

THEORETICAL ASPECTS OF MONITORING SYNERGISTIC PROCESSES IN THE ROCK MASSIF

¹*Palamarchuk T.A.*

¹*Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine*

ТЕОРЕТИЧНІ АСПЕКТИ МОНІТОРИНГУ СИНЕРГЕТИЧНИХ ПРОЦЕСІВ У МАСИВІ ГІРСЬКИХ ПОРІД

¹*Паламарчук Т. А.*

¹*Інститут геотехнічної механіки ім. М. С. Полякова НАН України*

ТЕОРЕТИЧЕСКИЕ АСПЕКТЫ МОНИТОРИНГА СИНЕРГЕТИЧЕСКИХ ПРОЦЕССОВ В МАССИВЕ ГОРНЫХ ПОРОД

¹*Паламарчук Т. А.*

¹*Інститут геотехнической механики им. Н. С. Полякова НАН Украины*

Annotation. In this article, the grounds for considering of rocks massif as a nonlinear medium with dissipative properties have been shown that as a result of the combined influence of normal and tangential stresses around the workings, synergistic effects are observed with the formation of similar structures, which leads to the appearance of a quasi-stationary damped stress wave, and this, in turn, makes it possible to predict the nature of changes in the stress-strain state of the rock massif in space-time continuum. A mechanism is proposed to explain the known wave nature of changes in rock pressure around disturbances in the rock massif and self-organization processes that occur in it, leading to a steady state as a result of self-destruction of macroscopic nonlinear dissipative systems, which include geomechanical systems. This mechanism is that as a result of exposure geological and technogenic factors the massif goes from one quasi-stationary equilibrium state with the minimum potential energy to another. If the increase in entropy characterizes the growth of chaos in the system, then the self-organization of the system is characterized a decrease in chaos are shown. Those, entropy are one of the most important parameters characterizing the processes of the system self-organization. The parameters characterizing the degree of the system self-organization can also include: the fragility of rocks, coefficient of loosening, coefficient of structural weakening. Taking into account the influence of the mining operations speed, a theoretical justification for diagnostics the physicomachanical properties and the stress state of sedimentary rocks have been developed by using the dynamic and kinematic characteristics of acoustic and electric fields. The theoretically established relationship of the stress state of massif of quartz-containing rocks with its elastic and electrical parameters follows taking into account the damped wave nature of the processes around the mine workings. Obtained results indicate the principal possibility of quantitative assessment of stress components acting in the rock massif using determined physical parameters of the massif.

Keywords: rocks massif, synergistic processes, geophysical monitoring, stress-strain state.

Introduction. Rocks, geological sections are characterized by a high degree of heterogeneity, the presence of large and small blocks, and various fracture systems. Efficiency and safety of operation of underground and surface structures substantially depend on the level of our knowledge about the geomechanical state of their environment and about the regularity by which various physical processes take place in the rock massif, how synergistic and structural phase transitions occur in natural and man-made systems. The speed and intensity of these processes determine the speed and intensity of underground structure's deformation. At the same time, the range of deformation can fluctuate from elusive changes to instantaneous gas-dynamic phenomena (emissions, rock bursts, etc.), as well as earthquakes.

One of the specific features of geosystems is their ability to self-organize (self-

construct) under the influence of the energy of the processes occurring on the Earth [1 – 3]. The question of the self-organization of open natural systems, covering living and inanimate nature, including geosystems, was raised by the second law of thermodynamics.

In [4], the process of a fracture development zone around a borehole drilled in clay rocks was investigated, and the walls of this borehole were strengthened by applying a Polymer coating. The authors established a complex sequence of cracks development around the borehole and proved the important role of pore pressure, which gradually dissipated as the fracture zone developed. However, from the standpoint of the possible occurrence of dissipative structures around the borehole, this process has not been studied and remained outside the attention of researchers.

