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Analyzing Strength Criteria for Assessing Mine Working Stability

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Abstract. *Analyzes the criteria for the rock strength. The Griffiths, Coulomb-Mohr, Hooke-Brown, Drucker-Prager, Von-Mises criteria and the Jaeger theory generally accepted and widely known in mining mechanics, are considered. In nature, the rock massif is heterogeneous, it consists of many layers and rocks, and the properties of the rocks vary depending on the length. To study the principle of destruction of anisotropic rocks, geomechanical scientists conducted research, the results of which were introduced into various strength criteria that explain the destruction of anisotropic rocks. The main idea of the Hooke-Brown criterion is the correct transition from the laboratory strength of rock samples to the strength properties of rocks in the massif by introducing additional parameters that take into account structural weakening. Taking into account fractures, weakening planes and other structural features in the massif gives more reliable results in assessing the strength and deformation of rocks.*

Keywords: *failure criteria, load, crack, strength, angle of internal friction, cohesion, anisotropic rock, strength passport, tensile strength, compressive strength.*

Introduction

Reliable efficient description of rock failure and post-failure behavior is a major concern of rock mechanics. To solve this problem, various criteria for the destruction of rocks and models of rock deformation are developed on the basis of experimental and theoretical approaches. At present, there are a number of well-known and generally accepted fracture criteria, among which there is the plane theory of Griffith cracks [7], the Coulomb-Mohr criterion [10], and the Hook and Brown fracture criterion [1].

The strength criteria must meet the following important requirements:

- they should be easy to use;
- they should be widely accepted;
- the data included in the theory of strength should be readily available.

In geomechanics, there are many approaches to explain the mechanism of rocks destruction.

To begin with, let's define what the rocks destruction is. This is a violation of the continuity of the natural structures of rocks during deformation during loading, and strength is the property of the rock to maintain its continuity. Fracture is a complex physical process, the nature of the development of which depends on the magnitude and rate of load application, the stress state of the object, strength and structural properties.

Using the strength criteria, the transition to the limit stress state and the level of loading, the stages of deformation and destruction are explained.

In this area, there are different approaches to presenting the theory of strength. The first of them took into account only the maximum stresses, then they began to concentrate on the maximum and minimum principal stresses. The value of the intermediate stress was neglected, but in recent years, researchers have begun to take into account the value of the average principal stress. Specially staged experiments to determine the degree of impact of the average normal voltage σ_2 show that the error from not taking into account σ_2 does not exceed 10-15% and is within the accuracy of the measured parameters. For brittle anisotropic rocks, the impact of σ_2 somewhat increases [2].

The existing ideas of strength can be divided into theoretical and empirical. The empirical ones can be limited to those rocks and geological conditions of the experiment, which are subsequently generalized on the basis of statistical and mathematical analysis of the measurement results.

The Griffith's theory [7] was the first work among theoretical approaches. He suggests that the failure

of brittle materials is the result of the existing cracks extension. In the surrounding area of these cracks, especially at the crack tip, stress concentration occurs under the action of an external force, and as soon as the tangential tensile stress becomes highly concentrated near the crack tip and reaches the value of the molecular adhesive strength of the material, brittle damage occurs in a certain direction.

To explain the Griffith's theory, a plate of unit thickness with a crack is assumed. A crack can be represented as an ellipse with semi-axes L and b (Figure 1). Then the radius of curvature at the crack tip is $r=b^2/L$. When the plate is stretched, the presence of a crack leads to stress concentration at its edges [7]:

$$\sigma_k = \sigma[1+\sqrt{L/r}]. \quad (1)$$

The Griffith's theory makes it possible to express brittle strength in terms of the physical and mechanical properties of the material and shows that the breaking load does not occur when an initial crack occurs, but after the crack reaches some critical size.

