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CALCULATION OF THE EFFECTIVE MECHANICAL CHARACTERISTICS OF THE UNDERMINED ROCK MASS

Abstract. An approach has been developed to construct functional expressions for calculating the effective mechanical characteristics of the undermined rock massif during its repeated mining, taking into account the disturbance of the different-type massif continuity and the time passed after the undermining. The approach was developed as applied to the conditions of the Starobin potash salt deposit. It is based on introducing special correction factors into the expressions for mechanical characteristics of the massif. At the same time, the state of the undermined massif area is considered in the continuum model approximation. It is shown that one of the most important factors to be considered when constructing the functional dependence for mechanical characteristics of the undermined layered massif is to take into account the mutual slippage of layers and their lamination related to it, because the strength characteristics such as bonding strength and internal friction coefficient mainly change when the massif is undermined. The algorithm for calculating the mechanical properties of the undermined massif proposes the use of correction factors that take into account the heterogeneity of the rock massif; lamination and slippage of the contacting layers; changes in the properties of the undermined massif with variation of the depth of repeated mining; changes in the properties resulting from the technological disturbance of the massif initial equilibrium state (primary undermining, time passed since the primary undermining).

Keywords: layered rock massif, mechanical characteristics, functional dependence, correction factors

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РАСЧЕТ ЭФФЕКТИВНЫХ МЕХАНИЧЕСКИХ ХАРАКТЕРИСТИК ПОДРАБОТАННОГО МАССИВА ГОРНЫХ ПОРОД

Аннотация. Разработан подход к построению функциональных выражений для расчета эффективных механических характеристик подработанного массива горных пород при его повторной подработке с учетом нарушений сплошности массива различного характера и времени, прошедшего после подработки. В основу подхода положено введение специальных поправочных множителей в выражения для механических характеристик массива. При этом состояние подработанной области массива рассматривается в приближении моделей сплошных сред. Показано, что одним из важнейших факторов, который требуется учитывать при построении функциональной зависимости для механических характеристик подработанного слоистого массива, является учет взаимного проскальзывания слоев и связанного с ним их отслоения, так как при подработке массива главным образом изменяются такие прочностные характеристики, как сцепление и коэффициент внутреннего трения. Алгоритм расчета механических характеристик подработанного массива предлагает использование поправочных множителей, учитывающих неоднородность массива горных пород; расслоение и проскальзывание контактирующих слоев; изменения свойств подработанного массива при изменении глубины повторной отработки, изменение свойств в результате технологического нарушения естественного равновесного состояния массива (первичная подработка, время, прошедшее со времени первичной подработки).

Ключевые слова: слоистый массив горных пород, механические характеристики, функциональные зависимости, поправочные множители

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Introduction. Due to the depletion of raw material reserves in old mine fields of the Starobin deposit, it was decided to re-mine some areas, previously mined out using different technological schemes, leaving significant reserves of minerals in pillars and in the underworked sylvinite layer**.** In order to assess the technological possibility, safety and economic feasibility of supplementary mining the ore from specific panels, it is necessary to carry out geomechanical modelling of the mining situation in the areas proposed for additional mining, to identify the degree of damage to the salt massif, which, in turn, is impossible without taking into account changes in the mechanical characteristics of the mined rock massif due to disturbances in the continuity of the massif of different nature and time after the mining. Some approaches to solve the problem of calculating the effective mechanical characteristics of the undermined rock massif were considered in the works of a some foreign and domestic scientists, for example, [1–3]. However, a complete methodological approach to solve the problem has not been developed. Development of such an approach, taking into account the mining and geological features of the Starobin potash salt deposit, was the purpose of the proposed research.

Results and discussion. The most widespread approach to take into account the influence of the undermined massif on its mechanical characteristics is the introduction of special correction factors into the expressions for the mechanical characteristics of the massif [3]. Proceeding from this approach, the functional expressions for mechanical characteristics of the disturbed structurally heterogeneous massif in general case can be written in the following form:

$$Z(x) = \prod_{i=1}^{k} Z_i(x), \tag{1}$$

where $Z(x)$ is any mechanical characteristics of the massif; $Z_i(x)$ are factors describing and/or defining the properties, structure and behavior of the massif (disturbance by mining).

The areas to be re-mined are characterized by well-developed, though closed, slip lines and fracture systems. During initial mining, fracturing is evident and, in case of large deformations, the rock mass displacements along the slip lines. After termination of the mining and transfer of deformation processes from the active stage to the attenuation period, over time the slip lines and fracture surfaces are “healed”. In case of repeated mining, the continuity of the massif is firstly damaged by the already existing fracture systems and developed slip lines.

