UDC 622.831:622.2:622.235

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EVOLUTION OF SECONDARY STRESS FIELD DURING UNDERGROUND MINING OF THICK ORE BODIES

Rapidly evolving economic crisis generated by the unbalanced confrontation between the technosphere and biosphere dictates finding and implementation of a drastically new technology paradigm of development in the mineral mining sector based on the novel models and ideas about transition to nature-like geotechnologies. Regarding anthropogenic change in subsoil in the course of mineral mining, it is necessary to study the evolution of the secondary stress field in space and time as the structure of this field exerts a dominant influence on parameters of promising mining technologies.

Keywords: *geosphere crisis, technology paradigm ecologization, anthropogenic change of subsoil, underground mining, secondary stress field, structure, geotechnical system model, calibration, experiment.*
DOI: *10.17580/em.2021.01.04*

Generalities

Emergence of a new biological species in the biosphere of the Earth – Homo Sapience – which evolves and lives off the natural balance of solar energy has initiated a new form of the biosphere development – an anthropogenic crisis. Such crisis arose in all ages of civilization. The crises had different nature and always the same cause: the discordance between consumption level and structure and resource capacities of the planet. At the present-day stage of evolution, we again have to deal with the crisis of the geosphere. The modern anthroposphere disturbs or absorbs the geosphere (atmosphere, hydrosphere and lithosphere) at the scale which is globally comparable with the natural protection capability of the geosphere and even exceeds these capacities on the local level. Regarding the lithosphere as the key source of minerals and energy for the modern techno-scientific civilization, the crisis consists in the fact that health growth of population and, thus, expansion in consumption of mineral resources is assured by extensive development of subsoil use based on efficient but environmentally unsound mining technologies. It is possible to resolve this discrepancy through ecologization of the technology paradigm of the mineral sector development, which needs ecological identification of geomechanical processes running in the lithosphere in the zone of extraction of a commercial value substance from it.

Methods and techniques

The general methodical approach to this problem in the framework of the theory of nature-like technologies is based on the homeostatic transfer and adaptation of eco-friendly principles of biological system function in the technosphere. Considering mineral mining as the drastic change in the ecological state of the lithosphere in the form of extraction of mineral substance and deformation of natural stress field, it is possible to primarily hypothesize that environmental safety is connected with the solution of the fundamental challenge in geomechanics, namely, overcoming of inevitable consequences of anthropogenic damage in the lithosphere and the related impact on the dynamic processes running there. In this case, ecologization of the technology paradigm should rest upon such geotechnologies that ensure persistent reproduction of stable dynamic structures, including fluid-bearing reservoirs. With the objective interpreted this way, the general research procedure is clearly definable by Dollo's law [1]. According to this law, in natural biota of the Earth, in critical evolving biosystems, external aggravating effects change the succession path in a wrong way. Then dynamics of the biota species experiences bifurcation, and every new eco-structure depends on the factors other than the factors which led the system to a bifurcation point. In geomechanics, this law of change in living systems can be transformed to a statement that reproduction of stable dynamic systems during mineral mining can be ensured if application of geotechnologies is founded on early and stage-wise elimination of geomechanically ineffective processes and operations by means of change of the generic functional configuration in time and space. In this case, the choice and design of geotechnologies will be governed exclusively by the behavior of secondary stresses induced by the anthropogenic invasion and alteration of natural geomechanical behavior in the lithosphere.

Results and discussion

Hybrid natural–technological systems of mineral mining are created with intent to take mineral resources from the lithosphere to develop the technosphere. These activities result in the formation of zones with drastically altered initial properties in the lithosphere, and the sizes of these zones are governed by the size of a mineral deposit. For studying and modeling the consequences of these processes, it is required to image a mineral deposit geophysically, as a critical component of a geosystem in the lithosphere. Using the ideas of Academician V. I. Vernadsky about a living matter and a dull matter, as well as the homeostatic theories, a mineral mining process represents an altered state of the technologically available and geodynamically dull envelope of the geodynamically living body of the planet [2, 3]. The alterations generate a new object in the lithosphere – the manmade subsoil as an integration of geology, technology and economy essences. Models of the structure and evolution of the manmade object are discussed in [4–6]. In these studies, the anthropogenically altered subsoil is identified as a hybrid natural–technological system, including the technological component as the zone of total destruction in the lithosphere (zone of actual mining) and the natural component as the zone of the mining-induced change in abiota and biota of a natural ecosystem within which the technological component exists and functions.