The main disadvantage of the Griffith's theory is that this approach predicts the destruction of the material only after reaching the critical stress value. At lower stresses, failure will not occur under any circumstances. This contradicts the actually observed behavior, when, over time, the body is destroyed under the action of loads that are much smaller than those predicted by the theory of brittle fracture.

The classical theory of strength in geomechanics is the Mohr-Coulomb failure criterion, which is based on the results of testing rock samples.

The essence of this criterion is that the destruction occurs when the shear stresses, which depend on the normal stresses on the shear area, reach the limit value [4].

The strength passport according to the Mohr-Coulomb criterion is a curve that envelops the Mohr limit stress circles in the coordinates of normal and shear stresses (Figure 2). The diagram gives a visual representation of the stresses in various sections passing through a given point, and corresponds to the limit stress state achieved at a given ratio of the largest and smallest principal stresses.

The Mohr-Coulomb criterion for the forward shift is expressed by the equation [11]:

$$\tau = C + \sigma_n \tan\varphi, \quad (2)$$

where τ is rock shear strength, MPa; C is adhesion, MPa; σ_n is normal stress, MPa; φ is angle of internal friction, deg. (tanφ is the coefficient of internal friction).

The Drucker-Prager failure criterion is similar to the Mohr-Coulomb criterion and is often used because it creates a cone as a failure envelope in 3D stress space instead of a hexahedral pyramid in the case of the Mohr-Coulomb criterion (Figure 3).

Initially, the criterion was developed to describe the plastic deformation of clay soils, afterwards it was suitable for brittle rocks. The criterion depends on two material parameters: uniaxial tensile strength and uniaxial compressive strength.

$$F(T_\sigma) = A + BI_1 - \sqrt{D_2} > 0, \quad (3)$$

where A and B are constants determined from experimental data:

$$A = \frac{2}{\sqrt{3}}\left(\frac{R_c R_t}{R_c + R_t}\right), B = \frac{1}{\sqrt{3}}\left(\frac{R_t - R_c}{R_c + R_t}\right).$$

This criterion is, as a rule, suitable for low friction angles (lower than 30°), typical of sand, cement or rocks. However, its application gives large errors if the compressive and tensile strengths of the material differ by an order of magnitude or more.

The Von Mises criterion is a very popular and simple criterion, according to the theory, when the shear stress reaches the limit value, plastic deformation of the material begins and has the following form [6]:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 9\sigma_s^2. \quad (4)$$

The rock massif consists of various layers, small and large cracks, ruptures, various kinds of inclusions, and most of the rocks are considered as an anisotropic material.

To study anisotropy of rocks and especially anisotropy of strength, various studies and analyzes were carried out. As a result of these studies, a variety of failure criteria were introduced that attempted to predict the behavior of anisotropic rocks under load and hence the rock strength.

One of the early studies of the anisotropic rocks strength is the theory of Jaeger (Jaeger, 1960) [6], where one through fracture is considered, and two modes of failure are assumed, failure along the fracture and failure through the intact material.