D. Sahar and co-workers investigated the problem of determining stress components in a rock massif using the parameters of the so-called break-out or fracture zone around the borehole. This method is widely used to restore the stress's components acting in a rock massif to the start of mining works. The authors investigated the stress-strain state around the borehole, which was destroyed due to exceeding the tensile strength of the massif surrounding this borehole. The authors found that the depth at which the break-out began, and its value are dependence on the stress in the massif surrounding the borehole [5].

In [6], an interesting phenomenon of rock massif destruction spread far from the front mining work. They called this phenomenon a domino effect, which contributes to the spontaneous maintenance of cracks growth under the condition that adjacent parts of the massif are in contact with the boundary state. In fact, the authors confirmed the possibility of the process of self-organization emergence during the irreversible deformation of the rock massif and identified another form of dissipative structures of strength loss in the form of a chain effect.

In the literature there are a large number of such experiments descriptions. However, their common flaw repeats what was formulated in the previous analysis: almost all publications are limited only to the identification of dissipative structures and do not determine their evolution. From the kinematics standpoint of dissipative structures, such data adds little information. However, it is obvious that dissipative structures in space and in time appear unevenly. There is also a large spatial variation in the places of occurrence of microseismic activity, which indicates the random nature of dissipative structures evolution.

The study of the rock massif structures as a form of self-organization of the geophysical environment will provide the most objective information about the properties and state of the rock massif, geomechanical systems and the stability of underground structures.

Methods. To solve this problem, we used methods of continuum mechanics, rock mechanics, mathematical physics, empirical and analytical methods, as well as analysis and synthesis of results. The reliability and validity of the results obtained is confirmed by the use of proven theoretical research methods, as well as by taking into account the results of experimental studies.

Results and discussion. Taking into account the results obtained when considering the processes occurring in the vicinity of the mining working of a circular section [2] in this article, taking into account the speed of mine working operations and experimental data, the following expression was obtained:

$$\sigma = \sigma_0 \left(0.11 \ln V + 1 \right) \exp \left(- \left(\alpha r + \frac{t}{\tau} \right) \right) \cos \frac{\pi}{2R_0} r ,$$

where σ_0 – the initial stresses on the mining working contour; V – the speed of mining work; r – the distance from the mining working contour to the deep into the massif; α – the attenuation coefficient of a quasi-stationary wave; t – time, s; τ – the relaxation time, s; R_0 – working radius, m.

Similar processes are also observed not only in the radial direction r around the mining working, but also along its generatrix L , therefore the change in stresses along mining workings is described by law:

$$\sigma = \sigma_0 \left(0.11 \ln V + 1 \right) \exp \left(- \alpha L + \frac{t}{\tau} \right) \cos \frac{\pi}{2R_0} L .$$

Thus, the effect of compression and tension zone displacement along the generatrix of extended underground objects, which can be defined as quasi-wave, is substantiated.

A mechanism is proposed to explain the known wave nature of changes in rock pressure around disturbances in the rock massif and self-organization processes that occur in it, leading to a steady state as a result of self-destruction of macroscopic nonlinear dissipative systems, which include geomechanical systems. This mechanism is that as a result of exposure geological and technogenic factors the massif goes from one quasi-stationary equilibrium state with the minimum potential energy to another.

For a nonequilibrium state of a system for which an inequality holds $dS/dt \geq 0$, its entropy can be defined as follows:

$$S = -kH + S_0 ,$$

where k – the Boltzmann constant; $S_0 = k \cdot \ln \omega$; ω – probability density function; H – Boltzmann function, equal to

$$H(t) = \int_{(\mathbf{r})} \int_{(\mathbf{v})} f(\mathbf{r}, \mathbf{V}, t) \ln(\mathbf{r}, \mathbf{V}, t) d\mathbf{r} d\mathbf{V} ;$$

$f(\mathbf{r}, \mathbf{V}, t)$ – distribution function over coordinates \mathbf{r} , velocities \mathbf{V} and time t , and for stationary states $dH/dt = 0$, and for non-stationary $dH/dt < 0$.

If the increase in entropy characterizes the growth of chaos in the system, then the self-organization of the system is characterized a decrease in entropy.

