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APPLICATION PROSPECTS FOR MODELS OF EQUIVALENT MATERIALS IN STUDIES OF GEOMECHANICAL PROCESSES IN UNDERGROUND MINING OF SOLID MINERALS

The experience gained in simulation of geomechanical processes in longwalls and development drifts in underground mining of solid minerals using models of equivalent materials is analyzed. The relevance and practical significance of solving problems connected with the study of dynamic geomechanical processes in rock masses of block and layered structure, characterized by deformation and discontinuities are emphasized. The study of such issues in the production environment by analytical methods is very difficult and, in some cases, impossible. The general methodology is proposed for modeling processes in rock masses of block and layered structure based on the developed set of similarity criteria, types of equivalent materials and technical solutions that provide both measurement of static and dynamic stresses and parameters of other physical fields in models of equivalent materials.

Application of this methodology to study regular patterns of change in the dynamic parameters of geomechanical processes in block and layered rock masses under mining-induced transformation of their structural parameters is exemplified.

Keywords: *physical simulation, equivalent materials, block and layered rock mass, dynamic geomechanical processes, similarity criteria, longwalls and development drifts, boundary conditions, concentration stresses, contact conditions.*

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Introduction

There are many practical examples of inefficient control over geomechanical properties of rocks in the solid mineral mining practices worldwide. As a consequence, underground excavations are destroyed, safety and benefits of mines drop, mineral losses grow, while induced accidents and ecological catastrophes are initiated. Amidst the disastrous effects of weak control over geomechanical properties of undermined rock strata, there are sinkholes of the ground surface at the Upper Kama potash–magnesium soil deposit, flooding of salt mines [1], or dynamic sagging of difficult main roof (rock bridges) in coal mining, with huge methane ejections in roadways [2].

Such accidents come into being pretty much due to the lack of the modern knowledge on the physics of the large-scale geomechanical processes that run in the inaccessible rock mass area for direct measurements, the continuously varying parameters f movements and induced fractures (dissection, diagonal joints), or the the parameters of rock pressure in the course of underground mining.

It is worthy of mentioning that the problem aggravates as mining intensifies and, consequently, deformation processes increase in the undermined rock mass [1–6].

Practical experience of using various methods to investigate stress state in undermined rock mass reveals higher capabilities of geotechnical modeling with equivalent materials (EM). Proposed by Kuznetsov [7, 8], the method was used to solve many theoretical and applied problems such as: finding of basic qualitative relationships between rock mass stress state parameters and geological and geotechnical factors; discovery of previously unknown phenomenon of zonal rock disintegration around underground openings [9]; studying of joint deformation of rocks in the immediate and main roofs in longwalls; analysis of general behavior of deformation and failure in stratified undermined rock mass during stoping with various ground control methods; investigation of stress distribution in zones of abutment pressure.

Modern mining in all mineral producing countries features high intensity of operations and transition to deeper levels where stresses are commensurable with strength of rocks, which considerably alters geomechanical behavior of rock mass and, thus, mining conditions. In particular, the mode of deformation and failure of rocks in the main and immediate roof during longwalling changes greatly [10, 11]. Furthermore, roof caving increment reduces as mining depth grows and increases as the advance rate is built.

To illustrate the urgent nature of the required improvement in research and modeling with EM, we are going to discuss the current situation in coal mining in the world. In extraction of the most profitable reserves from gently dipping coal seams 1.4–6 m thick, coal mines prefer the mining systems with coal pillars left between mined-out longwalls. This mining system is the one planned and applied without any alternative in all promising mines in the Kuznets Basin, in longwalling in gently dipping coal seams. I this case, with pillars and high rates of advance in longwalls, long spans of difficult roof appear and cave vigorously, with huge methane emissions from mined-out voids to operating longwalls and development drifts [2].

Considering actual situation and development prospects of geotechnologies, one of the main trends in improvement of modeling with equivalent materials is simulation of intensive dynamic and energy-exchange processes in rocks, as well as creation of methods and means for reliable recording of the parameters of these processes with no distortion of the initial and current geomechanical situations.

Procedure for modeling processes in rock mass of block and layered structure

The long-continued research at the Saint-Petersburg Mining University [7, 8, 10, 12–16] show that this urgent and critical problem for the science, technology and society is only possible to solved with new types of EM and engineering solutions intended to provide similarity of dynamic and energy exchange processes in the model, as well as with efficient integration of physical simulation and computer modeling methods in their joint testing.