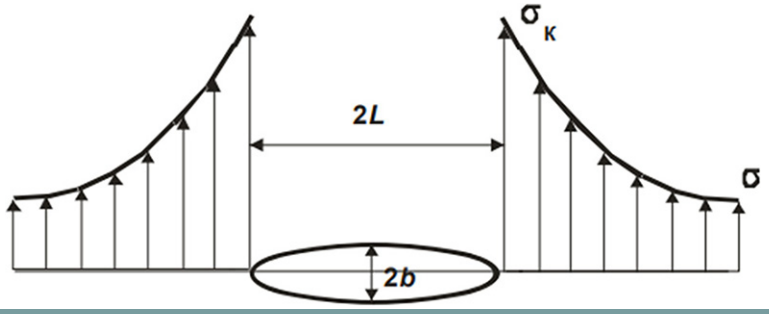


Figure 1 – Stress concentration at crack tips

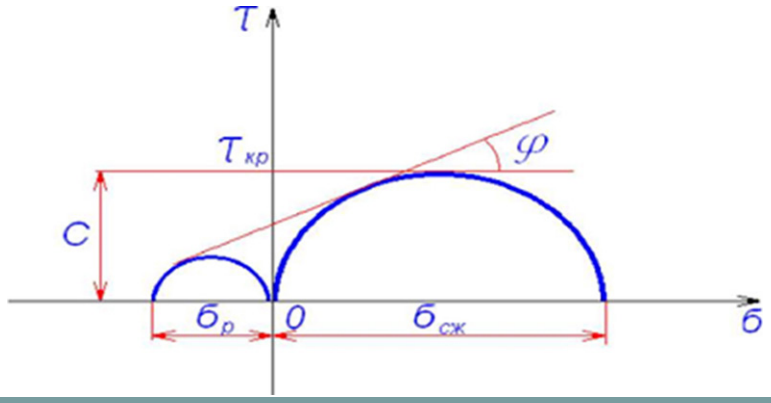


Figure 2 – Passport of rock strength

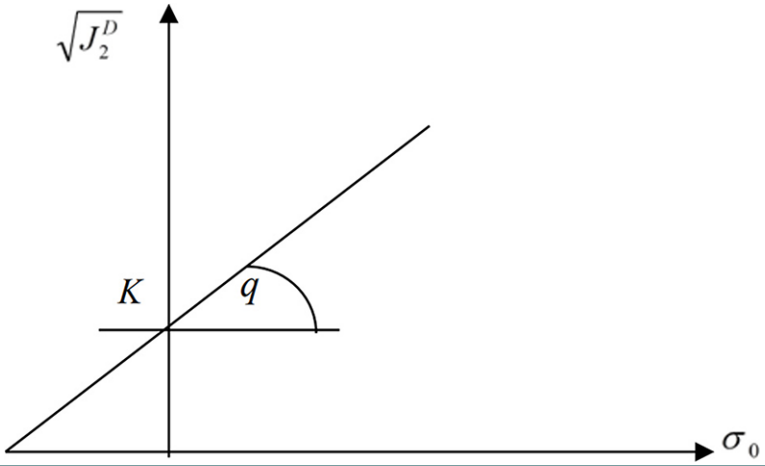


Figure 3 – Drucker-Prager criterion

Later, Jaeger and Cook (1979) [5, 6] developed a relationship for rock strength prediction that describes the uniaxial compressive strength of a sample characterized by cohesion and friction angle

$$\sigma_{1(\beta)} = \sigma_3 + \frac{2(C_j + \sigma_3 \tan\varphi_i)}{(1 - \tan\varphi_j \tan\beta)\sin 2\beta}. \quad (5)$$

Strength anisotropy of rocks means that the strength of rocks depends on the angle between the direction of the load and the orientation of the anisotropy planes. It is for the simplicity and due to the fact that this ratio is often found in engineering practice and laboratory testing. If we consider uniaxial loading of a rock sample with one plane of weakening, then in this case the minimum strength value will correspond to a 30°-45° angle between the direction of the load and the plane of weakening. The value of the load varies depending on the orientation of its inherent weakening planes [6].

The Hook-Brown criterion is also based on the results of analyzes of mine workings. It describes the non-linear increase in strength with increasing constraint as a non-linear envelope, from which the most appropriate Mohr-Coulomb strength envelope is projected over a stress range (low to high constraint).

The original Hook and Brown failure criterion was developed to evaluate the strength of a rock mass with a fractured structure. The fracture model was obtained on the basis of the results of laboratory triaxial tests of intact rock samples.

The Hooke-Brown failure criterion for intact rock is presented as follows:

$$\sigma_1 = \sigma_3 + \sigma_c\left(m_i \frac{\sigma_3}{\sigma_c} + 1\right)m^{0.5}, \quad (6)$$

where σ_1 and σ_3 are respectively, the main and secondary effective stresses at fracture; σ_c is the uniaxial compressive strength of intact rock material; m_i is an empirical parameter that depends on the mineralogy, composition and grain size of the intact rock.