Given such formulation, geophysical changes of this manmade object in the lithosphere can be presented in the terms and definitions of theoretical ecology: destruction of on object in the lithosphere in the course of mineral mining results in distortion (geophysical ‘contamination’) of **natural stress field**; via a transit medium (gravitation field), the ‘contamination’ is transferred to other areas of the lithosphere and sets there as the **secondary stress field** (geophysical ecotone).

This hypothesis means that the system is modeled as an integration of a rheological model of the subsoil area under mining, represented by a structured solid, a physicotechnical model of anthropogenic destruction of this area in the lithosphere, and a finite element model of the quasi-static change in the stress–strain behavior of subsoil within a geophysical ecotone.

The investigation of the first model above, in terms of an infinite solid (an area in the lithosphere) showed that the discontinuity changed the stress and strain fields, and the size of the discontinuity was the factor that governed the pattern of the change. Therefore, the characteristics of the study area in the lithosphere were added with a parameter of the discontinuity size limit B_0. This size limit means that strains induce no failure of material and stresses are fully relaxed at the external boundary of the test area:

$$B_0 = K_r \frac{\sigma_f}{v_{sh} q V_P^2},$$

where K_r is the coefficient of the rate of stress relaxation; σ_f is the excess stress at which geomaterial fails; v_{sh} is the shear strain rate; q is the density of the material; V_P is the P-wave velocity.

The presence of the parameter of a unit discontinuity, such that deformation of geomaterial develops at a constant rate without failure of the material, opens up prospects for finding technologies to control the secondary stress field in rock mass by means of intended separation of actual mining and ground control activities in time.

The developed physicotechnical model of anthropogenically induced destruction in the lithosphere reveals the features of a variable-size manmade void formation in the course of mining and thereby determines secondary stress field conditions. In the framework of the model, we discuss three basic classes of mining technologies: open stoping; caving; backfill mining.

In the first case, all stresses and strains induced at the boundaries of underground voids relax without a telling impact on surrounding rock mass and are well described with classical problems of elasticity.

In the second case, the anthropogenic alteration process runs along a diametrically opposite way until equilibrium is reached between the relaxation value of the lateral earth pressure coefficient in intact rock mass and the bearing reaction of caved and compacted enclosing rocks.

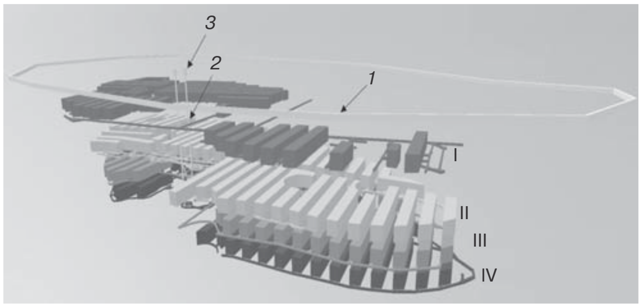

Fig. 1. 3D geomechanical model of geotechnical system in Sol-Iletsk Mine 2:
1 – mining lease boundary; *2* – shafts 5 and 6; *3* – headframes; *I* – flooded Mine 1; *II* –Level –32/–160 m; *III* – Level –185/–240 m; *IV* – Level –240/–270 m

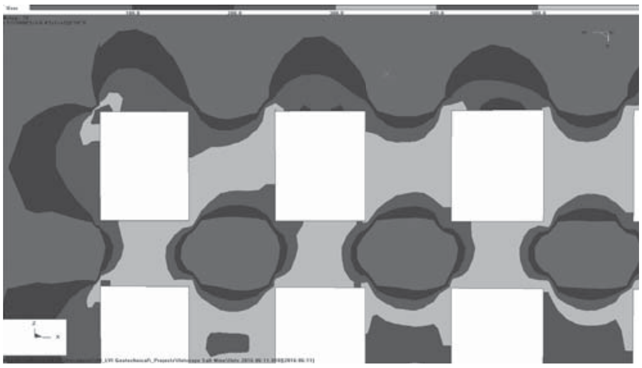

Fig. 2. Zones of tensile strains in enclosing rock salt surrounding rooms on Level -132/-160 m, including floor to depth to 25 m from exposure, found from numerical analysis.
100.0–300.0 (color spectrum) – micro-strain ε_μ

And, finally, in case of backfill, anthropogenic destruction of the lithosphere can be modeled as replacement of an extracted material by an artificial material with preset strength properties and deformation characteristics. With respect to the behavior in relaxation, the model is in-between the two previous models.

