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ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

♦

СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

♦

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НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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TRENDS OF THEROCK FAILURE CONCEPTIONS DEVELOPMENT*

Abstract. The analysis of existing research regarding rock failure criteria and justification of the analytical failure criterion for structurally heterogeneous materials in the volumetric stressed and deformed state.

The study is based on an integrated approach with the use of analysis and synthesis of the literature sources on the topic related to failure of the rock with heterogeneous structure, and use of analytical and empirical failure criteria to assess the strength of rocks.

Comparison of the analytical failure criterion with the results of testing rocks in the volume stressed state is carried out. It is proposed to assess the degree of danger of the rock failure media for any point of homogeneous rock mass in the vicinity of mine working through the safety factor n, by comparing the value of equivalent stress σ_e with a tensile strength in uniaxial compression R_c. Use of structural attenuation coefficient k_c allows transferring from strength assessment of the rock sample to the evaluation of the real strength of structurally inhomogeneous rock mass.

A failure criterion for structurally inhomogeneous materials with defects in the form of joints that allows to adequately assessing the stability of the rock mass is proposed.

Comparison of the analytical criterion with the results of laboratory testing of structurally heterogeneous materials in the volumetric stressed state allows predict the rock failure in the massif with the precision of 94%.

Keywords: failure criteria, structurally heterogeneous material, safety factor, tensile strength in uniaxial compression, equivalent stress, coefficient of the rock mass structural weakening.

Development of ideas about the strength and destruction of solids. Assessing the strength of the elements of the mineral deposit development systems, any researcher inevitably faces the problem of choosing one or another failure criterion for geomechanical calculations. Since at the present time all calculations of this kind are performed in specialsoftware applications, the researcher has to use the failure criterion that is initially

integratedin the software solver. Meanwhile, rock massifs of different genesis and structure require an individual approach to the choice of the relevant analytical expression. This analytical research deals with the evolution of approaches to the solution of the problem of solids failure with analysis of the application scope for two the most commonly used in geomechanics criteria: A. Griffiths in one of its modifications and Hoek-Brown [1, 2].

Mechanical destruction of rocks or solids can be considered as a result of the rupture of their structural connections due to the application of external forces. The study of this process, as a rule, occurs through analysis of the corresponding physical models. They are either structural models that consider the object of study at the atomic-molecular level, or structureless, when the solid is a continuous homogeneous continuum. There are also combined models that represent a medium in the form of a solid body, consisting of chaotically located elements that have their own microstructure of a lower level.

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The overwhelming majority of lithological differences are attributed to the class of polycrystalline solids. Considering the structural model of a solid body in the form of an ideal crystal lattice, at the corners of which there are particles held by communication forces, it is possible to calculate the amount of force that should be applied to break this bond and thereby destroy the deformed body. For the first time such a problem for brittle materials was solved by A. Griffiths (Reiner, 1965), who took the analytical studies of G. Kolosov and Inglis (Tymoshenko, 1975) as a basis. A. Griffiths proved that the strength of brittle bodies depends on the tensile strength of structural bonds weakened by microdefect, which inevitably are present in any solids.

In sedimentary rocks, for example, the presence of microcracks is associated with genesis and subsequent lithification, in magmatic – with the cooling of the melted mass, in metamorphic – with chemical reactions.

These studies of the solids strength were embodiedby A. Griffithsin the theory, which formed the basis for further work in the field of so-called microdefect theories of strength.

Griffiths criterion, on the basis of which it can be established whether or not a solid is destroyed, has the following expression(Tymoshenko, 1975)

$$(\sigma_1 - \sigma_3)^2 + 8R_p(\sigma_1 - \sigma_3) = 0, \text{если } 3\,\sigma_3 + \sigma_1 > 0, \qquad (1)$$

$$\sigma_3 = R_p, \text{если } 3\,\sigma_3 + \sigma_1 < 0. \qquad (2)$$

If $\sigma_3 = 0$ in the equation (1) we obtain the relationship between the uniaxial compressive strength $R_c$and the uniaxial tensile strength R_p:

$$R_c = -8\,R_p \; (3)$$

This equation is in good agreement with the results of testing different fragile rocks (Spivak, 1967; Fisenko, 1976).