The uniaxial compressive strength σ_c of intact rock is an important parameter of the Hooke-Brown failure criterion and should be determined by laboratory testing whenever possible.

The Hook-Brown criterion has been improved to expand its applicability. Additional empirical parameters mb and a associated with rock properties have been proposed, and the parameter s has been included representing the degree of fracture in the rock massif in the range of 0 to 1 to make the Hook-Brown test suitable for use in rock massifs.

The term mb was introduced to denote broken,

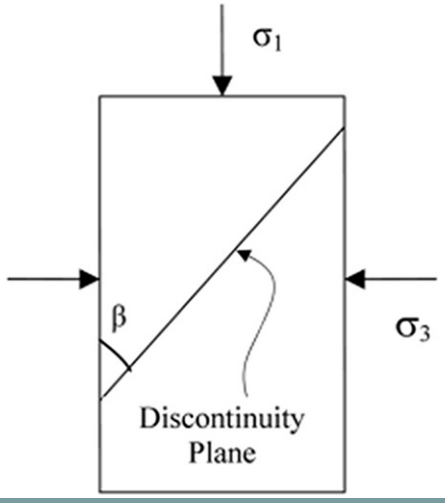


Figure 4 – Anisotropic rock with one fracture plane according to the Jaeger theory

fractured rock. The original value of mi has been re-evaluated and found to depend on the mineralogy, composition and grain size of the intact rock. The exponential term a was added to eliminate system bias towards hard rock and to better account for the lower quality of the rock, allowing the fracture envelope curvature to be corrected, especially at very low normal stresses. Subsequently, the geologic strength index GSI was introduced along with several relationships related to mb, s and a with the overall rock mass structure and fracture surface conditions. The principal stress components in the original equation have been replaced with the previously effective principal stress components, as the criterion was assumed to be valid for effective stress conditions:

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a. \quad (7)$$

In 2002, the relationship between GSI and mb, s and a was revised, and a new factor D was introduced to take into account explosion damage near the surface and stress relaxation. This edition of the criterion represents the last major revision of the Hooke-Brown system. The rock massif scaling ratios for mb, s and a were represented as follows:

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D} \right), \quad (8)$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D} \right), \quad (9)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} + e^{-\frac{20}{3}}\right). \quad (10)$$

The parameters mb, s and a depend on GSI, which ranges from 5 (for highly fractured, weak rock massifs) to 100 (for undamaged rock mass). The parameter mi is the Hooke-Brown constant for intact rocks, and its value (1.0-35.0) reflects the hardness of the rock mass.

The value of D ranges from 0 (for undisturbed rock massifs) to 1 (for disturbed rock massifs).

The values of the geological strength index GSI and the blast damage factor D depend on the qualitative description and the lack of specific quantitative parameters. The accuracy of this method depends mainly on the engineer's experience and judgment, with strong subjective factors; thus, the structural parameters of the rock mass are difficult to quickly and accurately determine.

Science does not stand in one place, scientists from all over the world are trying to improve those methods and criteria that were previously created, excluding those errors that existed. Wenkai Feng, Shan Dong, Qi Wang, Xiaoyu Yi proposed a new approach to the Hooke-Brown strength criterion [9].

The new method uses Surface Condition Rating (SCR), Structure Plane Compliance Ratio (Jc), Basic Rock Quality Index (BQ) and Rock Massif Structure Rating (SR). An improved formula for the explosion damage factor (D) using BQ has been established.