The models were constructed for specific geological conditions determined and calibrated for geomechanical modeling of conventional geotechnical systems; namely, Sol-Iletsk Mine (room and pillar); Tashtagol Mine (a site with bulk caving); Internatsionalny Mine (a site with cut-and-fill mining) [7–10]. The models were calibrated using the quantitative evaluation of rock mass in terms of tensile micro-strains determined on a full scale (**Figs. 1** and **2**) [11–14].

The characteristic of the secondary stress field is assumed to be the micro-strain $\varepsilon_\mu = \varepsilon \cdot 10^6$, where ε is the relative tensile strain: $\varepsilon = \Delta L/L$, ΔL is the change in size of the object subjected to deformation, m; L is the initial size of this object, m. Lab-scale tests find that the first cracks are observed in samples of rocks and equivalent materials at the tensile micro-strains $\varepsilon_\mu = 200$, which is a critical value of volumetric fracturing. In the mine, the first tensile fractures are detected at $\varepsilon_\mu \approx 350$, and at ε_μ of 500–800 and higher rock mass undergoes intense deformation, with zones and arches of possible caving. For this reason, the numerical criterion of the external boundary of

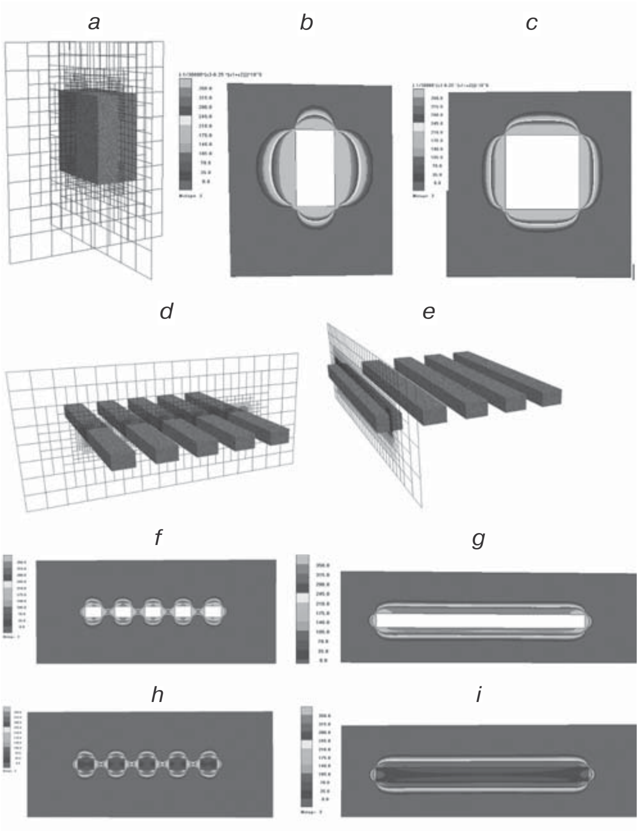

Fig. 3. Tensile straining zones in mineral mining with bulk caving (*a*)–(*c*), room-and-pillar (*d*)–(*g*) and stoping with paste backfill (*h*), (*i*)

the secondary stress field is assumed as $\varepsilon_\mu^k = 350$ which initiates tensile fracturing in rock mass.

During modeling and calibration, the stress–strain patterns induced by anthropogenic alteration of subsoil were determined (**Fig. 3**).

It is seen in Fig. 3 that the key role in configuration and size of the tensile strain zones as well as in the pattern of the micro-strains ε_μ belongs to the shape and size of the manmade discontinuities (stopes). In this connection, it is proposed to perform quantification of the natural stress changes during mining using a new index – the coefficient of influence E_M defined as a ratio of geometrical parameters of interaction components [14, 15]:

$$E_M = \frac{S_m}{S_{\varepsilon\mu}} K_C,$$

where S_m is the area inside the external outline of a mining structure (structural element) in the relevant mining system, m^2; $S_{\varepsilon\mu}$ is the area inside the external outline of the zones of tensile strains with $\varepsilon_\mu = \varepsilon_\mu^k$ at the boundary; K_C is the calibration factor.