T. Murrell showed (Murrell, S.A.F, 1958) that in the “τ–σ”coordinate system the basic equation of A. Griffiths can have the presented as

$$4\tau^2 - 2R_c\sigma - 0.25\,R_c^2. \qquad (4)$$

In the research [1], proceeding from completely different premises, a failure criterion is proposed, the basic formula of which has the following form

$$4\tau^2 - 2\sigma(1-\psi)R_c - \psi R_c^2 = 0 \qquad (5)$$

or

$$(\sigma_1 - \sigma)^2 - (1-\psi)R_c(\sigma_1 + \sigma_3) - R_c^2\psi = 0 \qquad (6)$$

Here $\psi = R_p/R_c$ – coefficient of brittleness equal to the ratio of the tensile strength to uniaxial tension R_p to the uniaxial compressive strength limit R_c; σ_1 and σ_3 are the maximal and minimal values of the principal stresses.

It should be noted that the expressions (4) and (5) are essentially similar. Thus, if we put $\psi = 0.125$ in the expression (3), according to A. Griffiths, both formulas will be practically identical.In this regard, the above-mentioned criterion of L. Parchevsky – A. Shashenko (formula 5) can be considered as a modified criterion of A. Griffiths.

The theory of strength, proposed by A. Griffiths in the early 20-ies of the last century, corresponds to modern ideas about the mechanism of destruction of solids and is confirmed by experimental data.

D. Prandtl showed that there are always two mechanisms in the deformation of solids that cause the material to break down: *brittle*, which occurs by tearing along planes perpendicular to the tensile force and *viscous* – from shearing. This concept was further developed in the works of N. Davydenkov (Davydenkov, 1936),Ya. Friedmann (Friedmann, 1952), G. Uzhik (Uzhik, 1935), etc. The concept of brittle and viscous destruction serves as a physical basis for the development of failure criteria.

The mechanism of solids plastic failure as a result of shear deformations was discovered in 1934 by J. Taylor. He was the first who came to the idea of the presence of linear defects in crystal lattices-dislocations (Taylor G.I., 1934), which originate at the tips of cracks or other stress concentrators.In rocks, plastic deformations appear at comparatively low loads, since among the set of chaotically located crystals there is always some number of them, the least favorably located with respect to external forces and having internal defects such as dislocations. These crystals are deformed already with small external forces. The number of them is usually small, and for this reason plastic deformations do not noticeably affect the relationship between force and displacement.

With large external forces, irreversible shifts occur in most crystals along the weakest surfaces, especially if they have a direction close to the surfaces of the maximum tangential stresses. This explains the formation of slip tracks (Chernov-Luders lines) on the polished surfaces of loaded rock samples. It is proved that plastic deformation as a result of shear is irreversible and proceeds without changing the volume of the material.

The second important stage in the development of ideas about strength, included consideration of thermal motion effects in a solid and their impact on the failure process. By this time, extensive experimental data on the properties of the "limits" of elasticity, strength, and fluidity have been accumulated. It was found that these limits are unstable, and their magnitude largely depends on the measurement conditions. The reason for this inconstancy was the fact of the thermal motion of atoms in a solid.

Consideration of the thermal motion of atoms has made serious changes in the "mechanical" formulation of the problem. After all, in this case, the external forces are no longer resisted by a static ensemble of bound atoms, but by some system that is in oscillatory motion [3, 4].

Experiments started by S. Zhurkov (Zhurkov, 1957, 1968, 1980) on the tensile stress of solids with very different structures showed that the dependence of the durability τ on the acting stress σ and temperature $T$is always described by an empirical formula of the same form

$$\tau = \tau_0 \exp(u_0 - \gamma\sigma) / kT, \quad (7)$$

where k – Boltzmann constant;u_0, τ_0и$\gamma$are some constants of the test material.

Fundamental research carried out by V. Regel, Ya. Frenkel(Regel, 1974; Frenkel, 1945, 1958) made it possible to determine the physical meaning and numerical value of the constants entering into the dependence (4): τ_0 is the period of oscillations of the atom near the equilibrium position ($\tau_0 \approx 10^{-13}$s); u_0 is the energy of interatomic bonds; $\gamma$is a quantity related to the structural features of the deformed body.

Thus, the basic equation of the thermofluctuation theory of strength (4) has a real physical meaning and reflects the regularities of the processes taking place in the solid state at the atomic level. The reason for the failure is the energy fluctuations of atoms during thermal motion [3, 4].