But in general, the state of the undermined massif area can be considered in the continuum model approximation after a rather long period of time following its undermining.

This fact is important when building models for an undermined rock massif. If there is no global bonds destruction between the layers after underworking, and if we examine the undermined massif after a sufficiently long time period, there are in principle no significant qualitative differences in the deformation of such a disturbed massif, examined in the continuum approach, from an “ordinary” rock massif without undermining.

Qualitative differences from the “normal” state of the massif occur when the shear resistance of the interlayer boundaries in the massif remains sufficiently small, or becomes so during re-deformation of the massif, because the layers can slip largely in relation to each other.

Therefore, the important strength characteristics for undermined massif of bedded deposit with a layered structure are bonding strength (C) and coefficient of internal friction (tg φ). These characteristics change mainly by the massif undermining.

Let us consider possible approaches for determining the values of φ and C in the undermined massif. We should note that as the two variables are unknown, it is necessary to know the results of at least two different experiments in order to determine them.

First approach. When considering the long-term strength of rock massifs, the Coulomb–More limit criterion ($\tau_n = \mathrm{tg}\varphi\sigma_n + C$) needs to be transformed taking into account temporal processes. The following expression is proposed in [4]:

$$f(\sigma_n) = \mathrm{tg}\,\varphi_t \sigma_n + C_t.$$

Here C_t and $\mathrm{tg}\,\varphi_t$ accordingly are bonding strength and coefficient of internal friction under long-term loading.

In the absence of experimental data on the long-term strength, it can be assumed [4]:

$$\varphi_t = \varphi; \quad C_t = (0{,}12 \div 0{,}42)\sigma_{\text{press}} \approx 0{,}25\sigma_{\text{press}}. \tag{2}$$

Here φ and σ_{press} are the friction angle and the uniaxial compressive strength under short-term loading, respectively.

Therefore, in the absence of reliable experimental data, in the first approximation the values (2) can be taken as input parameters for the bonding strength and the angle of internal friction of the undermined massif.

Second approach. To determine the values of bonding strength C' and the angle of internal friction φ' in the undermined massif (taking into account the presence of a developed, at the initial undermining stage, slip line system), one can use the dependence proposed in [5]:

$$C' = \frac{\sigma_n \mathrm{tg}(K \lg \sigma_{\text{press}} / \sigma_n)}{1 - \mathrm{tg}(K \lg \sigma_{\text{press}} / \sigma_n)\mathrm{tg}\,\varphi},$$

$$\mathrm{tg}\,\varphi' = \frac{\mathrm{tg}\,\varphi}{1 - \mathrm{tg}(K \lg \sigma_{press} / \sigma_n)\mathrm{tg}\,\varphi},$$

where σ_n is effective normal stress, MPa; σ_{press} is uniaxial compressive strength of rocks in the sample, MPa; K is coefficient characterizing rock contact along sliding lines (numerically equal to the average roughness slope angle); C and C' are rock bonding strength values in the sample and in the massif respectively, MPa; φ and φ′ are rock internal friction angle values in the sample and in the massif respectively, degree.

Third approach. If the tensile strength σ_{ext} and compressive strength σ_{press} of the undermined massif are known (i. e. performed tensile and compressive experiments respectively), then the corresponding formulas can be used:

$$\sin\varphi = \frac{\sigma_{\text{press}} - \sigma_{\text{ext}}}{\sigma_{\text{press}} + \sigma_{\text{ext}}}; \; C = \frac{\sigma_{\text{press}}(1 - \sin\varphi)}{2\cos\varphi}. \tag{3}$$

For undermined massifs the experiments for uniaxial compression and compression with lateral pressure under the scheme when $\sigma_1 > \sigma_2 = \sigma_3$ are important. If in this case the values of breaking stresses are $\sigma_1 = \sigma_1^*$; $\sigma_2 = \sigma_3 = \sigma_3^*$ (thus the values σ_1^* and σ_3^* are compressive), the modified conditions (3) take a form:

$$\sin\varphi = \frac{\sigma_1^* - \sigma_{\text{press}} - \sigma_3^*}{\sigma_1^* + \sigma_{\text{press}} - \sigma_3^*}; \; C = \frac{\sigma_{\text{press}}(1 - \sin\varphi)}{2\cos\varphi}.$$

It should be noted that other limit properties of rocks can also be derived from these ratios.

