

By setting certain parameters in (20), namely, the coal bed dip, the width of the mine tunnel and the rock density, and by varying the angle β in a range from 1° to 90°, we find the value of this angle when the tensile stresses in the cross-section AC are maximal (Fig. 2).

The obtained model allows analyzing the process of rock failure above a mine tunnel depending on the bedding dip, tensile strength and specific density of rocks.

After detachment of rocks along the surface ACB (Fig. 3), the remaining lower bed along CB can be assumed as a beam

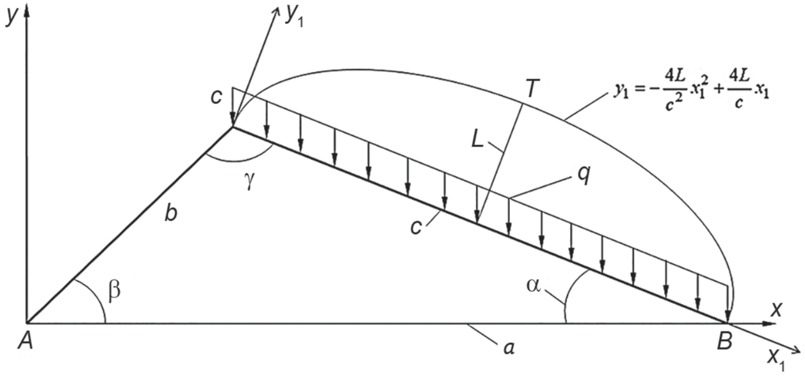

Рис. 3. Расчетная схема процесса сводообразования в породе над выработкой
Fig. 3. Analytical model of arching in rock mass above mine tunnel

supported on two sides, located at an angle α relative to the horizon and loaded by its own weight. Such analytical model of horizontal bedding in rock mass was earlier used to determine failure condition of beds [4]. In our case, the analytical model of the beam assumes that its ends are not fully fixed but hinged as is adopted in the design of engineering structures. This increases the bending moment in the middle of the beam span by 1.5 times and can partly counterbalance the impact of rock mass nonuniformity and jointing on the load-bearing capacity of the beam.

The maximal bending moment in the middle of the line CB is given by (Fig. 3):

$$M_{\max} = \frac{qc^2}{8}\cos\alpha . \qquad (21)$$

The strength condition:

$$\sigma = \frac{M_{\max}}{W_y} \leq [\sigma]. \qquad (22)$$

According to [2], “a parabolic arch forms above a mine tunnel, and the arching height is found from the condition”:

$$L = \frac{c}{k}, \qquad (23)$$

where c is the length of the line BC (Fig. 3); k is the factor of hardness of rocks [2].

Now, the total load on the support system in the tunnel is:

$$G = G_1 + G_2 = \rho g \Delta d \left(S_1 + S_2\right), \qquad (24)$$

where $S_2 = \frac{2}{3}Lc$ is the cross-section

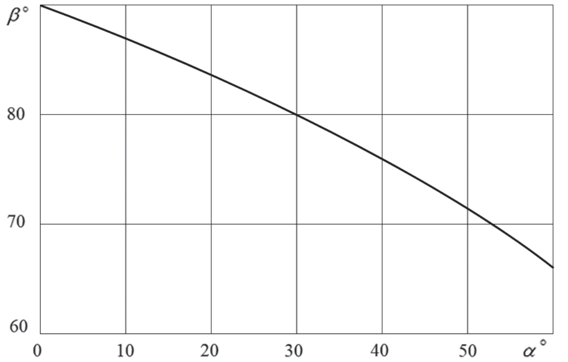

Рис. 4. Зависимость угла разрушения пласта породы β от угла падения пласта α
Fig. 4. Rock detachment angle β versus bedding dip angle α

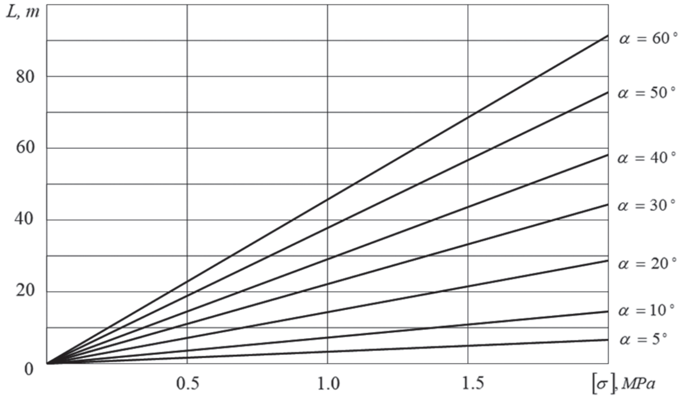

Рис. 5. Зависимость предельно допустимого пролета выработки от предела прочности породы на растяжение и угла падения пласта α

Fig. 5. Maximum permissible span of mine tunnel as function of tensile strength and bedding angle α *of rock mass*

area between the arching parabola BTC and the line BC (Fig. 3).