Recently, another theory of thermofluctuation strength has been actively developing (Kusov, 1979; Zhurkov, 1974), according to which the mechanism of crack initiation occurs as a result of pumping energy from the environment into a destructive density fluctuation – *dilaton*. This leads to heating and thermal expansion of dilatons to a critical value, their decay and the formation of microcracks in the solid.

The break at the boundary of the dilaton is accompanied by a pressure drop. As a result of this, the dilaton becomes not only a source of local destruction, but also a point source of dislocations. Thus, the elementary mechanisms of destruction and plastic deformation are interconnected and acting simultaneously.

The dilaton theory of strength explains the reason for the destruction of defect-free structures due to the internal instability inherent in any ensemble of atoms.

At present, the kinetic theory of strength, that explains the physics of the processes underlying the destruction of solids, cannot be used for quantitative calculations. It is designed, in fact, only for the case of uniaxial tension, while the rock mass in the vicinity of the mine workings is under conditions of a complex stress state.

The kinetic theory of strength does not explain how the microdefects merge into the main cracks, which are a sign of the destruction of a solid body. This defect of the theory could be eliminated if there was a way to summarize the individual acts of failure. The idea of failure summation was formulated by H. Boltzmann and was further developed in the works of L. Kachanova, Yu. Rabotnov, G. Litvinskyand other scientists.

Investigations of solids on the basis of structural models have made it possible to understand the mechanism of their strength, and to state the basic concepts of the theory of failure. However, real solids differ significantly from those idealized models presented in the theories discussed above. Engineering practice requires the presence of specific formulas that allow assessing the strength of the designed facilities, both surface and underground.

This circumstance has facilitated to the development of practical strength theories, which are based on the unstructured phenomenological models of continuous deformed solid. At the moment, this typeof the model has been most fully studied among all known models.

Engineering theories of strength originate from the assumption that the failure of solids occurs when a certain combination of stress components (strains) reaches a certain critical value. In the most general form, the failure condition for the principal stress components can be represented as

$$F(\sigma_1, \sigma_2, \sigma_3) \leq k, \tag{8}$$

where F is certain function that combines stress components into one relationship. In the critical state, this function is equal to the failure criterion k, which usually depends on the basic strength characteristics of the material, and these are commonly compressive, tensile and shear strengths.

Development of phenomenological theories of strength proceeded mainly along the path of substantiating analytical criteria that would allow the most accurate determination of the limit state in any structural materials, including those relating to brittle, unequally resisting tensile and compressive forces, such as the overwhelming majority of rocks.

With reference to such materials, O. Mohr (Mohr, 1915) proposed a theory of strength, the essence of which is the following: failure occurs if the tangential stresses, which are a function of normal, reach a certain level. At the same time, the strength of rocks does not practically depend on the value of the average stressvalue σ_2.

Specially performed experiments to determine the degree of influence of the average normal stress σ_2 showed that the error from ignoring σ_2 (Beron, 1969; Chirkov, 1876) does not exceed 10-15% and lies within the accuracy of the measured parameters. For brittle anisotropic rocks, the influence of σ_2 somewhat increases (Kuzhetsov, 1921).

The theory of O. Mohr does not have an analytical failure criterion. It is empirical, completely based on experimental data, which makes it very reliable. Following the development of this theory, it is reasonable to mention the empirical criterion of the strength proposed by Hoek-Brown, that is very popular in geomechanical calculations. A detailed analysis of this criterion will be carried out below.

Studying the problems of plastic deformation V. Mises in 1913 and Huber in 1914 independently came to the conclusion that a criterion of strength is not obligatory measured by all the magnitude of the whole potential energy, but that part that goes to change of the shape. The theory of the strength of Huber–Mises is well supported by experimental data for plastic materials.

The strength theory of O. Mohr, Tresca-Saint-Venant and Huber-Mises are the most commonly used for solving elastic-plastic problems in geomechanics.

Numerous studies of the strength and rock failure in a complex stressed state were fulfilled under supervision of A. Stavrogin who offered an exponential strength condition. The results of this paper are generalized in the monographs (Stavrogin, 1979, 1985). The elastic-plastic problem with an exponential strength condition was studied in detail by B. Annin(Annin, 1966).