Those, entropy is one of the most important parameters characterizing the processes of the system self-organization. The parameters characterizing the degree of the system self-organization can also include:

- the fragility of rocks

$$\psi = \frac{\sigma_p}{\sigma_c},$$

where σ_p – tensile strength of rocks; σ_c – compression strength of rocks;

- coefficient of loosening

$$k_p = 1 + \frac{\lg \rho^* - \lg \rho_1^*}{\lg \rho_2^*},$$

where ρ^* – the measured electrical resistivity; ρ_1^* – electrical resistivity of the undisturbed massif; ρ_2^* – electrical resistivity of the broken massif;

- coefficient of structural weakening [7]

$$k_c = \left[1 - \sqrt{0.5\eta} \exp(-0.25\eta) \right] \frac{\eta_0^2 + 1}{\eta^2 + 1},$$

where η – coefficient of variation of rock massif strength, determined by the formula

$$\eta = \sqrt{\frac{l_t + l_0}{l_t} (\eta_0^2 + 1)} - 1,$$

where l_t – the average distance between cracks; l_0 – the characteristic size of the standard rock sample; η_0 – coefficient of variation laboratory tests of rock samples results.

The effectiveness of technological solutions and the rhythm of equipment operation depend on the degree of knowledge of the geological conditions, stress-strain state, properties of the massif, structural heterogeneities, such as the boundary between rocks, tectonic disturbances in the formations, karst, voids and cracks. One of the decisive conditions for reducing the cost of mining and improving the safety of work is the timely monitoring of geotechnical structures stability, properties and stress-strain state of the rock massif, which from the point of view of efficiency and informativity should be based on express methods of mining geophysics.

In order to assess the degree of informativeness dynamic and kinematic characteristics of acoustic and electromagnetic fields for diagnosing the stress state of a rock massif, is considered sedimentary rocks that can be considered dielectrics. As is known, under normal conditions, the dielectric is electrically neutral, i.e. contains the same number of positive and negative charges. The introduction of a dielectric into an electric field strength changes this field. The electric field vector \mathbf{E} and the

induction vector \mathbf{D} will no longer be parallel, and their difference will give a polarization vector \mathbf{P} .

As a result of solving the system of equations describing the propagation of acoustic waves in seismoelectrically active layered rocks, taking into account the initial stress state, we obtain in the first approximation an expression for the velocities and attenuation coefficients of longitudinal waves and electric field strength:

$$V_{3p} = \left(\frac{\lambda_1 (1 \pm \sigma_{33}^0 / 3K)}{\rho} \right)^{1/2} \left(1 - \frac{\omega^2 \eta_1 \tau_1}{2\lambda_1 (1 + \omega^2 \tau_1^2)} - \frac{d_1^2}{\lambda_1 b_1} \right),$$

$$\alpha_{3p} = \left(\frac{\rho}{\lambda_1 (1 \pm \sigma_{33}^0 / 3K)} \right)^{1/2} \frac{\omega^2 \eta_1}{2\lambda_1 (1 + \omega^2 \tau_1^2)},$$

$$E_3^L = -a_1 P_1 = -\frac{a_1 d_1 (1 \pm \sigma_{33}^0 / 3K)}{b_1};$$

for shear waves

$$V_{is} = \left(\frac{4\lambda_5 (1 \pm \sigma_{ii}^0 / 3K)}{\rho} \right)^{1/2} \left(1 - \frac{\omega^2 \eta_5 \tau_5}{2\lambda_5 (1 \pm \sigma_{ii}^0 / 3K) (1 + \omega^2 \tau_5^2)} - \frac{2d_5 (2d_2 + d_3)}{\lambda_5 b_4} + \frac{\sigma_{33}^0 - \sigma_{ii}^0}{16\lambda_5 (1 \pm \sigma_{ii}^0 / 3K)} \right), \quad (i = 1, 2)$$

$$\alpha_{is} = \left(\frac{\rho}{4\lambda_5 (1 \pm \sigma_{ii}^0 / 3K)} \right)^{1/2} \frac{\omega^2 \eta_5}{2\lambda_5 (1 + \omega^2 \tau_5^2)},$$

where λ_i – the elastic parameters of the medium, Pa; K – compression module, Pa; σ_{ij}^0 – initial stresses perpendicular and parallel to stratification, Pa; ρ – density of rocks, kg/m³; ω – cyclic frequency of acoustic oscillations, s⁻¹; η_i – viscosity coefficients, Pa·s; τ_i – the relaxation time, s; a, b, d – electric constants; \mathbf{P} – polarization vector, C/m².