For example, the ultimate tensile strength and ultimate shear strength $\tau = \tau_0$ are calculated using the following expressions:

$$\sigma_{\text{ext}} = \frac{\sigma_{\text{press}} - \sigma_3^*}{\sigma_1^* - \sigma_{\text{press}}}; \ \tau_0 = \frac{\sigma_{\text{press}}\sigma_3^*}{\sigma_1^* - \sigma_{\text{press}} +}\sigma_3^*.$$

In the case of pure shear in the absence of normal stresses ($\sigma_1 = -\sigma_3 = \tau$) the ultimate shear strength $\tau = \tau_0$ is:

$$\tau_0 = C\cos\varphi \frac{\sigma_{\text{press}} - \sigma_{\text{ext}}}{\sigma_{\text{press}} + \sigma_{\text{ext}}}.$$

If the tensile strength of the interlayer boundaries is weak, the slippage between the layers can also be added to the layers lamination. In places where the load gradients on the layers are significant, bending deformation of the layers may become significant with slippage.

Thus, one of the important factors that must be taken into account when constructing the functional dependence for the mechanical characteristics of the undermined laminated massif in the continuum approximation is the consideration of mutual slippage of the layers and their associated delamination.

Let us develop expressions for the module of deformation of the undermined massif, taking into account the disturbances of different types. Mutual slip and delamination zones can be accounted for by the method proposed in [3]. If we assume that along the boundaries $i = k_1, k_2, \ldots, k_n$ of interlayer contacts in some intervals delamination with finite opening takes place, and along the boundaries $i = p_1, p_2, \ldots, p_m$ mutual slip of layers takes place. Using R-function theory [6] we develop the following equations:

$$\omega_{\text{ots}} = \sum_{j=1}^{N} \Lambda_\alpha \omega_{kj}; \ \omega_{pr} = \sum_{j=1}^{M} \Lambda_\alpha \omega_{pj}, \tag{4}$$

where Λ_α is symbol of R-conjunctions, $\omega_i = f(x) = 0$ is the equation of the boundary area between i and $(i + 1)$ layers in the chosen coordinate system, within which slippage or delamination takes place.

In order to take into account, the mutual slippage of layers and presence of delamination, based on (4), the next factors are introduced into expressions for mechanical properties of the massif [3]:

$$E_\perp = E_\perp^\infty \sin(\omega_{\text{ots}}^*), \ E_\| = E_\|^\infty \sin(\omega_{pr}^*). \tag{5}$$

Here $E_\perp$ and $E_\|$ are respectively the strain module of the massif in the direction perpendicular to the bedding and along the bedding, and $\omega^* = \omega\Lambda_\alpha\varepsilon$, where, in turn, α is close to one, and ε is close to the number $\pi / 2$. By introducing in (5) the function ω^* we achieve such behavior of sin (ω^*), when approaching to a zone disturbed in the sense defined in this context $\sin(\omega^*) \to 0$, and when moving away from it $\sin(\omega^*) \to 1$. Thus, by definition

$$\omega\Lambda_\alpha\varepsilon = \frac{1}{1+\alpha}\left[\omega + \varepsilon - \sqrt{\omega^2 + \varepsilon^2 - 2\alpha\omega\varepsilon}\right]. \tag{6}$$

With α close to one, according to (6), the operation $\omega\Lambda_\alpha\varepsilon$ can be approximated by the expression

$$\omega\Lambda_\alpha\varepsilon \xrightarrow[\alpha\to 1]{} \frac{1}{2}[\omega + \varepsilon - |\omega - \varepsilon|] \equiv \min(\omega, \varepsilon).$$

Now it is obvious that for an finite ε and α close to 1, we have

$$\text{at } \omega \to 0 \ \ \omega\Lambda_\alpha = \min(\omega, \varepsilon) = \omega \to 0; \ \text{at } \omega \to W \ \ \omega\Lambda_\alpha = \min(\omega, \varepsilon) = \varepsilon, W \gg \varepsilon, \ W, \varepsilon > 0. \tag{7}$$

Based on (7), it is not difficult to formulate a final conclusion.

Let us investigate the expression (5). Considering the boundary between the layers with a delamination with significant opening we obtain that

$$\omega^*_{\text{ots}} = 0;\ \sin(\omega^*_{\text{ots}}) = 0;\ E_{\perp} = 0,$$

and when considering the boundary between mutually slipping layers (without bonding strength)

$$\omega^*_{pr} = 0;\ \sin(\omega^*_{pr}) = 0;\ E_{\|} = 0,$$

These boundary areas are "special" surfaces and require individual consideration (e. g. by introducing special additional boundary conditions). In the case of moving away from "special" surfaces, the functions like (5) monotonously approach their values in the undisturbed massif; it is easy to show that the rate of functions' increase up to the natural values depends on the disturbance degree of the massif, on the number of "special" zones, and it is such, that the change of values $E_{\perp}$ and $E_{\|}$ from zero to $E_{\perp}^{\infty}$ and $E_{\|}^{\infty}$ is realized in the δ-neighborhood of the "special" zones. Thus, the introduction of factors of the form (5) is also justified from the physical point of view.