The studies of the rock failure under conditions of severe loading have made it possible to formulate a range of strength theories that take into account the inhomogeneity of materials emerged in the process of controlled failure (Stavrogin, 1979, 1985; Baklashov, 2004; Glushko, 1980; Vinogradov, 1983). For consideration of this condition, reflected in the parameters of the descending curve on the deformation graph, the so-called strength reduction function is usually introduced into the strength condition. Then the strength condition (5) can be written as follows:

$$F(\sigma_1, \sigma_2, \sigma_3) \leq k(x, y, z), \tag{9}$$

where $k(x, y, z)$is a criterion of strength, which value varies at different points in the failure range.

General requirements for phenomenological strength theories are formulated by G.S. Pisarenko and A.A. Lebedev in the works (Pisarenko, 1969, 1980).

The authors of all above mentioned strength theories proceeded from the assumption of the ideal structure of a rigid body, which either has a structure or has continuous (homogeneous) state. Real construction materials and rocks are far from perfect ones. For this reason, in particular, the theory of strength cannot require an ideal match with experimental data. This deviation is particularly considerable in the case when the studied material contains sufficiently large defects-inclusions, pores, etc., which differ substantially in their physical-mechanical properties. In fact, the most of rocks with imperfect structure belong to such materials.

For nonhomogeneous solids, the deterministic model of a continuous medium is insufficient. Since the places of stress concentration are local and confined to inhomogeneities, which are dispersed randomly in the material, the statistical interpretation of strength becomes essential.

The idea of the statistical nature of strength was first expressed by A.P. Alexandrov and S.I. Zhurkov in 1933 (Alexandrov, 1933: Zhurkov, 1957). Further development of statistical strength theory was developed in the works of W. Weibull (Weibull W., 1939), T.A. Kontorova and Ya. Frenke (Kontorova, 1941), J. Fisher and H. Hollomon (Fischer, 1947), S.D.Volkov (Volkov, 1960), N.N. Afanasyev (Afanasyev, 1953), L.G. Sedrakian (Sedrakian, 1958), B. Bredi (Brady, 1970), V.V. Bolotin (Bolotin, 1971), B.M. Strunin (Strunin, 1962) and others.

A general approach to the description of the strength of inhomogeneous media was proposed by I.M. Lifshits and L.N. Rosenzweig (Lifshits, 1946) based on the method of J. Gibbs. The most successful developments in this direction are statistical theories of the strength designed by S.D. Volkov and L.G. Sedrakian.

Thus, modern ideas about the failure of solids in their development have passed three stages. At the phenomenological stage, it was considered that failure occurs when some components of the stress tensor (strains) reach certain limiting values.

At the structural level, failure is represented as the overcoming of interatomic attraction by the applied and external forces, to a large extent reinforced by various defects in the structure.

The modern thermo-fluctuational strength theory considers failure as a process, although depending on the parameters of the defective structure, but carried out by fluctuations in the thermal motion.

The gradual nature of the development of ideas of rock failureis reflected in the existence of three corresponding approaches to solving the problem of strength, which co-exist, mutually complementing and enriching each other. As these methods and approaches are improved, all three directions will, apparently, eventually develop some general theory of the strength of solids.

Cam-Clay Model. The first critical state models for describing the behaviour of soft soils such as clay, the Cam-Clay (CC) and Modified Cam-Clay (MCC) were formulated by researchers at Cambridge University. Both models describe three important aspects of soil behaviour: 1) strength; 2) compression or dilatancy (the volume change that occurs with shearing);3) critical state at which soil elements can experience unlimited distortion without any changes in stress or volume.

A large proportion of the volume occupied by a soil mass consists of voids that may be filled by fluids (primarily air and water). As a result, deformations in soilare accompanied by significant, and often non-reversible, volume changes. A major advantage of cap plasticity models, a class to which the CC and MCC formulations belong, is their ability to model volume changes more realistically.

The primary assumptions of the CC and MCC models are described next. In critical state mechanics, the state of a soil sample is characterized by three parameters: 1) effective mean stress p'; 2) deviatoric (shear stress) q; 3) specific volume v.

Under general stress conditions, the mean stress, p', and the devaitoric stress q', can be calculated in terms of principal stresses σ_1, σ_2 and σ_3 as

$$p' = \frac{1}{3}\left(\sigma_1 + \sigma_2 + \sigma_3\right), \tag{10}$$

$$q' = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2}. \tag{11}$$

The specific volume is defined as $v = 1+e$, where e is the void ratio. The models assume that when a soft soil sample is slowly compressed under isotropic stress conditions ($\sigma_1 = \sigma_2 = \sigma_3 = p'$) and under perfectly drained conditions, the relationship between specific volume v, and ln p' consists of a straight virgin consolidation line (also known as the normal compression line) and a set of straight swelling lines. Swelling lines are also called unloading-reloading lines [2].