Experience of the conventional modeling with EM [7, 8, 17–19] demonstrates that the known equivalent materials are short of the required similarity criteria despite many components involved. For example, formulations for wide range of EM, based on more than 11 fillers and 13 binders [7. 8] mostly reproduce solely strength similarity. As Russian and foreign researchers select formulation of EM with regard to some one similarity criterion, sometimes, even without its exact implementation [20, 21].

Developed at the Saint-Petersburg Mining University, the methodology of modeling dynamic geomechanical processes in block and layered rock masses under solid mineral mining with EM (**Fig. 1**) is a set of coherent theoretical and engineering solutions based on new-generation equivalent models, satisfying the integrated similarity condition and ensuring reproduction of strength and deformation characteristics of different rocks in a wide range of linear modeling scale.

The backbone thesis of the methodology was the reliable similarity of the dynamic processes being modeled based on the general energy conservation law or the first law of thermodynamics with regard to the irreversible and nonlinear behavior of physical processes in the course of mining [22]:

$dU = TdS + SdT + \sum X_i dx_i + \sum x_i dX_i$,

where dU is the change in the internal energy U of rock mass; T is the temperature; dS is the change of the entropy S; dT is the temperature change; X_i are the external thermodynamic forces; dx_i is the change in thermodynamic coordinate x_i ; dXi is the change of X_i; TdS is the inflow of the external heat energy due to the anthropogenic factors; SdT is the generated heat energy, e.g., during oxidation; $\sum X_i dx_i$ is the mining-induced work of the external thermodynamic forces X_i; $\sum x_i dX_i$ is the work of rocks mass for changing X_i.

Similarity in the analysis of geomechanical processes without inflow of external heat energy requires that all components of energy balance in the rock mass element model are proportional, including potential energy in the earth's gravitational field: $W_{pot} = mgh$, kinetic energy $W_{kin} = mv^2/2$, elastic energy $W_{el} = \sigma\varepsilon V/2$ and heat energy $W_{heat} = cm\Delta T$, where g—gravitational acceleration; h—height of the element relative to the lower boundary of the model; m, v, σ, ε, V, c and ΔT—respectively, mass, velocity, mechanical stress, relative strain, volume, heat capacity and temperature variation of the element.

After the formulas are transformed using the known relations in the theory of similarity and dimensions [7], the resultant system of equations for transit factors, subject to fulfillment, ensures the wanted proportionality:

$\alpha_a = 1$;

$\alpha\varepsilon^2\ \alpha_E / \alpha_l = \alpha\rho\alpha_l$;

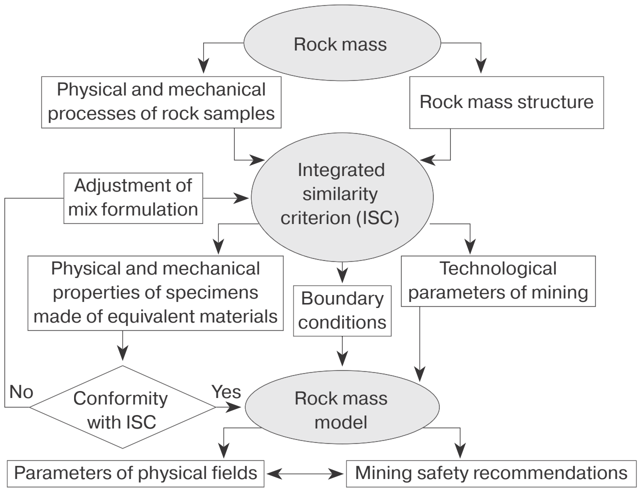

Fig. 1. Structure diagram of the new methodology for modeling dynamic geomechanical processes in block and layered rock masses with equivalent materials

$\alpha\rho\ \alpha_c\ \alpha\Delta_T = \alpha\rho\alpha_l$,

where α is the transit factor (the subscripts stand for the length l, density ρ, elastic modulus E, acceleration a, heat capacity c, etc).

