Górnictwo i Geoinżynieria • Rok 34 • Zeszyt 2 • 2010

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FUNDAMENTAL LAWS AND NEW CLASSIFICATION OF ROCK PRESSURE OCCURRENCE

1. Introduction

Rock pressure, in Prof. G.A.Krupennikov's terminology, is a collective concept in mining geomechanics, uniting a set of force fields (intense conditions), formed in earth interior causing by natural and industrial influences [1]. More common term, which has been recently spread out, is considered to be the term of "rock pressure occurrence" (RPO), which should be understood as various mechanical processes of deformation and destruction of rock mass under mine working conditions.

The main reason for RPO is usually considered an intense-deforming condition (IDC) of rock mass, caused by gravitational forces and geotectonic processes. The processes connected with RPO, are rather various and, as a rule, represent a serious danger in mine working: displacement and destruction of rock exposures and surface, stressing and deformation of the engineering constructions co-operating with a rock mass, rock bumps, rock outbursts and gas emissions, etc. In spite of considerable achievements in RPO description, processes of rock destruction and deformation are still studied insufficiently

To 1980 an outstanding success is considered to be a study of rock behavior in out-breaking point under decision of boundary problems of mine working stability. Nevertheless, a choice of the most adequate description of out-of-limit rock behavior under decision of boundary problems of rock destruction and stability in underground workings is still remained actual. However, the most essential blank in mining geomechanics is a mess existing till now in various forms of RPO systematization that considerably complicates further conducting of theoretical and experimental researches in this actual direction of mining science. The basic idea of work is to use the fundamental laws and features of rock destruction processes around mine working for solving the problem of their systematization and working out of a new RPO classification.

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2. To the methods of the forecast of rock pressure occurrence (RPO)

As experimental researches and analytical decisions of tasks as to rock resistance in underground workings show, mechanical processes of rock destruction and deformation differ greatly, that considerably complicates a choice of resistance criterion and the corresponding calculation scheme of a task about rock pressure. Therefore the problem of RPO classification and mine working resistance is so important. Methods of RPO forecast in development mine working existing now, are worked out in Ukraine and abroad as well [2–7], they are basically based on one, quite certain calculation scheme, which is even not formulated quite precisely in many cases. Earlier, in conducting mine works on shallow depths of working out, conceptions [3–7] about rock pressure as about shaping domes of natural equilibrium (NAr) prevailed. Thus calculations were mainly based on the simplified approaches, where resistance of materials methods prevailed, and the primary stresses of rock mass was not considered. Subsequently, with transition of mine works to deeper horizons, this initial concept of rock pressure forecast (as domes of natural equilibrium — NAr), as a matter of fact, has been rejected and changed by more difficult calculation scheme, which considered, as a rule, an axis-symmetrical task of formation around mine working a zone of out-of-limit (nonelastic) deformations — ZOD [5–7, 9–11].

It has appeared that at such description of rock pressure occurrence it is necessary to consider not only rock pressure on support, but also a destroyed rocks displacement into a mine working, which depends on deformation-power interaction between support and destroyed rocks. To some similar nonlinear problems it was necessary to use mechanics of continua methods — the theory of elasticity, plasticity and creeping. Complexity of such problems about mine workings resistance has led to rather great variety of calculation schemes that, in turn, has caused contradicting results and become a source of rather sharp disputes among experts about the basic laws of rock pressure.

Finally, in domestic design practice of rock pressure calculation has prevailed simplified, mainly empirical approach, a typical representative of which is a standard document on underground mine workings design [8]. It appeared in 1980 and has been used by designers and industrial organizations with some insignificant amendments up to present time. The basic advantage of this document is ultimate simplicity and availability in use, absence of requirements to carry out tool engineering researches for definition of properties and the initial stress-deformed condition of rock mass.