Hoek-Brown empirical failure criterion. By the method of obtaining the failure criteria can be divided into two large groups: analytical and empirical. Analytical criteria of destruction are known: Tresca-Saint-Venant, Yu. Yagna, P. Balandin, Parchevsky-Shashenko, etc. The most popular empirical criteria are O. Mohr, Hoek-Brown, Z. Beniavsky, Cam-Clay and others (Ponomarev, 1956; Drukker, 1957; Macclinton, 1970; Kuznetsov, 1951).

Empirical criteria of failure are obtained on the basis of processing laboratory tests of rocks in complex stress-strain states and results of field measurements. Their application should be limited to those rocks and geological conditions of the experiment, which subsequently were generalized on the basis of statistical and mathematical analysis.

Let us consider in detail the empirical criterion of strength, popular in geomechanics, developed by Evert Hoek and Edwin T. Brown [5]. Its generalized formula is presented as

$$\sigma_1 = \sigma_3 + R_c\left(m_b \frac{\sigma_3}{R_c} + s\right)^a, \tag{12}$$

where σ_1 и σ_3 – maximum and minimum effective stresses, R_c – the average value of the ultimate strength for uniaxial compression of rock samples, m_b – Hoek-Brown constant, that takes into consideration genesis and condition (quality) of the rock massif, *s* and *a* are the constants resulting from the approximation by the power function of the envelope of the stress circles obtained by three-axial volume compression Karmanndevice.

For the untouched (undisturbed) rock massif, the equation (12) have the following expression

$$\sigma_1 = \sigma_3 + R_c\left(m_i \frac{\sigma_3}{R_c} + 1\right)^{0,5}. \tag{13}$$

Here the constant in contrast to the constant m_b,takes into account only the genesis and texture of rocks ($4 \le m_i \le 33$).

The largest m_i values describe fragile rocks, but the lowest values describe soft and plastic rocks, and $m_i = 0$ corresponds to the state of ideal plasticity.

For a disturbed rock massif, the constant m_b is defined as follows:

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

where GSI (Geological Strength Index) is a parameter that takes into account the geological features of the rock massif, in particular its structure and the presence of cracks ($5 \le GSI \le 100$). The parameter GSI is in many respects similar to the parameter RMR (Rock Mass Rating) proposed by Z.T. Beniavsky.

For a rock mass with "good" quality (GSI >25)we obtain

$$s = \exp\left(\frac{GSI - 100}{9}\right), \quad a = 0{,}5. \tag{15}$$

For a rock mass with "poor" quality (GSI <25) we obtain

$$s = 0, \quad a = 0{,}65 - \frac{GSI}{200}. \tag{16}$$

With a purpose of a smoother transition from strong rocks with good quality to very weak rocks with poor quality, an additional parameter *D*has been applied. Parameter *D* takes into consideration disturbance of the rock mass, for example, as a result of blasting operations. Taking into design *D* parameter as a "disturbance factor", the constants m_b, *s*, *a* are determined through the following relations:

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right), \tag{17}$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D}\right), \tag{18}$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right). \tag{19}$$

Comparison of two failure criteria. In order to evaluate the adequacy of above mentioned failure criteria (6) and (13) in the dimensionless coordinate system ($X=\sigma_3/R_c$; $Y=\sigma_1/R_c$), the corresponding graphs were constructed (figure 1). According to results of the lab experiments performed by A.N. Stavrogin, the averaging curve was constructed (Stavrogin, 1979). Failure criteria were estimated by the degree of their deviation from the averaging curve.