The velocities of longitudinal and transverse waves depend on the elastic, electrical and piezoelectric properties of rocks, and the dependence on the stressed state remains the same as in rocks that are not modified by an electric field.

The experimental values of the energy density of acoustic and electromagnetic waves can be determined from the following expressions

$$W_E = \sum_{i=1}^n (A_i^E)^2 T_i^E;$$

$$W_u = \sum_{i=1}^n (A_i^u)^2 T_i^u,$$

where $A_i^{u,E}; T_i^{u,E}$ – respectively, the amplitude and duration of acoustic and electromagnetic pulses for longitudinal waves.

Taking into account the expressions for the bulk density of acoustic waves

$$W_u = \rho V^2 \varepsilon^{*2} = \rho u_0^2 \omega^2,$$

and bulk density of electromagnetic waves

$$W_E = \varepsilon \varepsilon_0 E^2,$$

will get

$$\frac{W_E}{W_u} = \frac{\varepsilon \varepsilon_0 a_1^2 d_1^2 (1 \pm \sigma_{33}^0 / K)^2}{\rho b_1^2 \omega^2}.$$

From here, after simple transformations, taking into account the wave nature of geomechanical processes around the mining working, we obtain the expression

$$\sigma_{33}^0 = 3K \left(\frac{W_E}{W_u} \frac{\lambda_1 b_1^2 \varepsilon^{*2}}{a_1^2 d_1^2 \varepsilon \varepsilon_0} \mp 1 \right) \exp \left(- \left(\alpha r + \frac{t}{\tau} \right) \right) \cos \frac{\pi}{2R_0} r,$$

from which the theoretically established relationship of the stress state of massif of quartz-containing rocks with its elastic and electrical parameters follows, which indicates the principal possibility of quantitative assessment of stress components acting in the rock massif using determined physical parameters of the massif.

Similarly, the remaining components of the main stresses can be determined.

In the formulas obtained, it is also possible to take into account the speed of mining work, replacing strength and elastic parameters with expressions of the form:

$$X_i = X_0 (0.11 \ln V + 1),$$

where X_0 – the strength or elastic parameters of rocks.

The dependence of stresses on the mining works velocity at various depths is given in Table 1.

From the table it follows that with increasing depth and mining works velocity operations within the specified limits, the stresses increase.

Table 1 – The dependence of stresses on the mining works velocity at various depths

The mining works velocity V , m/s	Depth of mining working H , m				
	300	500	600	700	800
	Stresses σ , MPa				
3	1.1	166.5	194.25	222.0	277.5
4	1.39	170.85	199.32	227.8	284.75
5	1.6	174.0	203.0	232.0	290.0
6	1.8	177.0	206.5	236.0	295.0
7	1.94	179.1	208.95	238.8	298.5

Conclusions. The grounds for considering of rocks massif as a nonlinear medium with dissipative properties have been shown that as a result of the combined influence of normal and tangential stresses around the workings, synergistic effects are observed with the formation of similar structures, which leads to the appearance of a quasi-stationary damped stress wave, and this, in turn, makes it possible to predict the nature of changes in the stress-strain state of the rock massif in space-time continuum.

Taking into account the influence of the mining operations speed, a theoretical justification for diagnostics the physicommechanical properties and the stress state of sedimentary rocks has been developed by using the dynamic and kinematic characteristics of acoustic and electric fields. The theoretically established relationship of the stress state of massif of quartz-containing rocks with its elastic and electrical parameters follows taking into account the damped wave nature of the processes around the mine workings. Obtained results indicates the principal possibility of quantitative assessment of stress components acting in the rock massif using determined physical parameters of the massif.