The method is distinguished by minimum requirement for initial data, low level of requirements to a designer qualification. However, the advantages of such simplified approaches, which are so essential for the period of due laboratory and theoretical base absence, turn into their opposite, i.e. disadvantages: as there are no obvious physical concepts as to the mechanism of RPO development, and also there is no substantial theoretical base and the proved calculation scheme of support and mass interaction, so, accepted RPO criteria (for example, absolute rock displacement on mine working U contour), are not invariants and reflect not the initial reason, but one of RPO consequences etc.

Further transition to the depth of underground space development and conducting mine works under difficult mining and geological conditions (MGC) has opened an inconsistency of existing approaches and has set the task of their cardinal change. Besides, as a rule, the overwhelming majority of boundary problems of rock mass mechanics were considered in axis-symmetrical (unidimensional) statement and only some of them considered whether a multiplicity of initial stress field, or noncircular form of mine working. However the majority of non axis-symmetrical factors (strength anisotropy and heterogeneity of rocks, gravitational forces in nonelastic deformations zone, non-uniformity of a surface force vector, or support reactions) are still remained not investigated. It is especially important to establish the basic laws to which processes of rock deformation and destruction in rock pressure development are submitted. These laws should possess a sufficient generality to cover all variety of RPO and, at the same time, to be informative and specific in order to substantiate calculation schemes and area of their application.

3. Fundamental laws of RPO

For the adequate description of rock destruction around mine working we offer a convenient dimensionless parameter — **local normalized criterion of destruction** (LNCD) ω^*, allowing to compare operating pressure with rock hardness in observed point of a rock mass:

$$\omega^* = \frac{F(\sigma_{ij})}{S(\sigma_{ij}; c_{ij})} \tag{1}$$

where:

$F(\sigma_{ij})$ — is a function of operating stress tensor in the given point of a rock mass, Pa;

$S(\sigma_{ij}, c_{ij})$ — is a function calculated according to the theory of rock strength (hardness) [9], depends on operating stress tensor σ_{ij} and parameters of strength c_{ij}: normal σ_0 and shear τ_o cohesions, friability factor α.

LNCD ω^* allows to specify a variety of important rock conditions. At $|\omega^*| < 1$ there is no destruction (rock contour is steady), to destruction made by tension corresponds an inequality $\omega^* < -1$, and to destruction made by compression — $\omega^*_+ > 1$. An important role in understanding of mine working stability plays the concept of mine working **optimum form** without which it is hard to estimate its rock pressure development. A mine working optimum form has previously been understood as such a form at which a uniform pressure concentration of its rock contour is achieved.

In terms of the introduced concept of local normalized criterion of destruction (LNCD) at a contour of mine working we offer more general condition ω^* = const. In this case it is easy to receive a very important ratio for calculation of mine working optimum form on the basis of rather simple transformations from the theory of mining geomechanics — it is an ellipse with strictly set ratio between horizontal a and vertical b semiaxes:

$$\left(\frac{a}{b}\right)_{opt} = \lambda; \quad \lambda = \left(\frac{p_2}{p_1}\right) \tag{2}$$

where λ — is a factor of horizontal stress, equal to the ratio of horizontal p_2 and vertical p_1 components of initial stress field of rock mass.

Thus, initial stress condition of a rock mass set by λ, requires that form of mine working at which it will be the steadiest. Then throughout the whole contour of elliptic mine working tangential rock pressures are constant and equal:

$$\sigma_0 = p_1(1 + \lambda) \tag{3}$$

However, if at mine working contour, as it often happens, rock hardness of roof and walls essentially differs, then it is necessary to change the equality (2) into a new ratio of mine working optimum form:

$$\left(\frac{a}{b}\right)_{opt} = \sqrt{\frac{s}{\lambda} + \frac{(s+1)^2(1-\lambda)^2}{16\lambda^2}} + \frac{(s+1)(1-\lambda)}{4\lambda}; \quad s = \frac{[\sigma_c^{roof}]}{[\sigma_c^{wall}]} \tag{4}$$

where s — is a ratio of rock strength in roof and walls of mine working.

The concept of mine working optimum form is an important criterion to estimate the development of rock pressure occurrence: if rock destruction makes new mine working contour closer to the optimum form, then it should be considered that mine working stability in process of its forming increases, otherwise stability decreases.