The most commonly used approach to determine the strain module E of the undermined massif is its representation in terms of the module of elasticity of the undisturbed massif E_0. Thus, for example, a possible expression for the strain module of the undermined massif could be as follows [7]:

$$E = E_0 / (1 + \eta), \tag{8}$$

where η is the coefficient of the massif disturbance.

Then, the equation describing the deformation of such a massif, derived from Hooke's law equation, is

$$\varepsilon = \frac{\sigma}{E} = \frac{\sigma}{E_0}(1 + \eta).$$

The module of elasticity E_0 of the massif before undermining is considered to be known. The coefficient η is uncertain. The value of the coefficient η can be determined, for example, on the basis of the phenomenological approach, so that the experimental and calculated strain diagrams correspond to each other as much as possible. Such an approach requires in-situ testing, which is not always possible. Scientific and technical literature proposed various approaches for constructing the η coefficient.

Considered one of the possible algorithms for accounting the technological disturbance of the undermined massif by constructing a special expression for the disturbance coefficient η. This algorithm is based on the method proposed in [3].

It is clear that the recovery of the mechanical characteristics of the deeper areas of the disturbed massif occurs more rapidly over time than for the areas located not so deep. This effect can be accounted for by the introduction of an appropriate "depth factor" $\eta(x_3)$, which depends on the depth of mining operations together with the post-mining time factor.

The expression for $\eta(x_3)$ is as follows:

$$\eta(x_3) = 1 - \exp(-\zeta x_3). \tag{9}$$

In formula (9) the variable x_3 is the depth of mining and ζ is the coefficient. As a result of processing the experimental data for the conditions of the Starobin potash salt deposit, it is obtained that the coefficient ζ can be taken as equal to $\zeta = (3 \div 5)10^{-4}$.

In [3], the coefficient of disturbance of mechanical properties of the undermined massif η(*t*), taking into account the time interval after the start of mining, was introduced. The expression for this coefficient is obtained by introducing the hypothesis that the law of change of mechanical properties of the undermined massif in time corresponds to the law of change of massif points displacements inside the subsidence trough.

For example, for the potash mines of the Starobin deposit, field studies have shown that the function $\eta(t)$ using certain mining systems can be represented as

$$\eta(t) = 1.1285 - 0.401/(t+0.2) + 3.365\cdot 10^{-2}/(t+0.2)^2,\ t \ge 0. \quad (10)$$

In (10), the time is defined in years.

The technological heterogeneity of the massif due to the disturbance of its continuity caused by the excavation can be accounted for in the way described, for example, in [8]. In order to take into account the character of strength and deformation parameters distribution in the area of technological impact, the dependence in the form of generalized hyperbola should be used, i. e.

$$E(r) = E_0[1 - aR^n / r^n], \quad (11)$$

where E_0 is the value of the elasticity module outside the area of technological impact; a and n are approximation parameters of the distribution curve of deformation characteristics within the area of technological impact; r is current coordinate; R is equivalent (reduced) radius of the working.

The parameters a and n can be determined by processing the field data or by carrying out the modelling studies. It is clear that these parameters depend on the strength characteristics of the rock strata at the mining site and the linear dimensions of the working.

Thus, the expression for the deformation module of the undermined rock mass in the influence area of the mined-out space with regard to (9), (10) and (11) can be presented in the following form:

$$E(x,t) = \langle E_0(x)\rangle[1 - aR^n / r^n]\eta(x_3)\eta(t). \quad (12)$$

Here $\langle E_0\rangle$ is an effective strain module of the massif, taking into account its structural features (inclusions, lamination, etc.).

Let us describe the general scheme for constructing expression (12) when there is a system of workings with different spatial configurations in a massif.

Let us consider a continuous inhomogeneous weighted half-space with effective characteristics $\langle E_0(x)\rangle$, $\langle \nu_0(x)\rangle$ at time t_0, taken as a starting point. At time $t = t_1$ the excavation 1 is made in massif, whose contour geometry in the chosen coordinate system is described by the equation $\omega_1(x) = 0$. Let us modify the parameters a and n in dependence (11) as follows:

$$n = n_1\omega_1^*(x);\ a = a_1^{(1-\omega_1^*(x))}. \quad (13)$$

Here $\omega_1^*(x) = \omega_1(x)\Lambda_\alpha\varepsilon$ is a cutoff function of the boundary equation $\omega_1(x) = 0$, where in turn α and ε are constant numbers sufficiently close to one. Note that $\omega_1(x) \ge 0,\ \forall x$.