REFERENCES

1. Pashkin, Ye. M. (1992), "Synergetics of geosystems: a new approach in engineering geology", *Ingenemaya geologiya*, no. 6, pp. 11–13
2. Palamarchuk, T. A., Kirichenko, V. Ya. and Usachenko, B. M. (2006), *Elementy mekhanosinergetiki porodnogo massiva*. [Mechanoenergetics pedigree array cells], Lira LTD, Dnipropetrovsk, UA.
3. Zakharova, L. M., (2016). *Fizychni osnovy evoliutsii dysypatyvnykh struktur v geomekhanitsi* [Physical bases of evolution of dissipative structures in geomechanics], Lambert Academic Publishing, Saarbruken, GE.
4. C. S. Villy and A. Kontogianni (2009), "Coulomb stress changes: From earthquakes to underground excavation failures Stathis", *International Journal of Rock Mechanics and Mining Sciences*, no. 46(1), pp. 182-187.
5. D. I. Sahar, M. Schoenball, E. Gerolymaton and T. Kohl (2017), "Analysis of borehole breakout development using continuum damage mechanics Show more", *International Journal of Rock Mechanics and Mining Sciences*, no. 97, pp. 134-143.
6. D. Wallis, G. E. Lloyd, R. J. Phillips, A. J. Parsons and R. D. Walshaw (2015), "Low effective fault strength due to frictional-viscous flow in phyllonites, Karakoram Fault Zone", *NW India. Journal of Structural Geology*, no. 77, pp. 45-61.
7. Shashenko, A. N., (2001), *Mekhanika gornyykh porod* [Mechanics of mine rocks], NGAU, Dnipropetrovsk, UA.

СПИСОК ЛІТЕРАТУРИ

1. Пашкин Е. М. Синергетика геосистем: новый подход в инженерной геологии. Инженерная геология. 1992. № 6. С. 11–13.
2. Паламарчук Т. А., Кириченко В. Я., Усаченко Б. М. Элементы механосинергетики породного массива. Днепропетровск: Лира ЛТД. 2006. 208 с.
3. Захарова Л. М. Фізичні основи еволюції дисипативних структур в геомеханіці. Saarbruken: Lambert Academic Publishing. 2016.
4. Villy C. S., Kontogianni A.. Coulomb stress changes: From earthquakes to underground excavation failures Stathis // *International Journal of Rock Mechanics and Mining Sciences*. 2009. Vol. 46(1). Pp. 182-187
5. Sahar D. I., Schoenball M., Gerolymaton E., Kohl T. Analysis of borehole breakout development using continuum damage mechanics Show more // *International Journal of Rock Mechanics and Mining Sciences*. 2017. Vol. 97. Pp. 134-143
6. Wallis D., Lloyd G. E., Phillips R. J., Parsons A. J., Walshaw R. D. Low effective fault strength due to frictional-viscous flow in phyllonites, Karakoram Fault Zone // *NW India. Journal of Structural Geology*. 2015. Vol. 77. Pp. 45-61
7. Шашенко А. Н. Механика горных пород. Днепропетровск: НГАУ. 2001. 302 с.

About the author

Palamarchuk Tetiana Andriivna, Doctor of Technical Sciences (D.Sc), Senior Researcher, Principal Researcher in the Rock Mechanics Department, Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine (IGTM, NASU), Dnipro, Ukraine, tp208_2008@ukr.net

Про автора

Паламарчук Тетяна Андріївна, доктор технічних наук, старший науковий співробітник, провідний науковий співробітник у відділі механіки гірничих порід, Інститут геотехнічної механіки ім. М.С. Полякова НАН України (ІГТМ НАН України), Дніпро, Україна, tp208_2008@ukr.net