As the value of horizontal stress factor λ for the majority of mining regions including Donbass, as a rule, satisfies to $\lambda < 1$, it appears that mine working optimum form from theory points should have a ratio of dimensions, $(a/b)_{opt} = \lambda < 1$ i.e. to be “narrow and high”. At the same time technological and functional requirements which mine working form should meet, are vice versa: a mine working should be “low and wide”.

Thus, requirements of the theory of mining geomechanics and requirement of practice of mine working use are mutually excluding. This is the sense of **main technical contradiction** in mining geomechanics. While mine works were being conducted at rather shallow depths (to 400...600 m) and at rather favorable mining-geological conditions, RPO intensity was low and infringement of the law of mine working optimum form did not lead to sharp decline of its stability.

But then, in the process of further deepening, situation has radically changed — in the majority of mine workings stability became catastrophically low, and expenses on repairs and resupport — excessive. The solving of this problem has appeared impossible within the limits of old RPO conceptions which could not conceive the main contradiction of mining geomechanics at all. How does the mine working form change under rock contour destruction? Does it wander from optimum (2) or approach? To study the laws of mine working contour forming under destruction of rock mass in its vicinity, the photo elasticity method had been used to investigate a difficult nonlinear task concerned with gradual development and movement of fragile destruction front in mine working vicinity [10].

Thus for the first time it was possible to establish the important generalized law of pressure redistribution under destruction and forming of mine working contour: if a contour curvature under rock destruction increases, then stress increases as well, and under curvature reduction — decreases up to tension stress (taking into account signs — plus for compressing and a minus for tension stress). This generalized law of destruction processes development round mine working allowed to prove fundamental laws to which all known forms of RPO obey. Fundamental laws of RPO development in mine working which consider not static rock balance, as previously, but kinetics of contour destruction processes, defining its forming features, are proved experimentally and analytically and admit simple enough and intuitively clear formulation.

The first fundamental law (FL-I): under rock destruction around mine working tension stress decreases concentration of stress around it, LNCD$^{\omega^*_+}$ criterion becomes lower, mine working form in destruction process comes closer to optimum, speed of movement for fragile destruction front drops to zero, destruction stops, and the final mine working contour gets the steady form of natural equilibrium dome (fig. 1).

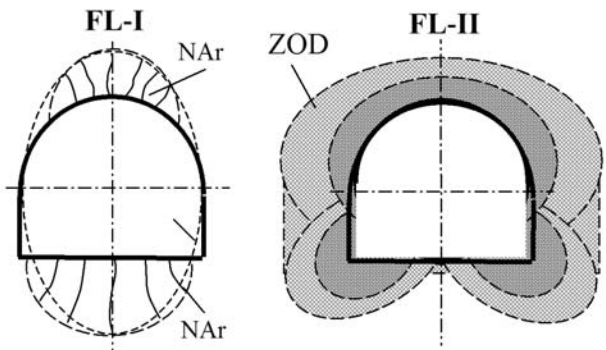

Fig. 1. The rock pressure occuerence under I or II fundamental law

The second fundamental law (FL-II): under rock destruction around mine working compressing stress increases concentration of stress on its contour, LNCD$^{\omega^*_+}$ criterion becomes higher, the form of a new mine working contour in the process of rock destruction wanders from optimum, speed of movement for fragile destruction front grows, therefore without additional measures on its protection mine working loses stability (a collapse takes place).

If mine working has a proper support, then under FL-1 conditions rock pressure is imparted onto mine working support as natural arch (NAr), and under FL-II conditions a zone of out-of-limit deformations (ZOD) appears around mine working, passing (under Prof. B.A. Kartoziya's term [11]) into a zone of "ruin" destruction, co-operating with support in nonlinear way. We should notice that definition of parameters of interaction between ZOD and support is among the challenging problems of mining geomechanics and still has not found any satisfactory decision. In table 1 the rates of limit conditions of RPO realization are given.