The value of the span *c* in (21) decreases during arching; therefore, when

$$c = 2b\sqrt{\frac{\Delta d[\sigma]}{3q\cos\alpha}},$$

strength condition (22) is satisfied, the arching process stops and a part of the arch remains flat.

Results

Fig. 4 depicts the relationship between the failure angle β of a bed and its dip angle α (see Fig. 1). The analysis of the results yields that as the dip angle of a bed increases, the rock detachment angle β decreases.

Fig. 5 shows the maximal span of a mine tunnel as function of the bedding angle α and the tensile strength of rocks upon condition of sustainable bearing capacity of rock mass above the mine tunnel.

Conclusions

The analysis of the obtained results shows that as the angle of bedding in rock mass increases, the rock detachment angle β decreases. The value of the bedding angle substantially influences the maximum permissible span of mine tunnels. The higher angle of bedding allows the greater value of the span. These results agree with the earlier evidence [22]. At the same time, if the tensile strength of rocks is low and allows detachment of rocks along the line AC (Fig. 2), the load on the mine support grows with the increasing bedding angle α and substantially exceeds the load exerted on the support systems in mining of horizontal beds, which agrees with the other research findings [15].

СПИСОК ЛИТЕРАТУРЫ

1. *Ritter W.* Die Static der Tunnel-Gewolbe. Berlin, 1879. p.347.

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

3. *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.

4. *Schulz F.* Untersuchungen fiber die dimensionen der sicherheitspfeiler. Zeitschrfur das Berg-Hfitten und Solinenwesen im Preussichen Staate, 1867. p.86.

5. *Вознесенский А. С., Кидима-Мбомби Л. К.* Формирование синтетических структур и текстур горных пород при их моделировании в среде COMSOL Multiphysics // Горные науки и технологии. — 2021. — № 6(2). — С. 65—72. DOI: 10.17073/2500-0632-2021-2-65-72

6. *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.

7. *Демин В. Ф., Немова Н. А., Демина Т. В.* Аналитическое моделирование геомеханических процессов в приконтурном массиве горных выработок // Журнал Сибирского федерального университета. Серия: техника и технологии. — 2015. — Т. 8. — № 1. — С. 74—97.

8. *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.

9. *Паньков И. Л., Морозов И. А.* Деформирование соляных пород при объемном многоступенчатом нагружении // Записки Горного института. — 2019. — Т. 239. — С. 510—519. DOI: 10.31897/pmi.2019.5.510.

10. *Reedlunn B., Guadalupe Argüello J., Hansen F. D.* A reinvestigation into Munson's model for room closure in bedded rock salt // International Journal of Rock Mechanics and Mining Sciences. 2022, vol. 151, article 105007. DOI: 10.1016/j.ijrmms.2021.105007.

11. *Демин В. Ф., Портнов В. С., Демина Т. В., Жумабекова А. Е.* Исследование деформированного состояния приконтурного углепородного массива вокруг горной выработки с анкерным креплением // Уголь. — 2019. — № 7. — С. 72—77. DOI: 10.18796/0041-5790-2019-7-72-77.

12. *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.

13. *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.

14. *Игнатьев С. А., Судариков А. Е., Имашев А. Ж.* Современные математические методы прогноза условий поддержания и крепления горных выработок // Записки Горного института. — 2019. — Т. 238. — С. 371—375. DOI: 10.31897/PMI.2019.4.371.

15. *Трушко В. Л., Протосеня А. Г., Очкуров В. И.* Прогнозирование геомеханически безопасных параметров очистных забоев при разработке богатых железных руд в сложных горно-геологических условиях // Международный журнал прикладных инженерных исследований. — 2016. — № 11(22). — С. 11095—11103.

16. *Казанин О. И., Ильинец А. А.* Обеспечение устойчивости выемочных выработок при подготовке выемочных участков пологих угольных пластов тремя выработками // Записки Горного института. — 2022. — Т. 253. — С. 41—48. DOI: 10.31897/PMI.2022.1. 65.

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. *Басалаева П. В., Куранов А. Д.* Оценка влияния угла падения литологически неоднородной прослойки пород на устойчивость горизонтальной горной выработки при ее проходке // Горный информационно-аналитический бюллетень. — 2024. — № 3. — С. 17—30. DOI: 10.25018/0236_1493_2024_3_0_17.

20. *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.

21. *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.