The Surface Condition Rating (SCR) is determined by summing the values of three parameters: infill R_f, weathering R_w and roughness R_r:

$$SCR = R_f + R_w + R_r. \quad (11)$$

The J_c parameter depends on the degree of roughness, the surface smoothness evaluation parameter, and the crack change evaluation coefficient:

$$J_c = \frac{J_w J_s}{J_a}. \quad (12)$$

The BQ parameter is determined as follows:

$$BQ = 100 + 3R_c + 250K_v, \quad (13)$$

$$K_v = \left(\frac{v_{mp}}{v_{rp}} \right)^2, \quad (14)$$

where K_v is the rock mass integrity index (ranging from 0 to 1), v_{mp} is the rock mass wave velocity, v_{rp} is the rock block wave velocity, and R_c is the uniaxial saturated compressive strength.

The SR parameter can be expressed using a volumetric crack count (J_v) [9]:

$$SR = -17.5 \ln J_v + 79.8. \quad (15)$$

The formula for J_v is as follows:

$$J_v = \sum_{i=1}^{n} \frac{1}{S_i} + \frac{N_r}{5\sqrt{A}}, \quad (16)$$

where S_i is the average distance between i groups, N_r is the random number of cracks in a certain area of cracks, A is the statistical area.

A new chart (Figure 5) is proposed for determining the GSI value using the parameters for assessing the state of fractures and the basic index of quality of the rock massif. In the new method, the following values must be defined in order: SCR, BQ, SR, and Jc. The range of values where the four parameters intersect is the GSI value.

Conclusion

In geomechanics, there are two widely used main failure criteria, the Hooke-Brown and the Coulomb-

Mohr ones.

With the increasing depth of mining, more and more scientists are interested in the rock massif behavior, and the methods and criteria that scientists have developed are still being studied and improved. The analysis of the criteria for the destruction of rocks showed that among the known criteria, the Hooke-Brown criterion undergoes more frequent changes. The additional parameters *mb*, *a*, *s* were introduced, which made it possible to take into account the fracturing of the massif and its characteristics. A system for evaluating lithology, the structure and state of the fracture surface were introduced, which together were included in the index of the geological strength index GSI. All those innovations made it possible to approach real conditions when predicting the stress-strain state of a rock massif and substantiating the stability parameters of anthropogenic rocks outcrops.

The Hook-Brown criterion is one of the most widely used and recommended criteria worldwide and is proposed by various experts in rock mechanics. Adaptation of this criterion to the mining and geological conditions of mineral deposits in Kazakhstan will make it possible to predict reliably the geomechanical state of the rock massif, which in turn will increase the safety of mining operations.