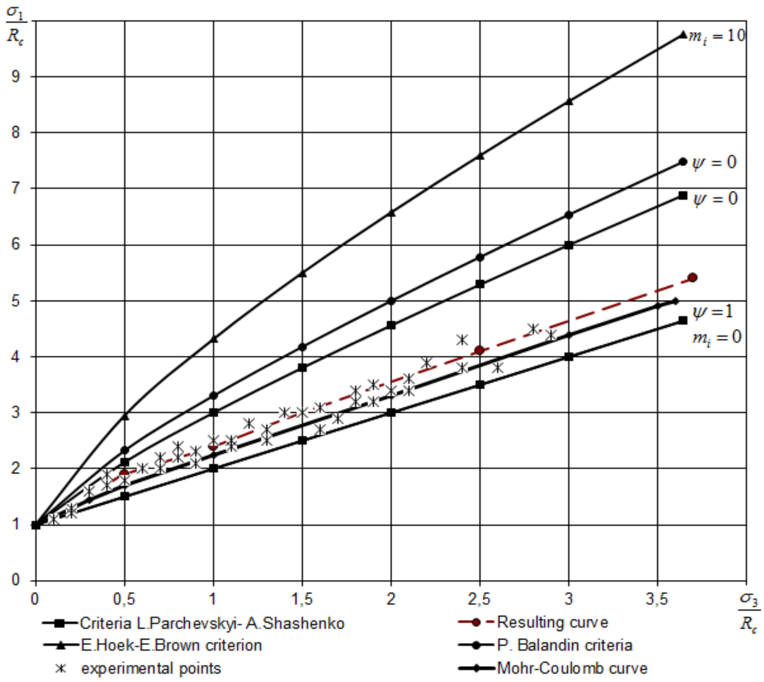

Figure 1 – Comparison of existing strength criteria with experimental data

In accordance with the given coordinate system, the criteria for brittle rocks ($\psi = 0$) will take the following form:

• criterionofdestruction (6):

$$\frac{\left(\frac{\sigma_1}{R_c} - \frac{\sigma_3}{R_c}\right)^2}{\left(\frac{\sigma_1}{R_c} + \frac{\sigma_3}{R_c}\right)} \le 1 \tag{20}$$

• Hoek-Brown failure criterion (average value of constant *m* for brittle rocks accepted as 3.5):

$$\left(\frac{\sigma_1}{R_c} - \frac{\sigma_3}{R_c}\right)^2 - 3{,}5\frac{\sigma_3}{R_c} \le 1. \tag{21}$$

For plastic rocks with a brittleness index ψ close to 1, or for m_i close to 0, both criteria have the same formula and describe the process for plastic rock failure.

For brittle rocks, comparable strength criteria give different results. Slightly below the resulting curve is the criterion curve for equation (12). The curve corresponding to the Hoek-Brown criterion, for m_i = 3.5, which corresponds to the test rocks in the studies of A.N. Stavrogin, is located above the resulting curve. For m_i> 10, the curve goes up sharply. The points scattering field is almost completely covered by two curves: bottom – by criterion (6), and above – by Hoek-Brown criterion (13).

Calculations performed by the Hoek-Brown criterion will be more accurate if the rocks are weaker and more plastic. In the case of strong and brittle rocks, the calculations performed by this criterion will be somewhat overstated, which should be corrected when assessing the strength of the designed structures by introducing an appropriate safety factor.

In two criteria considered above, there is a transition from an estimate of the strength of an undisturbed rock mass and a rock mass containing structural defects in the form of cracks. In the first case, this is achieved by introducing into the main dependence the coefficient of structural weakeningk_c, taking into account the scale effect, the presence of internal heterogeneity and block structure in real rocks. To determine the value of the coefficient of structural weakening, it is sufficient to know two parameters: the average cracks spacing l_T and the variation of rock samples tests for uniaxial compression η_0. The physical meaning of these quantities is clear and understandable, and their obtaining is not difficult.

In the second case, five parameters are introduced into the generalized strength criterion: m_b, s, a, GSI, D, the determination of which is rather complicated and, to some extent, a subjective procedure. The objective to take into calculations all parameters with variable values of the rock mass inevitably makes the empirical dependences increasingly cumbersome and less precise [6].

Conclusions.

1. Modern ideas concerning the failure of solids in its formation have gone through three stages. At the phenomenological stage it was considered that a failure occurs when some components of the stress tensor (strains) reach certain limiting values. At the structural level, destruction is represented as the overcoming of interatomic attraction by the applied and external forces, to a large extent reinforced by various defects in the structure. The thermofluctuation stage considers destruction as a process carried out by fluctuations in thermal motion.

The gradual nature of the development of ideas about solids failureis reflected in the availability of three appropriate approaches to solving the problem of the strength of structural materials, which mutually complement and enrich each other. As these methods and approaches improve, all three directions will, apparently, eventually develop some general theory of the strength of solids.