TABLE 1
Features of RPO realization at relatively "small" and "deep" depths

Influence of major factors on RPO	Fundamental laws	
	FL-I	FL-II
Factor of horizontal stress of mass λ	< 0.3...0.5	> 0.3...0.5
LNCD criterion ω^*	$\omega^*_- < -1$	$\omega^*_+ > 1$
Type of rock destruction around mine working	tension	compression
Form of rock pressure occurrence	NAr	ZOD
Code name of working out depth	"small"	"deep"

It is worth paying attention, that in terms of fundamental laws RPO finds the explanation as well as widely used, but rather uncertain concepts of "small" and "deep" depths of working out. Now these terms find quite certain meaning.

Concepts of "small" and "deep" depth should not be taken literally. So, the 300 m depth under conditions of «Pavlogradugol'» union will be deep, and 1000 m in "Roven'kiantracit" can be "small", depending on LNCD$^{\omega^*_+}$ criterion significance.

Let's analyze RPO features at relatively "small" and "deep" depths of working out, i.e. when various types of destruction take place. The results will be reflected in summary table to avoid vast text descriptions. We will search for required rock mass pressure q on support and rock displacement U into mine working as a result of surrounding rock mass destruction (tab. 2) relation:

$$\begin{aligned} q &= q(H;[\sigma];r_0;U;\ldots); \\ U &= U(H;[\sigma];r_0;q;\ldots); \end{aligned} \tag{5}$$

where:

σ — is a rock strength,

r_0 — is the typical mine working size.

In table 2 the rates of the basic relations characterizing RPO in mine working under FL-I or FL-II realization are given, i.e. in "usual" and "complicated" mining-geological conditions. In table 2 q and U and the most important influencing factors $X_k (k \in 1\ldots4)$ relations as a rate of sign and range of their partial differential coefficient $\partial q/\partial X_k$ and $\partial U/\partial X_k$ by each factor respectively are shown.

As we see, features of RPO under MGC when realized FL-I or II are opposite. At I–FL RPO does not depend on depth H and rock compressive strength σ_c, but is considerably influ-

TABLE 2
Laws of change RPO parameters *q* and *U* under different FL

Fundamental laws FL of RPO		Support q pressure load $\partial q/\partial X_k$ — factor X_k relation				Rock U displacement $\partial U/\partial X_k$ — factor X_k relation			
		H	$[\sigma_t]$	r_0	U	H	$[\sigma_c]$	r_0	U
FL-I	$\omega^*_- < -1$ $\lambda < 0.3...0.5$	$= 0$	< 0	> 0	$= 0$	$= 0$	$= 0$	> 0	$= 0$
FL-II	$\omega^*_+ > 1$ $\lambda > 0.3...0.5$	$\gg 0$	$= 0$	$= 0$	$\ll 0$	$\gg 0$	$\ll 0$	$= 0$	< 0

enced by the size of mine working r_0 and tensile strength σ_t. The operating mode of support (yielding or rigid) — is insignificant, as $\partial U/\partial q$. On the contrary, at II–FL the depth H and rock compressive strength $[\sigma_{tc}]$ strongly influences RPO intensity whereas the size of mine working r_0 and tensile strength $[\sigma_t]$ are insignificant. It is especially important, that under these conditions the relation is $\partial U/\partial q \ll 0$ that proves the necessity of application rather yielding than rigid designs of support.

The laws reflected in table 2, are especially important for understanding basic differences of RPO under conditions of realization whether the first or second fundamental laws. Even simple comparison of the given rates in corresponding columns of table 2 shows, that the laws essentially differ, that causes the necessity of taking rather various engineering decisions in the field of RPO operating.

4. New classification of rock pressure occurrence

As all set of existing RPO classifications is based, as a rule, on consideration of only one of its possible forms, and in static only, they are not quite capable to completely reflect difficult processes of changes in mine working stability. What kind of demands should be made to RPO forecast and classification method? Unfortunately, not enough attention has been given to formulation of such demands. It has been caused, in certain degree, by influence of traditions which have arisen at the very beginning of RPO studying, when problems of definition of support pressure load — "rock pressure" were put on the foreground. Now, on the ground of considerable achievements of mining geomechanics and both gained designing and industrial experience, it is possible, proceeding from modern conceptions about the mechanical processes occurring in rock mass, to formulate these requirements.