The initial stress field variation can be evaluated not only by the estimates of the surface areas of bulk structures but also by the parameters of structural elements in cross-section of a mining system (plane problem). In the latter case, the calculation formula is given by:

$$E_{MP} = \frac{P_m}{P_{\varepsilon\mu}} K_C,$$

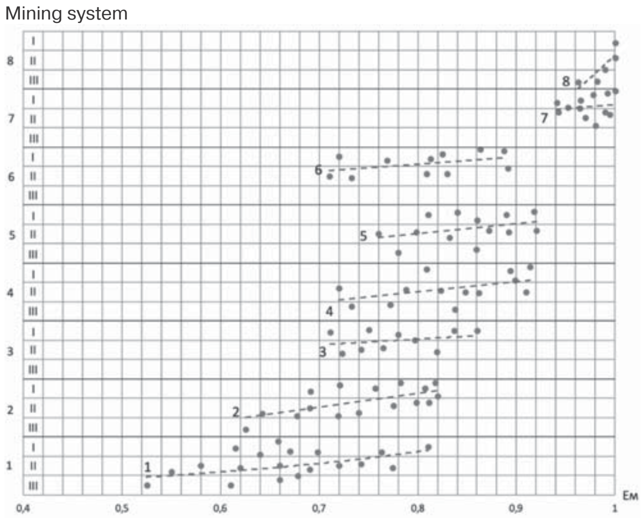

Fig. 4. Diagram of influence exerted by underground excavation geometrics on natural stress field:
1–8 – underground mining systems; *I–III* – rock mass stability categories: *I* – stable; *II* – fairly stable; *III* –unstable

where E_{MP} is the local coefficient of influence; P_m is the external perimeter of a structure in cross-section of a mining system, m; $S_{\varepsilon\mu}$ is the perimeter of the tensile strain zone with the values $\varepsilon_\mu = \varepsilon_\mu^k$ at its boundary.

It is worth mentioning that the local coefficient of influence E_{MP} can be either higher o lower than the coefficient of influence E_M since the patterns of the tensile strain zones are nonuniform in different cross-sections of a mining system.

The calculation formulas are added with the coefficient K_C for calibrating the numerical models and the values of the micro-strains ε_μ obtained from the numerical modeling and physical simulation. The models are calibrated with regard to in-situ testing data obtained in mines using various stress–strain control methods, specifically, the optical study. When the area of the external outline of a tensile strain zone with $\varepsilon_\mu > \varepsilon_\mu^k$ ($S_{\varepsilon\mu}$) and of the external outline of a mine structure, S_m, are determined in mines, $K_C = 1$. If $S_{\varepsilon\mu}$ and S_m are calculated from modeling data, then $K_C = 0.2$–0.9 at overestimated rock strength and $K_C = 1.1$–1.8 at underestimate strength.

We want to emphasize that E_M can never be higher than 1 as the enclosing rock mass surrounding a geotechnical system always contains induced zones of tensile strains. It is found that in case of bulk caving and sublevel caving, E_M varies within the ranges of 0.53–0.81 and 0.62–0.82, respectively, in rock mass having stability categories I–III. In room-and-pillar mining and in cut-and-fill, the ranges of E_M are, respectively, 0.71–0.86 and 0.72–0.92 (rock mass stability categories I–III). In cut-and-fill with paste backfill and in room-and-pillar mining in rock mass of stability categories I and II, E_M ranges from 0.76 to 0.91 and from 0.72 to 0.89. In nature-like mine structures – honeycomb and frame mines, the coefficient of influence varies from 0.94 to 1.0 and from 0.96 to 1.0, respectively (rock mass stability categories I–III).

From the evidence of the in-situ research, numerical modeling, physical simulation and calibration of the numerical models, the influence of geometrics of underground excavations in the conventional and new convergent technologies of underground mining on the rate of change in the natural stress field has been determined (Fig. 4) [14–18].

For each system of mining, the interpolating function is plotted for the coefficient of influence with regard to the stability categories of rock mass, which is a benefit.

Conclusions

The authors have put forward and partway worked out the hypothesis on congruence between the mining-induced secondary stress field configuration and the behavior and magnitude of rock mass anisotropy, which has been experimentally proved during comparison of the mathematical modeling results and in-situ observation data.

The geomechanical models are developed for the conventional geotechnical systems and for the new frame and honeycomb mine structures for the specific geological conditions of mineral mining based on the lab-scale testing data and from the quantitative and qualitative estimates of rock mass inside and outside the influence zone of stoping in operating mines.

The new index is proposed and justified for the quantitative evaluation of change in the secondary stress field during mining – the coefficient of influence, which is a ratio of geometric parameters of interacting elements, namely, the ratio of the external outline area of a mine structure (structural elements) in the conventional mine or in newly developed mine structures to the external outline area of the induced tensile strain zones with the micro-strain values of 350 (which is the value of initiation of the first tensile cracks in rock mass).

Acknowledgment

The study was supported by the Russian Science Foundation, Project No. 19-17-00034.

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