A cut-off operation $\omega_1(x)$ with the indicated values of the parameters α and ε makes it possible to achieve such a behavior of the value $(1-\omega_1^*(x))$, that when moving away from the region of technological influence $(1-\omega_1^*(x)) \to 0$; when approaching it $(1-\omega_1^*(x)) \to 1$ (the reasoning on this subject is similar to that carried out when formula (13) is received). The characteristics a_1 and n_1 are determined from *in situ* observations.

The function $\eta(t)$ is also represented as

$$\eta(t) = \eta(t)^{(1-\omega_1^*(x))}. \quad (14)$$

By introducing operations (13) and (14), we achieve automatic, monotonous and continuous checking the location of the given some point x in the technical influence area of the mining.

As a result, the expression for $E(x, t)$ has the following structure:

$$E(x,t) = \langle E_0(x)\rangle\left[1 - a^{(1-\omega_1^*(x))}(R_1/r_1)^{n_1\omega_1^*(x)}\right]\eta(t)^{(1-\omega_1^*(x))},\quad t \ge t_1,$$

where $r_1 = \|x - x_1\|$ is the distance from the formal centre of the excavation 1 x_1 to the point x under consideration. If at some time t_2 (t_2 is in general different from t_1) a new excavation 2 is made in the massif, the geometry of the contour of which is described in the chosen coordinate system by the equation $\omega_2(x) = 0$, then the procedure of the function $E(x, t)$ building is repeated. As a consequence, it can be written:

$$E(x,t)=\langle E_0(x)\rangle\left[1-a_1^{(1-\omega_1^*)}(R_1/r_1)^{n_1\omega_1^*}\right]\left[1-a_1^{(1-\omega_2^*)}(R_2/r_2)^{n_1\omega_2^*}\right]\times$$
$$\times\eta(t+t_2-t_1)^{(1-\omega_1^*)}\eta(t)^{(1-\omega_1^*)},\ t\geq t_2. \quad (15)$$

Here $r_2=\|x-x_2\|$ is the distance from the formal centre of the excavation 2 x_2 to the point x under consideration. Summarizing the formula (15) to the case of the m^{th} number of workings, we obtain

$$E(x,t)=\langle E_0(x)\rangle\prod_{j=1}^{m}\left[1-a_1^{(1-\omega_j^*)}(R_j/r_j)^{n_1\omega_j^*}\right]\eta(t+t_m-t_j)^{(1-\omega_j^*)},\ t\geq t_m. \quad (16)$$

Conclusion. Developed an approach to the construction of functional expressions for calculating the effective mechanical characteristics of the undermined rock massif during its repeated mining, taking into account the disturbance of the massif continuity of various types and the time passed after the undermining.

The approach was developed as applied to the conditions of Starobin potash salt deposit. It is based on introduction of special correction factors into expressions for mechanical characteristics of the massif. At the same time, the state of the undermined massif area is considered in the continuum model approximation. It is shown, that one of the most important factors to be considered when constructing the functional dependence for mechanical characteristics of the undermined layered massif is to take into account mutual slippage of layers and their delamination related to it, because the strength characteristics such as bonding strength and internal friction coefficient mainly change when the massif is undermined. The algorithm for calculating the mechanical properties of the undermined massif proposes the use of correction factors that take into account the heterogeneity of the rock massif; delamination and slippage of the contacting layers; changes in the properties of the undermined massif with changes in the depth of repeated mining, changes in properties resulting from technological disturbance of the natural equilibrium state of the massif. Thus, to calculate the module of elasticity, the general functional expression (1) can be represented as

$$Z(x, t) = Z_1(x)Z_2(x)Z_3(x)Z_4(x, t),$$

where $Z_1(x)$ is an effective module of elasticity taking into account the heterogeneity of the rock massif; $Z_2(x)$ is based on formulas (5) and takes into account delamination and slippage of contacting layers; $Z_3(x)$ is introduced to determine changes in the properties of the undermined massif with changes in the depth of repeated working and is determined on the basis of formulas (8), (9); $Z_4(x, t)$ is based on formula (16) and determines the change in elastic module as a result of the technological disturbance of the natural equilibrium state of the massif (primary undermining, time passed since the primary undermining).

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