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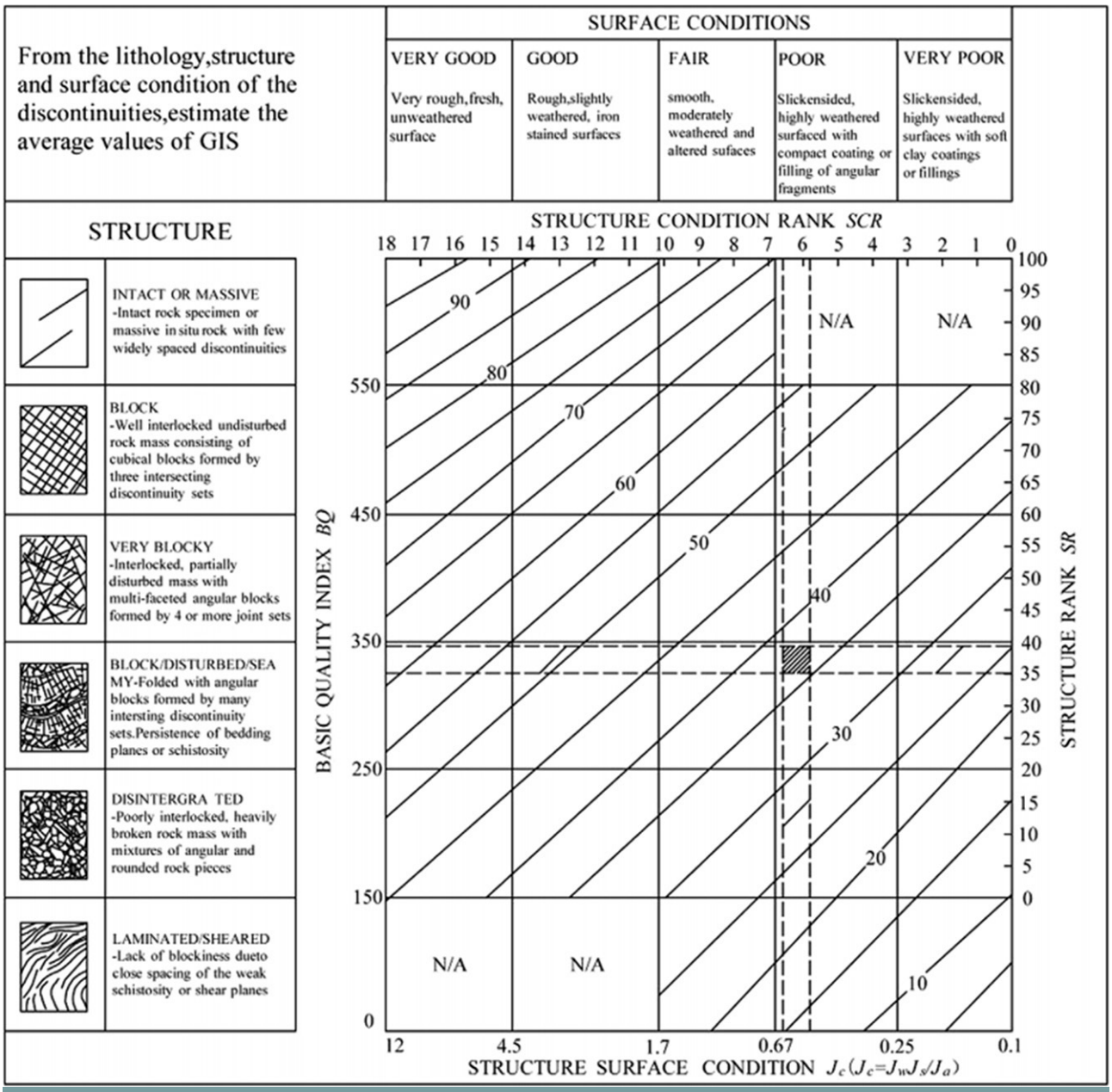


Figure 5 – Diagram for determining the GSI value using the parameters of the assessment of the crack state and the basic quality index of the rock massif

