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APPLICATIONS OF EQUIVALENT MATERIAL MODELS IN GEOMECHANICAL PROCESS STUDIES IN UNDERGROUND SOLID MINERAL MINING

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Introduction

There are several real-world instances of ineffective control over the geomechanical characteristics of rocks in solid mineral mining operations across the globe. As a result, subterranean excavations are ruined, mine safety and benefits decline, mineral losses increase, and accidents and ecological disasters are brought on. Sinkholes at the Upper Kama potash-magnesium soil deposit, flooding in salt mines [1], dynamic sagging of challenging main roofs (rock bridges) in coal mining, and massive methane ejections in roads [2] are just a few of the catastrophic consequences of poor control over the geomechanical properties of undermined rock strata.

The physics of the large-scale geomechanical processes that operate in the inaccessible rock mass area for direct measurements, the constantly changing parameters of movements and induced fractures (dissection, diagonal joints), or the parameters of rock pressure during underground mining are the main causes of these accidents.

It is important to note that the issue gets worse as mining gets more intense, which leads to an increase in the undermined rock mass's deformation processes [1–6]. Higher capabilities of geotechnical modeling with equivalent materials (EM) are revealed by practical experience utilizing various approaches to examine stress condition in undermined rock mass. The technique, which was first proposed by Kuznetsov [7, 8], was used to solve a number of theoretical and practical issues, including: determining the fundamental qualitative relationships between rock mass stress state parameters and geological and geotechnical factors; discovering the hitherto unidentified phenomenon of zonal rock disintegration around underground openings [9]; examining the joint deformation of rocks in the immediate and main roofs in longwalls; analyzing the general behavior of deformation and failure in stratified undermined rock mass during stopping with different ground control techniques; and examining the distribution of abutment pressure zones.

The geomechanical behavior of the rock mass and, consequently, mining conditions are significantly altered by the high intensity of activities and shift to deeper levels where stresses are commensurate with the strength of the rocks in all mineral-producing nations. Specifically, during longwalling, the primary and immediate roof's rock deformation and collapse modes undergo significant modifications [10, 11]. Additionally, roof caving increases as the advance rate is built and decreases as mining depth increases. We will talk about the current state of coal mining worldwide to highlight how urgently research and modeling with EM need to be improved.

Coal mines use mining systems with coal pillars left between mined-out long walls in order to recover the most profitable reserves from gently dipping coal seams 1.4–6 m thick. In all promising mines in the Kuznets Basin, this mining system is the one that is planned and implemented without any alternatives for longwalling in gently dipping coal seams. In this instance, vast spans of challenging roofs emerge and cave violently due to pillars and high rates of longwall advancement, along with massive methane leaks from mined-out voids to operating longwalls and development drifts [2].

One of the primary trends in improving modeling with equivalent materials, taking into account the current state of geotechnologies and their potential for development, is the simulation of intense dynamic and energy-exchange processes in rocks, as well as the development of techniques and means for accurately recording the parameters of these processes without distorting the initial and current geomechanical situations.

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

The ongoing research at Saint-Petersburg Mining University [7, 8, 10, 12–16] demonstrates that the only way to solve this pressing and crucial issue for science, technology, and society is to develop new EM and engineering solutions that are meant to provide similarity of dynamic and energy exchange processes in the model, as well as to effectively integrate computer modeling and physical simulation techniques in their joint testing.

Despite the numerous components involved, experience with traditional modeling with EM [7, 8, 17–19] shows that the known equivalent materials fall short of the necessary similarity criteria. For instance, formulations for a variety of EM based on over 11 fillers and 13 binders [7, 8] primarily replicate strength similarities. Researchers from Russia and other countries choose EM formulations based on a single similarity criterion, sometimes even without its precise application [20, 21].

The methodology for modeling dynamic geomechanical processes in block and layered rock masses under solid mineral mining with EM (Fig. 1) was developed at the Saint-Petersburg Mining University. It is a set of logical theoretical and engineering solutions based on new-generation equivalent models that satisfy the integrated similarity condition and guarantee reproduction of strength and deformation characteristics of various rocks in a wide range of linear modeling scale.

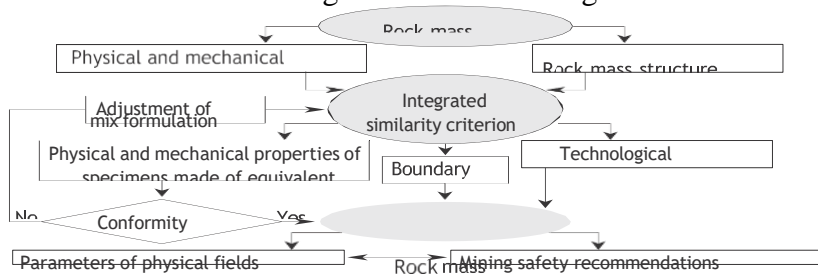


Fig. 1. Structure diagram of the new methodology for modeling dynamic geomechanical processes in block and layered rock masses with equivalent materials

where $\alpha \rho a \alpha \Delta T \alpha \rho \alpha l$ 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 $\alpha \rho \alpha l$ (), connecting the model stresses with the preset dependence of the natural stresses and relative natural strains, as well as when $\alpha \Delta T \alpha l$, ensures the uniform transition coefficient for the deformation modulus, stresses and main specific components of the energy balance: E