The solution of this system shows that in a general case, given that the integrated similarity criterion $\sigma_m = \alpha\rho\ \alpha_l\ \sigma_n\ (\varepsilon_m)$, connecting the model stresses σ_m with the preset dependence of the natural stresses σ_n and relative natural strains ε_n, as well as when $\alpha\Delta_T = \alpha_l/\alpha_c$, ensures the uniform transition coefficient for the deformation modulus, stresses and main specific components of the energy balance: $\alpha_E = \alpha\sigma = \alpha_{W\text{pot. sp}} = \alpha_{W\text{kin/sp}} = \alpha_{W\text{el.sp}} = \alpha_{W\text{heat.sp}} = \alpha\rho\ \alpha_l$, and provides equality of acceleration and relative strains in the model, similarity of elastic wave processes, equal scales of velocities and times in the event when frequencies of dynamic processes are amplified by $1/(\alpha_l)^{0.5}$ times.

In a special case of similarity ensured only for strength characteristics and with only gravitational acceleration g included, the similarity criterion acquires the conventional form presented by Kuznetsov [7,3, 4]: $N_m / \gamma_m l_m = N_n / \gamma_n l_n = K$, where N_i is the force characteristic with the dimension of force, divided by the area; γ_i is the specific weight; l_i is the linear size with the subscripts for the nature (i = n) and model (i = m), K is a dimensionless number, or the constitutive similarity criterion.

In order to develop EM with such physical and mechanical parameters that satisfy the integrated similarity criterion, parameters of different type rocks were analyzed. The input data were the uniaxial compression test results of more than 500 samples of 20 types of rocks (coal, sandstone, siltstone, argillite, etc.) from different research works [22, 23, 16]. The value of $W_{el.sp}$ was calculated using standard test results: R_{com}, E_{el} in the studies by Rzhevsky, Kartashov and other researchers: $W_{sp} = R^2_{com} / 2E_{el}$ [12], while these parameters for EM were determined from the similarity of the maximum accumulated specific elastic energy: $W_{el.sp.m} = \alpha\rho\alpha_l\ W_{el.sp.n}$.

The obtained data were used to develop EP with such physical and mechanical parameters that ensure fulfillment of the similarity conditions for a wide range of rocks.

During justification of energy parameters, the formulations of EM were varied using two types of finely disperse fillers (quarts sand and rubber chips) and four types of binders: silicon resin, resins DEG-1 and ED-20, and mineral wax. As a result, five types of EM with different strength, deformation and energy characteristics were obtained.

With regard to the energy similarity coefficients, for the scales in the range from 1:300 to 1:10, the experimental points and the related curves plotted for EM were transposed to the distribution field of energy intensities for rocks in the coordinates W_{sp}—R_{com}.

By way of illustration of the aforesaid, **Fig. 2** shows the relationship between the accumulated specific elastic energy W_{sp} and the uniaxial compression strength R_{com} for the EM type P-Ea (quartz sand+epoxy-aliphatic resin+poly ethylenepolyamide+glicerin).

From the analysis of the obtained results, the energy similarity conditions are best satisfied by the materials made of epoxy-aliphatic resin) DEG-1) and finely disperse quart sand; this material reproduces almost all main types of rocks with R_{com} = 1–400 MPa in the selected scale range (1:300–1:10) [13].

Reproductive modeling of dynamic events in rocks is ensured by EM with similar specific energy accumulations both in compression and in tension. It is recommended to estimate these parameters, as well as the brittle failure criteria using the ratio of uniaxial compression and tension strengths: $X_{str} = R_{com}/R_{ten}$. For most solid rocks, X_{str} is assumed as 10 from the actual range from 5 to 30 [23]. More accurate reproduction of dynamic events requires plotting the deformation curve in σ–ε both in post-limiting and pre-limiting domains.

Formation of different boundary conditions in the tests of the models was ensured by the dedicated automated system composed of 32 adjustable loading elements with the total force of 96 kN. The system using special program set nonuniform load distributions at the model boundaries, from modes of preset loads to modes of preset strains.

Concerning the system operation, in conformity with the required mode, from a personal computer each force element is assigned the required load to fit the value of the outlet signal of the strain gauge transducer. The amplifier unit supplies the preset mode-specific voltage to the control winding of the dc motor. The motor, via the built-in gear system, actuates the worm gear which transforms rotational motion to the translational motion of rod. The latter, through the force-measuring strain-gauge beam and loading plate, directly act on the model. The automatic control system compares the outlet signal of the transducer with the preset signal. In case the signals are equal, the voltage is cut off and the motor is shutdown.

The long-term use of the automatic control shows that the discussed program and equipment make it possible to set loading diagrams by hand, by steps and in unattended mode, as well as allows their self-adjustment. The system operates both with preset loads and preset strains.