Анотація. У даній статті на підставі розгляду масиву гірських порід як нелінійного середовища, що володіє дисипативними властивостями, показано, що в результаті спільного впливу нормальних і тангенціальних напружень навколо виробки спостерігаються синергетичні ефекти з утворенням подібних структур, що призводить до виникнення квазістаціонарної згасаючої хвилі напружень, а це, у свою чергу, дає можливість прогнозувати характер зміни напружено-деформованого стану породного масиву в просторово-тимчасовому континуумі. Запропоновано механізм, що пояснює відомий хвильовий характер зміни гірського тиску навколо порушень у породному масиві і процесів самоорганізації, що виникають у ньому; це призводить до стійкого стану в результаті саморуїнування макроскопічних нелінійних дисипативних систем, до яких відносяться геомеханічні системи. Цей механізм полягає в тому, що в результаті впливу гірничо-геологічних і техногенних факторів відбувається перехід масиву з одного квазістаціонарного рівноважного стану з мінімальною потенційною енергією в інше. Показано також, що якщо зростання ентропії характеризує зростання хаосу в системі, то самоорганізацію системи характеризує зменшення хаосу. Тобто ентропія є одним з найважливіших параметрів, що характеризують процеси самоорганізації системи. До параметрів, що характеризують ступінь самоорганізації системи, можна також віднести: коефіцієнт крихкості гірських порід, коефіцієнт розпушення, коефіцієнт структурного ослаблення. З урахуванням впливу швидкості ведення гірських робіт розроблено теоретичне обґрунтування діагностики фізико-механічних властивостей і напруженого стану осадових гірських порід шляхом використання динамічних і кінематичних характеристик акустичних і електричних полів. Теоретично встановлений зв'язок напруженого стану масиву гірських порід, що містять кварц, з його пружними і електричними параметрами з обліком згасаючого хвильового характеру процесів навколо гірських виробок. Отримані результати вказують на принципову можливість кількісної оцінки компонент напружень, що діють у масиві гірських порід, за попередньо визначеними фізичними параметрами масиву.

Ключові слова: масив гірських порід, синергетичні процеси, геофізичний моніторинг, напружено-деформований стан.

Аннотация. В данной статье на основании рассмотрения массива горных пород как нелинейной среды, обладающей диссипативными свойствами, показано, что в результате совместного влияния нормальных и тангенциальных напряжений вокруг выработки наблюдаются синергетические эффекты с образованием подобных структур, что приводит к возникновению квазистационарной затухающей волны напряжений, а это, в свою очередь, дает возможность прогнозировать характер изменения напряженно-деформированного состояния породного массива в пространственно-временном континууме. Предложен механизм, объясняющий известный волновой характер изменения горного давления вокруг нарушений в породном массиве и возникающих в нем процессов самоорганизации, приводящих к устойчивому состоянию в результате саморазрушения макроскопических нелинейных диссипативных систем, к которым относятся геомеханические системы. Этот механизм заключается в том, что в результате воздействия горно-геологических и техногенных факторов происходит переход массива из одного квазистационарного равновесного состояния с минимальной потенциальной энергией в другое. Показано также, что если возрастание энтропии характеризует рост хаоса в системе, то самоорганизацию системы характеризует уменьшение хаоса. Т.е. энтропия является одним из важнейших параметров, характеризующих процессы самоорганизации системы. К параметрам, характеризующим степень самоорганизации системы, можно также отнести: коэффициент хрупкости горных пород, коэффициент разрыхления, коэффициент структурного ослабления. С учетом влияния скорости ведения горных работ разработано теоретическое обоснование диагностики физико-механических свойств и напряженного состояния осадочных горных пород путем использования динамических и кинематических характеристик акустических и электрических полей. Теоретически установлена связь напряженного состояния массива кварцесодержащих горных пород с его упругими и электрическими параметрами с учетом затухающего волнового характера процессов вокруг горных выработок. Полученные результаты указывают на принципиальную возможность количественной оценки компонент напряжений, действующих в массиве горных пород, по предварительно определенным физическим параметрам массива.

Ключевые слова: массив горных пород, синергетические процессы, геофизический мониторинг, напряженно-деформированное состояние.

Стаття надійшла до редакції 03.07.2019.

Рекомендовано до друку д-ром техн. наук С.І.Скіпочкою