СПИСОК ЛИТЕРАТУРЫ

1. Xiangchao Shi, Xu Yang, Yingfeng Meng, Gao Li Modified Hoek-Brown failure criterion for anisotropic rocks // Environmental Earth Sciences. – 2016. – Issue 11. – URL: https://doi.org/10.1007/s12665-016-5810-3
2. Жабко А.В., Волкоморова Н.В. О механизме и степени влияния промежуточного главного напряжения на прочность горных пород // Проблемы недропользования. – 2019. – № 2. – С. 88-92.
3. Баклашов И.В. Геомеханика: Учебник для вузов. – М.: Издательство Московского государственного горного университета, 2004. – 208 с.
4. Оловянный А.Г. Механика горных пород. Моделирование разрушений. – СПб: ООО «Издательско-полиграфическая компания «КОСТА», 2012. – 280 с.
5. Mohammad Hossein Bagheripour, Reza Rahgozar, Hassan Pashnesaz, Mohsen Malekinejad. A complement to Hoek-Brown failure criterion for strength prediction in anisotropic rock // Geomechanics and Engineering – 2011. – Vol. 3. – No. 1. – pp. 61-81.
6. Saeidi O., Vaneghi R.G., Rasouli V., Gholami R. A modified empirical criterion for strength of transversely anisotropic rocks with metamorphic origin // Geology Bulletin of Engineering Geology and the Environment. – 2013. – Issue 2. – pp. 257-269.
7. Кочарян Г.Г. Деформационные процессы в массивах горных пород: Учебное пособие. – М.: МФТИ, 2009. – 378 с.
8. Shi, X., Yang, X., Meng, Y. et al. Modified Hoek-Brown failure criterion for anisotropic rocks [Электрон. ресурс] // Environmental Earth Sciences. – 2016. – URL: https://doi.org/10.1007/s12665-016-5810-3
9. Wenkai Feng, Shan Dong, Qi Wang, Xiaoyu Yi Improving the Hoek-Brown criterion based on the disturbance factor and geological strength index quantification // International Journal of Rock Mechanics and Mining Sciences. – 2018. – Volume 108. – pp. 96-104.
10. Joseph F. Labuz, Arno Zang. Mohr-Coulomb Failure Criterion // Rock Mechanics and Rock Engineering. – 2012. – Issue 6. – pp. 975-979.
11. Imashev, A.Z., Sudarikov, A.E., Musin, A.A., Suimbayeva, A.M., Asan, S.Y. Improving the quality of blasting indicators by studying the natural stress field and the impact of the blast force on the rock mass // News of the National Academy of Sciences of the Republic of Kazakhstan: Series of Geology and Technical Sciences. – 2021. – No. 4 (448). – pp. 30-35.
12. Adoko, A.C., Saadaari, F., Mireku-Gyimah, D., Imashev, A. A Feasibility Study on The Implementation of Neural Network Classifiers for Open Stope Design // Geotechnical and Geological Engineering. – 2021 – URL: https://doi.org/10.1007/s10706-021-01915-8

Тау-кен қазбаларының тұрақтылығын бағалау үшін мықтылық критерийлерін талдау

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Аңдатпа. *Тау жыныстарының мықтылық критерийлеріне талдау жасалды. Тау механикасында жалпы қабылданған және кеңінен танымал критерийлер Гриффитс, Кулон-Мора, Хук-Браун, Друкер-Прагер, Фон-Мизес және Джегер теориялары қарастырылды. Табиғатта тау сілемі біркелкі емес, бірнеше қабаттар мен жыныстардан тұрады, ал жыныстардың қасиеттері бағытқа байланысты әр түрлі болады. Анизотропты жыныстардың бұзылу принципін зерттеу үшін геомеханик-ғалымдар көптеген жұмыстар атқарды, нәтижесінде анизотропты тау жыныстардың бұзылуын түсіндіретін мықтылық критерийлері енгізілді. Хук-Браун критерийінің негізгі идеясы – физикалық және механикалық қасиеттердің зертханалық үлгілерден сілемдегі тау жыныстарының қасиеттеріне құрылымдық ақауларды ескеретін қосымша параметрлерді енгізу арқылы дұрыс ауысуы. Сілемдегі жарықтар, әлсіреу жазықтықтары және басқа құрылымдық ерекшеліктерді ескеру тау жыныстарының мықтылығы мен деформациясын бағалау кезінде сенімді нәтижелер береді.*

Кілт сөздер: *бұзылу критерийі, кернеу, тасжарық, мықтылық, ішкі үйкеліс бұрышы, ілінісу, анизотропты тау жынысы, мықтылық паспорты, созылу мықтылығының шегі, сығылу мықтылығының шегі.*