In physical simulation with EM, the most important information on geomechanical processes in block-hierarchical [14] and layered rock masses can be obtained from direct stress measurements using sensors. On the other hand, sensors arranged in the models changed their

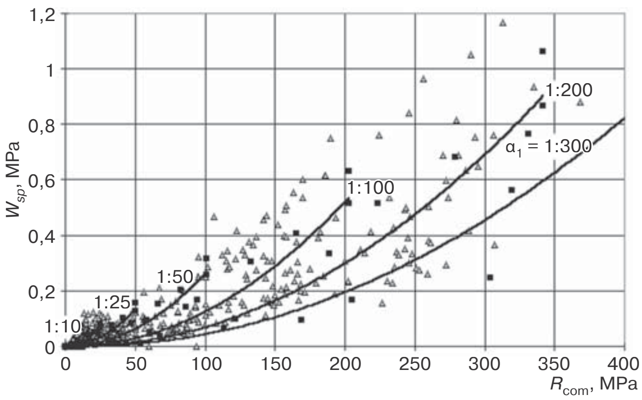

Fig. 2. W_{sp}–R_{com} for EM type P-Ea

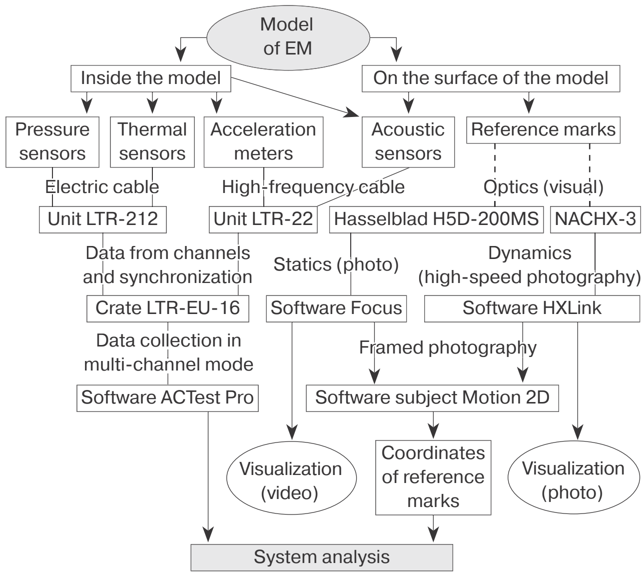

Fig. 3. Basic diagram of the integrated information and measurement system in modeling with EM

stress–strain state and failed to maintain reliable measurement of static and dynamic stresses [15].

For solving this problem, the procedure is developed [22]; it allows determining efficient parameters of the transducer with regard to the system of inequalities below:

$$E_t > E_{EM};\ h/d < 0.1–0.15;\ d_{se}/d < 0.6–0.7;\ d_{se} > 10d_3 \quad (1)$$

where E_t and E_{EM} are the deformation moduli of the transducer and material, respectively; h/d is the thickness/diameter ratio of the transducer; d_{se} is the diameter of the sensitive element; d_{gr} is average grain size of the material.

Considering the inequalities above, the transducer MDG-3 is designed [16] and effectively used to measure static and dynamic stresses in the models of EM.

The tests of the model find that the measurement accuracy of the transducer MDG-3 is mostly influenced by such factors as: absolute sizes of the model, nonuniformity of EM, selectivity, temperature, contact conditions, orientation of the transducer, the ratio E_t/E_{EM}, creep and plasticity strains, and frequency characteristics of measured stresses. In stress measurements in the frequency range from 0 to 500 Hz, total relative error is not higher than 15%