2. Verification of the two most popular failure criteria in geomechanics, A. Griffiths and Hoek-Brown, showed that their applicability is limited by the structure and genesis of rocks.

3. The transition from the strength of rocks, determined on the samples, to the strength of the rock massif, which has a micro- and macrostructure, is easier and more reliable to perform in accordance with the technique described in [4].

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ТАУ ЖЫНЫСТАРЫНЫҢ ҚИРАУ ІЛІМІНІҢ ӨНУ ЖОЛДАРЫ

Аннотация. Мақалада тау жыныстарын қирау критерийлері жөнінде жүргізілген зерттеулер сарапталған. Құрылым әртекті материалдардың көлемдік кернеулі деформация жағдайында қирауының аналитикалық критерийі негізделген.

Жүргізілген зерттеулер әркелкі құрылымды тау жыныстарын қирауы жөніндегі әдеби мәліметтерді сарапталған, оларды қорытынды жасап, жыныстарының беріктілігін бағалайтын аналитикалық және эмпирикалық критерийлерін қолдану сияқты кешенді тәсілдерге негізделеді.

Тау жыныстарын қирауының аналитикалық критерийі мен көлемдік кернеулі жағдайында сынау нәтижелерімен салыстыру орындалған. Тау жыныстарының қирау қауіптілік дәрежесін ортаның біртекті тау жынысының кез келген нүктесінің игеріліп жатқан аумақ маңайында n беріктік қамдануы σ_e эквивалентті кернеу шамасын бірөстік сығылуға беріктік шегі R_c мен салыстыра отырып бағалау ұсынылған. Құрылымдық әлсіреу k_c коэффициентін пайдалану тау жыныс үлгісінің беріктігін бағалаудан нақты құрылымдылығы әртекті тау жыныстар массивінің беріктілігін бағалауға көшуге мүмкіндік береді.

Сызық сияқты ақаулары бар құрылымдылығы әртекті денелердің қирау критерийлері ұсынылған. Олар тау жыныстар массивін тұрақтылығын айқын бағалауға мүмкіндік береді.

Аналитикалық критерийді құрылымдылығы әртекті материалдардың көлемдік кернеулі күйін зертханалық бақылау нәтижелерімен салыстыру арқылы массивтегі тау жыныстарының қирауын 94 % дәлдікпен болжауға болады.

Түйінді сөздер: қирау критерийлері, құрылымы әркелкі материал, беріктік қамдану коэффициенті, бірөстік сығылудың беріктік шегі, баламалы кернеу, жыныс сілемінің құрылымдық әлсіреу коэффициенті.

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ТЕНДЕНЦИИ РАЗВИТИЯ ПРЕДСТАВЛЕНИЙ О РАЗРУШЕНИИ ГОРНЫХ ПОРОД

Аннотация. В статье выполнен анализ существующих исследований по критериям разрушения горных пород. Дано обоснование аналитического критерия разрушения для структурно неоднородных материалов в объемном напряженно деформированном состоянии.

Исследования базируются на комплексном подходе с использованием анализа и обобщения литературных источников по тематике разрушения горных пород с неоднородной структурой, применении аналитических и эмпирических критериев разрушения для оценки прочности горных пород.

Выполнено сравнение аналитического критерия разрушения с результатами испытаний горных пород в объемном напряженном состоянии. Предложено оценивать степень опасности разрушения породной среды для любой точки однородного породного массива в окрестности выработки посредством коэффициента запаса прочности n, сравнивая величину эквивалентного напряжения σ_eс пределом прочности на одноосное сжатие R_c. Применение коэффициента структурного ослабления k_c позволяет перейти от оценки прочности породного образца к оценке прочности реального структурно неоднородного породного массива.

Предложен критерий разрушения для структурно неоднородных тел с дефектами в виде систем трещин, позволяющий адекватно оценивать устойчивость массива горных пород.

Сравнение аналитического критерия с результатами лабораторного тестирования структурно неоднородных материалов в объемном напряженном состоянии позволяет с точностью 94 % прогнозировать разрушение горных пород в массиве.

Ключевые слова: критерии разрушения, структурно неоднородный материал, коэффициент запаса прочности, предел прочности на одноосное сжатие, эквивалентное напряжение, коэффициент структурного ослабления породного массива

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