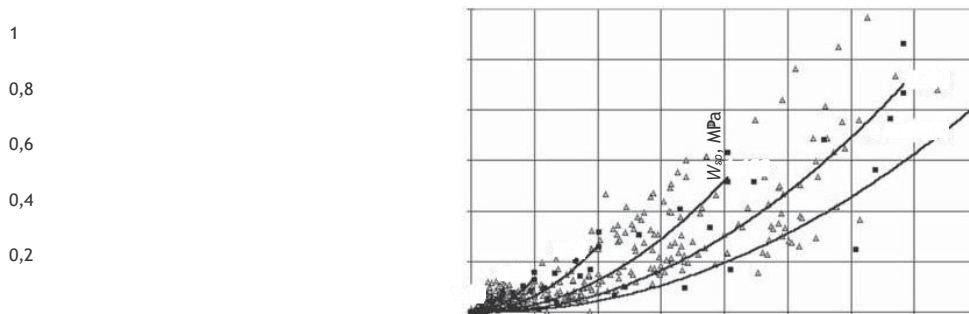
$W_{pot. sp} W_{kin/sp} \alpha W_{el.sp} \alpha W_{heat.sp} \alpha \rho l$, and provides equality of acceleration and relative strains in the model, similarity of elastic wave processes, equal scales of velocities and times in the event when frequencies of dynamic processes are amplified by $1/(l)^{0.5}$ 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]: $N / \gamma l^3 = N' / \gamma' l'^3 = K$, where N is the force characteristic with the dimension of force, divided by the area; γ 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: $R = E \epsilon$ in the studies by Rzhnevsky, Kartashov and other researchers: $W_{sp} = R^2 / 2E_e$ [12], while these parameters for EM were determined from the similarity of the maximum accumulated specific elastic energy: $W_{el.sp.m} = \alpha \rho \omega l W_{el.sp.n}$.

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 (quartz 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 $W_{sp} - R$. 1,2



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 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 $R = 1-400$ 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: $X_{str} = R / R_{ten}$. 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 $\sigma - \epsilon$ 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

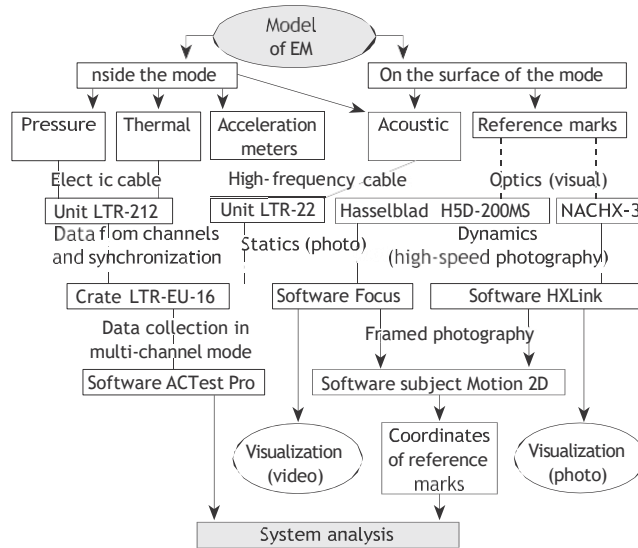


Fig. 3. Basic diagram of the integrated information and measurement system in modeling with EM

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:

$E_t > E_{EM}$ $h/d < 0.1-0.15$; $d/d < 0.6-0.7$; $d > 10d$ (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 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.

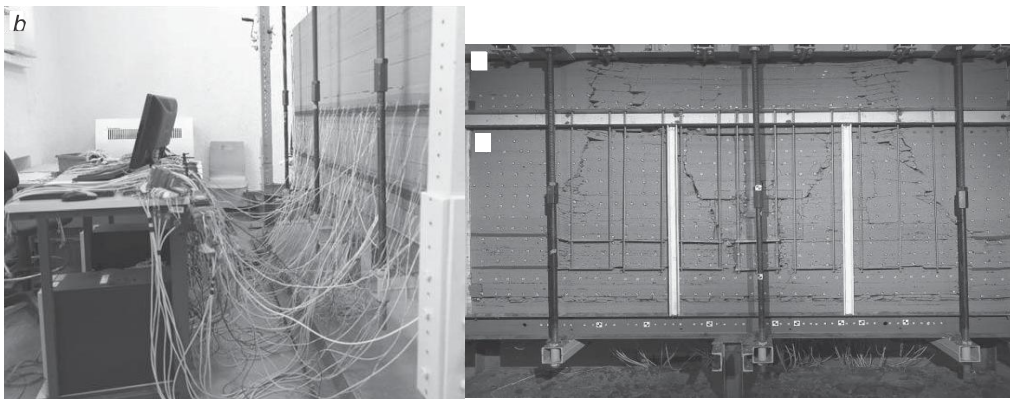


Fig. 4. General view of the model for studying dynamic processes in rock mass during destressing of pillar in mined-out void

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 geomechanical 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 speaking, inadequate knowledge of 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 the extraction of panels with geological disjunctive dislocations is directly or indirectly linked to ineffective ground control, which leads to man-made disasters, unsafe mining, increased mineral loss, and other aggravations. The rock mass of block or layered structure, which is marked by deforestation, discontinuities, and constantly changing stress state characteristics, is now the most challenging object to investigate and forecast in deep solid mineral mining. Applying and refining the created modeling methodology with EM is linked to overcoming these obstacles. This approach is based on new-generation equivalent materials that meet the integrated similarity criterion and allow for the replication of various rock types' structural, strength, and deformation properties across a broad range of linear modeling scales. It is feasible to replicate boundary conditions for intricate geotechnical scenarios and to process signals from sensors of physical fields under study thanks to the collection of developed methods, tools, and software. Overall, the methodology enables the acquisition of adequately trustworthy quantitative and qualitative data on the parameters of geomechanical processes in block and layered rock masses during their structural transformation under the influence of underground mining.

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