Procedure for lab-scale strength and failure testing of physical models of frame mine structures

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Abstract: Operation of any mine, including frame structured mines, alters the stress–strain behavior of enclosing rock mass. The laboratory research requires a plan and a procedure, with description of data acquisition methods (monitoring of strength and deformation characteristics of physical models of the frame mine structure). The implemented laboratory tests used the specially manufactured physical models, a hydraulic pressing machine meant for simulation of strata pressure, as well as a monitoring system including acoustic emission converters and strain gauges. The equipment allows getting an overall picture and enables the stress–strain analysis in a unit block using the theories of similarity and dimensions to understand the influence exerted by the shape, size and arrangement of mined-out stopes on enclosing rock mass stability in case of the frame mine structure.

1. Introduction – the goal of the study

With a view to modelling initiation and growth of the secondary stress field in rock mass, the authors have selected the conventional systems of underground mining [1-4], as well as two brand-new mine design solutions (a frame mine structure and a honeycomb mine structure) [5, 6] justified within Russian Science Foundation R&D Project No. 19-17-00034.

The general research methodology is based on the concept that geomechanical safety of underground mining is connected with abatement of the effects caused by manmade destruction on the dynamic structure of lithosphere. The review of the underground mining technologies resulting in formation of a manmade destruction zone in the subsoil and on the surface [7, 8], reveals a common interference feature of geomechanical and geotechnical evolution—mineral mining in the manmade destruction zone and protection of this zone from the geomechanical disturbance aftereffects in adjacent areas should always proceed synchronously [9-15].

In this respect, stoping operations obligatory include activities aimed at dynamic equilibrium control and safety in mines. In mining with conventional technologies with extensive ground control and disposal of waste, the price for the geomechanical safety of mining is initiation of hazardous stress zones in enclosing rock mass and loss of high-quality reserves which have to be left in pillars of different size and various purpose. Moreover, when enclosing rocks bear fluids (water, oil, brines or gas), mines are never safe from inflows and the related consequences.
2. Materials and methods

The advance creation of a supporting frame (frame mine structure [16, 17]) to envelope a future mining area offers a real opportunity to combat the local geomechanics/geotechnology interference mentioned above.

In this case, during initiation and growth of the manmade destruction zone in the lithosphere, the processes of mining and mine protection from geomechanical disturbance aftereffects are de-synchronized, which improves mining safety and efficiency.

This provision constitutes the contents of the geomechanical idea of nature-like geotechnology. This idea consists in the advance isolation of the manmade destruction zone from the field of secondary alterations in the geomechanical behaviour of rock mass by means of implementation of actual mining and mine protection from geomechanical disturbance aftereffects at different times, not simultaneously. From the analysis of geological and geotechnical conditions of mining, the required parameters are determined from the primary models of different mining systems. Thus, the input modelling parameters are assumed as the height/width of mined-out and stoping areas and the thickness of ore body. In rock mass enclosing the geotechnical system of a mine, the secondary stress field is formed due to mining. The structure of the secondary stress field is governed by the size of the mine design elements, by the physical and mechanical properties of rocks, natural stresses, quality of rocks and ore, and by other factors. The envelope of the mine includes structural elements of stopes, different-purpose pillars, mined-out voids, etc. Thus, we need a physical model of frame mine structures to study physical and mechanical properties of rock mass and to evaluate advantages of the frame structures over the open stoping systems currently in use.

Modelling as a method of laboratory testing enjoys wide application recently in the analysis of strata pressure, ore drawing processes and blast effects. The theories of similarity and dimensions define conditions to make different events precisely or approximately similar [14]. In the similarity theory, this problem is solved by correlation of equations of constraints, i.e. equations which describe a certain event.

The theory of dimensions analyses sizes of representative physical volumes of this event. For this reason, it is advisable to determine the similarity criteria from the analysis of the constraint equations. Yet, there are events with the unknown equations of constraints. And the dimensional analysis, especially at an early stage, is the only way of finding functional relations to describe a certain event. The first and the second theorems of the similarity theory determine properties of events but indicate no method to find out if the compared events are similar. The third theorem reads, “Events are similar if they take place in geometrically similar systems and obey the same equations of constraints such that the monovalued attributes in these equations belong to numerically constant ratios and the criteria composed of these monovalued attributes are equal to each other.”

Thus, the aforesaid can serve a framework for the conditions to be obeyed for the events to be similar:
• Geometrical similarity of systems and similarity of alphabetic notations in equations of constraints;
• Similarity of single-valuedness conditions;
• Similarity indicators composed of constant values included in the single-valuedness condition for the monovalued attributes are equal to one.