22. *Голик В. И.* Определение безопасных пролетов выработок с использованием несущей способности пород при разработке месторождений // Горная промышленность. — 2024. — № 5S. — 59 — 63. DOI: 10.30686/1609-9192-2024-5S-59-63. ГИАБ

REFERENCES

1. Ritter W. *Die Static der Tunnel-Gewolbe*. Berlin, 1879. p.347.

2. Protod'yakonov M. M. *Davlenie gornykh porod i rudnichnoe kreplenie. Ch. 2. Rudnichnoe kreplenie* [Rock Pressure and Mine Support. Part 2: Mine Support], Moscow; Leningrad; Novosibirsk, Gosgorizdat, 1933, 222 p.

3. Petrenko V. D., Tyutkin A. L., Petrenko V. I. Review of analytical and experimental methods for studying rock–support interaction. *Bridges and Tunnels: Theory, Research, Practice*. 2012, no. 1, pp. 75 — 81. [In Russ].

4. Schulz F. Untersuchungen fiber die dimensionen der sicherheitspfeiler. *Zeitschrfur das Berg-Hfitten und Solinenwesen im Preussichen Staate*, 1867. p.86.

5. Voznesensky A. S., Kidima-Mbombi L. K. Formation of synthetic structures and textures of rocks when simulating in COMSOL Multiphysics. *Mining Science and Technology (Russia)*. 2021, no. 6(2), pp. 65 — 72. [In Russ]. DOI: 10.17073/2500-0632-2021-2-65-72

6. 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.

7. Demin V. F., Nemova N. A., Demina T. V. Analytical modeling of geomechanical processes in the marginal array mining. *Journal of Siberian Federal University. Engineering & Technologies*. 2015, vol. 8, no. 1, pp. 74 — 97. [In Russ].

8. 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.

9. Pankov I. L., Morozov I. A. Salt rock deformation under bulk multiple-stage loading. *Journal of Mining Institute*. 2019, vol. 239, pp. 510 — 519. [In Russ]. DOI: 10.31897/pmi.2019.5.510.

10. Reedlunn B., Guadalupe Argüello J., Hansen F. D. A reinvestigation into Munson's model for room closure in bedded rock salt. *International Journal of Rock Mechanics and Mining Sciences*. 2022, vol. 151, article 105007. DOI: 10.1016/j.ijrmms.2021.105007.

11. Demin V. F., Portnov V. S., Demina T. V., Zhumabekova A. E. Study of the deformed state of the marginal coal-rock massif around a mine working with anchor fastening. *Ugol'*. 2019, no. 7, pp. 72 — 77. [In Russ]. DOI: 10.18796/0041-5790-2019-7-72-77.

12. 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.

13. Korchak P. A., Karasev M. A. Geo-mechanical prediction of the brittle fracture zones in rocks in the vicinity of the excavation junction of Ltd «Apatit». *Sustainable Development of Mountain Territories*. 2023, vol. 15, no. 1, pp. 67 — 80. [In Russ]. DOI: 10.21177/19984502-2023-15-1-67-80.

14. Ignatyev S. A., Sudarikov A. E., Imashev A. Z. Modern mathematical forecast methods of maintenance and support conditions for mining tunnel. *Journal of Mining Institute*. 2019, vol. 238, pp. 371 — 375. [In Russ]. DOI: 10.31897/PMI.2019.4.371.

15. Trushko V. L., Protosenya A. G., Ochkurov V. I Prediction of the geomechanically safe parameters of the stopes during the rich iron ores development under the complex mining and geological conditions. *International Journal of Applied Engineering Research*. 2016, no. 11(22), pp. 11095 — 11103. [In Russ].

16. Kazanin O. I., Ilinets A. A. Ensuring the excavation workings stability when developingexcavation sites of flat-lying coal seams by three workings. *Journal of Mining Institute*. 2022, vol. 253, pp. 41 — 48. [In Russ]. DOI: 10.31897/PMI.2022.1. 65.

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. Basalaeva P., Kuranov A. D. Influence of dip angle of lithologically nonuniform interburden on horizontal mine opening stability during driving. *MIAB. Mining Inf. Anal. Bull.* 2024, no. 3, pp. 17—30. [In Russ]. DOI: 10.25018/0236_1493_2024_3_0_17.

20. 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.

21. 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, no. 3, pp. 54—63. [In Russ]. DOI: 10.25018/0236_1493_2025_3_0_54.

22. Golik V. I. Determination of safe spans of workings using the bearing capacity of rocks during deposit development. *Russian Mining Industry Journal.* 2024, no. 5S. 59—63. [In Russ]. DOI: 10.30686/1609-9192-2024-5S-59-63.

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» (ООО «ШахтНИУИ»), e-mail: boris4721@mail.ru,
ORCID ID: 0000-0002-8296-7922,
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, Шахты, Россия.
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, Shakhty, Russia,
e-mail: boris4721@mail.ru, ORCID ID: 0000-0002-8296-7922,
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 15.03.2026; получена после рецензии 07.05.2026; принята к печати 10.07.2026.
Received by the editors 15.03.2026; received after the review 07.05.2026; accepted for printing 10.07.2026.