Thus, a working out of a method for RPO forecast should be started with formulation of the basic requirements to the forecast, and then on the basis of fundamental RPO laws it is necessary to give physically proved classification of forms.

So, the method of RPO forecast should:

1) Start with precisely set and proved calculation scheme of the task based on physically proved mechanical model of deformation and destruction processes in rock mass of mine working vicinity,

2) Consider features of the initial stress and the strain state of rock mass (SSS), and also its anomalies arising under mine works,
3) Consider RPO not as a static phenomenon of final rock balance around mine working, but as the process developing in time and, depending on specific conditions, capable "to branch", i.e. to change the direction of its development in time and space;,
4) Consider features of interaction of support elements and ways of protection with surrounding rock mass in the process of its deformation and destruction,
5) Notice the influence of "non axisymmetrical" mining factors capable to deform considerably the form and the sizes of a zone of out-of-limit deformations around mine working,
6) Define the reliability of RPO forecast results and their probable spread.

The established fundamental laws have been taken as a basis for a new classification of rock pressure and mine working stability. Classification is based on drawing up the passport of mine working contour stability and LNCD ω^* calculation, and then the analysis of change of its sign and sizes under contour forming in the process of its destruction.

According to fundamental laws of rock pressure occurrence, if in the process of rock destruction a universal destruction on the module of local criterion ω^* takes place, then destruction will spontaneously stop and new contour of mine working will be steady, and under LNCD ω^* increase the rock contour of mine working will be unstable, so, finally, it will be destroyed unless the corresponding measures on its support and protection will be taken.

The secondary classification signs, allowing to allocate numerous subclasses in the offered classification, are:

— model of rock behavior (ductile, crisp, visco-elastic, etc.),
— a site at mine working contour where destruction processes take place (a roof, soil, walls),
— geostructure of rock mass (fracturing, stratification, inhomogeneity, amount of inclination, etc.),
— mine working space and stratification orientation (horizontal, vertical, inclined, across the pitch, diagonally and along the bedding, etc.).

Conception of rock pressure occurrence classification is introduced in table 3. Recommendations for choice an operating mode and support design are also given there. The types of mining-geological conditions (MGC) which divide all possible forms of RPO, referring them to relatively "small" and "deep" depths of working out, and, as a matter of fact, to usual and intensive RPO conditions are given in the first column of the table.

From the offered classification follows that the method of calculation of rock pressure in mine working should be based on the different calculating schemes which vary depending on whether rock destruction in mine working will occur from compressive stress or tensining. We should underline the important difference of new classification: it is based on the important parameter — horizontal stress factor λ, which characterizes an initial stress condition of rock mass (nowadays it is not measured at mine works in Ukraine).

Taking into account the lack of data about horizontal stress factor λ, besides the main criterion of stability — LNCD ω^*, it is expedient to use auxiliary criteria:

1) Criterion of stability by Prof. J.Z. Zaslavsky [7] which allows to estimate approximately the intensity of rock pressure occurrence:

TABLE 3
Classification of rock stability

MGC Type	RPO Class	Criteria value	Forms of rock pressure occurrence	Types of support
FL-I – “small” working out depth, $\lambda \ll 0.3...0.5$	I — quite stable	$\lvert\omega\rvert \ll 1$ $k_z < 0.1$ $\varepsilon < 1\%$	Rock contour has possible cracks, small layer separations and separate falls on the sites with lowered rock hardness or contour irregularities.	No support, light, isolating and protecting designs
	II — stable	$\omega^+ < 1 < \lvert\omega^-\rvert$ $0.1 < k_z < 0.4$ $1 < \varepsilon < 5\%$	Rock contour destruction from tension prevails. DNE is formed in roof and (or) soil of mine working.	Isolating support
	III — not quite stable	$1 < \omega^+ < \lvert\omega^-\rvert$ $0.2 < k_z < 0.5$ $5 < \varepsilon < 10\%$	Rock destruction from tension advances destruction from compression. DNE is formed with secondary rock destruction in walls from compression	Support with limited yielding
FL-II – “deep” working out depth, $\lambda \gg 0.3...0.5$	IV — weak stable	$1 < \lvert\omega^-\rvert < \omega^+$ $0.2 < k_z < 0.5$ $10 < \varepsilon < 20\%$	Rock destruction from compression in mine working walls causes destruction from tension in a roof	Bearing, support, with limited yielding
	V — unstable	$\omega^+ > 1$ $0.5 < k_z < 1$ $20 < \varepsilon < 40\%$	Destruction of the most part of a contour from compression, formation of ZOD in asymmetric form by tension perpendicularly to rock stratification	Bearing, weight-bearing and yielding, rock-bearing constructions
	VI — quite unstable	$\omega^+ \gg 1$ $0.7...1 < k_z$ $40\% < \varepsilon$	Special forms of rock pressure: a) viscous or plastic rock flow; b) dynamic crisp rock destruction in the form of outbursts and rock bumps.	Thick, yielding or rock-bearing, unloading and rock hardening

$$k_z = \frac{\gamma H}{\sigma_c^0} \tag{6}$$

where γH — is a pressure of overlying rock thickness, equal, as a rule, to a vertical operand p_1 of initial stress field in a rock mass, Pa.

2) Deformation criterion for evaluating relative (by no means absolute as it is accepted now!) rock displacement:

$$\varepsilon = \frac{U}{\sqrt{\frac{A}{\pi}}} \tag{7}$$

where:

U — is a displacement of mine working rock contour, m,

A — is a mine working sectional area in rough, m^2.

Depending on rock hardness and uniaxial tension ratio both in a roof and a soil of mine working, it possible that natural arch (NAr), single and double-sided (in roof or soil), is formed.

The height h_c of NAr under its formation in roof or soil can be defined with the formula:

$$h_c = \frac{a}{\lambda}\left(1 - \lambda - \frac{\sigma_0}{p_1}\right) - 2b \tag{8}$$

where:

- a, b — are halves of width and heights of mine working respectively taking into account the rocks destroyed in walls, m;
- λ — is horizontal stress factor, equal to the relation of horizontal p_2 and vertical p_1 operands of initial stress field in rock mass, Pa;
- σ_0 — is rock strength at uniaxial tension or cohesion of separation [9], Pa.

If NAr is formed simultaneously in roof and walls of mine working (that happens in case of negative pressure at these sites of contour and under ω^*_k, $\omega^*_n > 1$ condition), then height of NAr in roof h_k and soil h_n should follow from more difficult formulas:

$$\begin{aligned} h_k &= \left[\frac{a}{\lambda}\left(1 - \lambda - \frac{\sigma_0}{p_1}\right) - 2b\right]\frac{\omega^*_k}{\omega^*_k + \omega^*_n} \\ h_n &= \left[\frac{a}{\lambda}\left(1 - \lambda - \frac{\sigma_0}{p_1}\right) - 2b\right]\frac{\omega^*_n}{\omega^*_k + \omega^*_n} \end{aligned} \tag{9}$$

where: ω^*_k, ω^*_n — are LNCD values in roof and soil respectively.

5. Conclusions

On the basis of use new Local Normalized Criterion of Destruction (LNCD criterion) and analysis of development of rock destruction processes around mine working, fundamental laws of rock pressure occurrence which have allowed to develop new RPO classification are formulated. Irrelevance of rock pressure occurrence calculations according to universal and uniform calculation schemes and techniques as well as necessity of working out new standard documents are shown. Advantage of the offered approach is precise identification of possible calculation schemes of RPO from which follow some important recommendations as to support parameters option and ways of RPO operating which vary essentially at “small” and “deep” depths.

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