Анализ критериев прочности для оценки устойчивости горных выработок

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Аннотация. *Проведен анализ критериев прочности горных пород. Рассмотрены общепринятые и широко известные в горной механике критерии Гриффитса, Кулона-Мора, Хука-Брауна, Друкера-Прагера, Фон-Мизеса и теория Джегера. В природе горный массив неоднороден, состоит из множества слоев и пород, и свойства пород в зависимости от протяженности разнятся. Для изучения принципа разрушения анизотропных пород учеными-геомеханиками проведены исследования, результаты которых введены в различные критерии прочности, объясняющие разрушение анизотропных пород. Основной идеей критерия Хука-Брауна является корректный переход от лабораторной прочности образцов горных пород к прочностным свойствам горных пород в массиве путем введения дополнительных параметров, учитывающих структурные ослабления. Учет трещиноватости, плоскостей ослаблений и других структурных особенностей в массиве дает более достоверные результаты при оценке прочности и деформации горных пород.*

Ключевые слова: *критерий разрушения, нагрузка, трещина, прочность, угол внутреннего трения, сцепление, анизотропная порода, паспорт прочности, предел прочности на растяжение, предел прочности на сжатие.*

REFERENCES

1. Xiangchao Shi, Xu Yang, Yingfeng Meng, Gao Li Modified Hoek–Brown failure criterion for anisotropic rocks // Environmental Earth Sciences. – 2016. – Issue 11. – URL: https://doi.org/10.1007/s12665-016-5810-3
2. Zhabko A.V., Volkomorova N.V. O mehanizme i stepeni vlijanija promezhutochnogo glavnogo naprjazhenija na prochnost' gornyh porod // Problemy nedropol'zovanija. – 2019. – No. 2. – pp. 88-92.
3. Baklashov I.V. Geomehanika: Uchebnik dlja vuzov – Moscow: Publ. Moskovskogo gosudarstvennogo gornogo universiteta, 2004. – 208 p.
4. Olovjannyj A.G. Mehanika gornyh porod. Modelirovanie razrushenij. – SPb.: OOO «Izdatel'sko-poligraficheskaja kompanija «KOSTA», 2012. – 280 p.
5. Mohammad Hossein Bagheripour, Reza Rahgozar, Hassan Pashnesaz, Mohsen Malekinejad. A complement to Hoek-Brown failure criterion for strength prediction in anisotropic rock // Geomechanics and Engineering – 2011. – Vol. 3. – No. 1. – pp. 61-81.
6. Saeidi O., Vaneghi R.G., Rasouli V., Gholami R. A modified empirical criterion for strength of transversely anisotropic rocks with metamorphic origin // Geology Bulletin of Engineering Geology and the Environment. – 2013. – Issue 2. – pp. 257-269.
7. Kocharjan G.G. Deformacionnye processy v massivah gornyh porod: Uchebnoe posobie. – Moscow: MFTI, 2009. – 378 p.
8. Shi, X., Yang, X., Meng, Y. et al. Modified Hoek-Brown failure criterion for anisotropic rocks [Electron. resource] // Environmental Earth Sciences. – 2016. – URL: https://doi.org/10.1007/s12665-016-5810-3
9. Wenkai Feng, Shan Dong, Qi Wang, Xiaoyu Yi Improving the Hoek-Brown criterion based on the disturbance factor and geological strength index quantification // International Journal of Rock Mechanics and Mining Sciences. – 2018. – Volume 108. – pp. 96-104.
10. Joseph F. Labuz, Arno Zang. Mohr-Coulomb Failure Criterion // Rock Mechanics and Rock Engineering. – 2012. – Issue 6. – pp. 975-979.
11. Imashev, A.Z., Sudarikov, A.E., Musin, A.A., Suimbayeva, A.M., Asan, S.Y. Improving the quality of blasting indicators by studying the natural stress field and the impact of the blast force on the rock mass // News of the National Academy of Sciences of the Republic of Kazakhstan: Series of Geology and Technical Sciences. – 2021. – No. 4 (448). – pp. 30-35.
12. Adoko, A.C., Saadaari, F., Mireku-Gyimah, D., Imashev, A. A Feasibility Study on The Implementation of Neural Network Classifiers for Open Stope Design // Geotechnical and Geological Engineering. – 2021 – URL: https://doi.org/10.1007/s10706-021-01915-8