The latter requirement is satisfied by the equality of criteria composed of monovalued attributes. Such criteria are called monovalued or constitutive as their invariance is included in the conditions of similarity of events. It should be added that the conditions of single-valuedness or monovalued attributes should define geometrical characteristics of events, numerical values of physical constants, as well as initial and boundary conditions. In case of complicated mechanical processes (phenomena induced by confining pressure, etc.), it is difficult to construct a differential equation.

A simpler way of finding the required criteria and constants of similarity is using Newton’s law of dynamic similarity in combination with the dimensional method. Only the complete and correct record of the main physical factors participating in a process or an event under analysis can ensure the satisfactory solution of the set problem.
3. Description of laboratory testing equipment and methodology

The primary aim of the laboratory research is to determine the influence exerted by the shape, size and arrangement of mined-out voids on the stability of a unit block. The test subject is a physical model made of an equivalent material—a limestone-sandstone mixture. The pressing tests involve cubic models with an edge 20 cm long.

The similarity criterion is assumed to be the strength–density ratio $\Delta \sigma$ of the frame mine structure (1):

$$\Delta \sigma = \frac{\gamma}{\sigma}$$ (1)

where: $\gamma$ is the density of material, kg/cm$^3$; $\sigma$ is the compression strength, N/cm$^3$.

On the basis of the modeling objectives and goals, each series of tests consisted of 4 physical models of mine frames enclosing four rectangular stopes, with different combinations of the frame thickness (Figures 1 and 2):

a) Ore recovery is 0.3 and 0.7 from the stopes and frame, respectively;

b) Ore recovery is 0.51 and 0.49 from the stopes and frame, respectively;

c) Ore recovery is 0.36 and 0.64 from the stopes and frame, respectively;

d) Ore recovery is 0.42 and 0.58 from the stopes and frame, respectively.

![Figure 1. Geometrics of the frame mine structure models.](image)

![Figure 2. Physical forms of the frame mine structure models: 1 – roof of the mine frame; 2 – internal partitions; 3 – outer frame.](image)

![Figure 3. Hydraulic pressing machine P-125.](image)

The density of the material was calculated for each frame model, and the compression strength was determined in the tests of each sample of equivalent material using hydraulic pressing machine P-125 (Figure 3). The pressing machine is meant for the static tests of standard rock samples by compression
force of 125 t and consists of a loading facility and a control board. The Research Center for Geomechanics and Convergent Technologies in Mining at the NUST MISIS’s College of Mining, in the framework of Russian Science Foundation R&D project, has designed an integrated installation for physical and optical modeling of geomechanical processes in stress fields in the course of mineral mining using present-day geotechnologies, including hydraulic pressing machine P-125.

The strength and deformation characteristic of the physical models of the frame mine structures are determined on two laboratory pressing test benches (Figure 4). Lateral compression was created by two hydraulic jacks capable to generate pressure up to 10 MPa (Figure 4a).

![Figure 4. Laboratory benches for (a) three-axial compression tests and (b) uniaxial compression tests for studying strength and deformation characteristics of physical models.](image)

Control of deformation and failure of structural elements in the physical models was executed by acoustic emission converter A-Line DDM-1 including multi-channel modular-structure systems of different AE data accumulation and processing, with serial high-speed wireless digital data link. This equipment is on the register list of measurement instrumentation of Russia. Such AE instrumentation is composed of a central computer (data concentration and processing) and some measurement channels of series-connected modules of AE data acquisition and processing (AE modules). Amplification of AE signals, data cleaning, digitalization, recording and processing, as well as determination of AE parameters is implemented in the AE module arranged nearby the AE converter directly on the unit under testing. The baseline configuration of the test facility includes:

- Data collection and processing Ethernet Box compatible with any computer (laptop);
- Module ALM-01 with magnetic holder;
- Acoustic emission converter GT200 (Figure 5);
- Magnetic holder for AE converters;
- Cable UTP (70 and 30 m) on a drum;
- Terminator (end plug);
- Laptop and software.

![Figure 5. Acoustic emission converter GT200.](image)
Figure 6. Scalable modular architecture QMBox.

Figure 7. Constantant foil strain gauge.

Automation of the lab test bench is represented by scalable modular architecture QMBox (Figure 6) capable to perform multichannel measurements and analog and digital input/output. Data from thermal couples, heat-variable resistors, strain gauges and other sensors are input using special AD converters capable of data acquisition. Foil strain gauges employed in the tests are shown in Figure 7.

4. Conclusions

The authors have developed and presented the test procedure for strength and deformation characteristics of equivalent material models under the influence of shape, size and arrangement of mined-out voids for the frame mine structure and different convergent geotechnologies. The validated equipment for the experimentation includes hydraulic pressing machine P-125, AE converter A-Line DDM-1, scalable modular architecture QMBox; foil strain gauges, and other.

In the uniaxial and triaxial compression tests, the limit stress of the physical models of frame structures was changed in the ranges of 6-5 and 8-20 MPa, respectively.

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