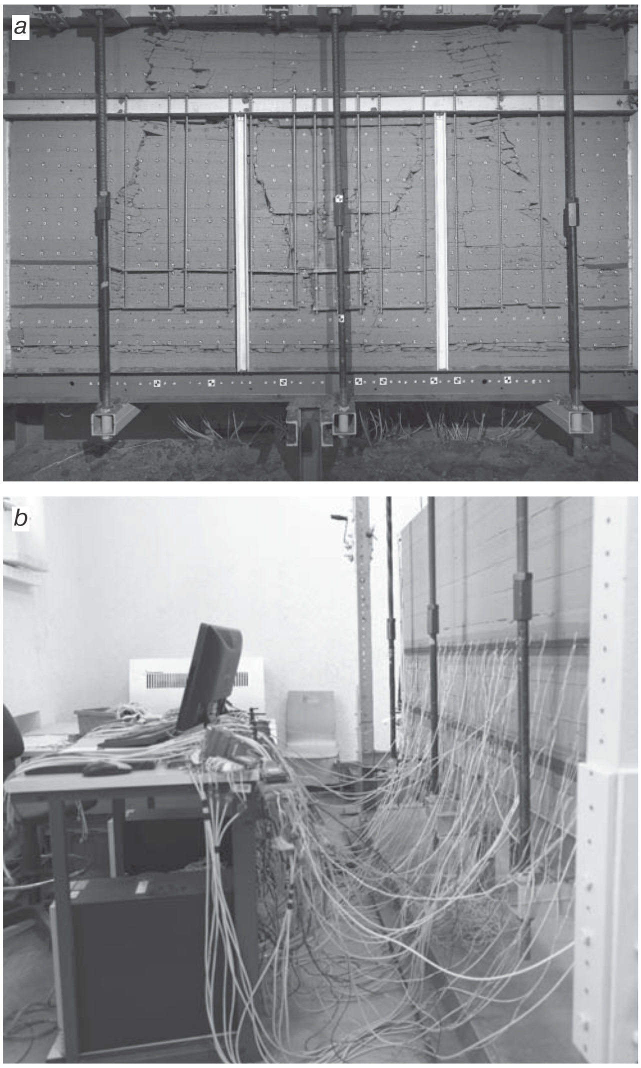

Fig. 4. General view of the model for studying dynamic processes in rock mass during destressing of pillar in mined-out void

while absolute error of measurement is 0.0006 MPa. The structural layout of the integrated system for taking and interpreting data from sensors of stresses and other physical fields in the model of EM is demonstrated in **Fig. 3**.

Using the developed methodology of modeling with EM, some significant scientific results have been obtained, namely:

- mechanisms of deformation, fracture and displacement of structured elements in undermined rock mass within wide range of velocities and accelerations under the action of gravity forces and accumulated elastic energy; the revealed mechanisms make it possible to include dynamic parameters of physical and geophysical fields in assessment of possible hazardous effects of dynamic phenomena;
- qualitative and quantitative dependences on normal vertical and shear stresses in the centers of different hierarchy blocks on the values of weighted average cohesion and internal friction angle of fillers in joints between blocks;
- regular patterns of redistribution of major stresses in rock blocks in mined-out areas of longwalls during main roof caving, as well as dependences of these stresses on geological and geotechnical factors;
- dynamic processes in undermined rock mass during relaxation of pillars in mined-out voids from higher stresses in the course of undermining and as function of yielding during hydraulic fracturing of the pillars (**Fig. 4**);
- mechanism of time-and-space formation of water-conductive fractures and cleavages in water-tight strata at different stages of potash mining;
- modeling procedure for determination of tectonic stresses by readings of multi-component downhole deformometers;
- procedure to assess adequacy of modeling dynamic gemechanical processes with equivalent materials depending on the accuracy of reproduction of structural geometry of rocks mass, physical and mechanical characteristics of rocks, initial and boundary conditions and precision of the parameters of physical fields in the models.

Conclusion

Generally ineffective ground control, resulting in man-made disasters, unsafety of mining, higher mineral loss and other aggravations, is directly or indirectly connected with the lack of sufficient knowledge on the physical nature of large-scale geomechanical processes in rock mass areas inaccessible for direct measurements, in transition to deeper level mining, under high mining intensity, or in extraction of panels with geological disjunctive dislocations.

At this conjuncture in underground solid mineral mining, the most difficult object to study and forecast is rock mass of block or layered structure, characterized by deformation, discontinuities and permanently varying stress state parameters. Meeting of these challenges is associated with application and improvement of the developed methodology of modeling with EM.

This methodology is based on the new-generation equivalent materials which fulfill the integrated similarity criterion and enable reproduction of structural, strength and deformation characteristics of different rock types within wide range of linear scales of modeling. The set of developed procedures, equipment and programs makes it possible to reproduce boundary conditions for complex geotechnical situations and to process signals from sensors of studied physical fields. All in all, the methodology allows obtaining sufficiently reliable quantitative and qualitative information on parameters of geomechanical processes in block and layered rock masses in the course of their structural transformation under the impact of underground mining.

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