Advancing of the geomechanical forecasting system and substantiation of mining at rockburst hazardous deposits

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Abstract. The paper presents the main approaches and their advancing for the systems of rock mass stress-strain state forecasting during mining of adjacent rockburst hazardous deposits. Such systems based on the original Sigma GT software are used at several Russian mining companies which develop solid rock deposits, prone to brittle fracturing and undergoing the gravitational-tectonic stress-strain state. At that, the mining-induced impact on the rock mass is accompanied by occurrence of dynamic rock pressure. The geomechanical situation forecast systems have been applied directly at mining companies for more than 10 years and have shown their high efficiency. The efficiency is associated primarily with the operative calculation of stress-strain state in case of exacerbations of the geodynamic situation and the potential consideration of various mining options in order to reduce stress concentration and give recommendations for supporting and unloading measures in mine workings. In addition, the Sigma GT software is used in annual and long-term mining planning. Initially, such systems were developed for individual rockburst hazardous mining blocks, and their efficient operation time was limited to a 3-5 year period, that is, the block mining time. Further on, taking into account the needs of companies, the systems began to include a whole deposit or even several deposits. Being applied, the system is constantly developed and advanced and adapted to specific conditions and tasks. The most actual tasks are combination of the results of stress-strain state modeling with seismic monitoring data; creation of a hierarchical system of interconnected multiscale volume models; more complete consideration of structural heterogeneities of the rock mass and development of a recommendation block for safe mining operations, taking into account the geomechanical situation forecast data. The solution of these problems is considered on the example of a section of the Khibiny apatite arc, within which underground and open mining is carried out in the zone of mutual influence.

1. Introduction
To date, there is a worldwide steady trend towards deepening the mining operations. The development of mineral deposits at great depths inevitably entails deterioration in geomechanical conditions associated with an increase in the stresses acting in the rock mass [1-3]. This problem is especially acute for mining companies that carry out mining operations in hard rock deposits prone to brittle fracture in the gravitational-tectonic type of stress-strain state. Quite often the mining-induced impact on the rock mass at such deposits is accompanied by a dynamic rock pressure [4-6].

In the current conditions, an increasing number of mining companies that develop deposits prone to and hazardous to rockbursts start using systems of geomechanical forecasting and justification of mining operations. Several Russian mining companies apply such systems based on the original Sigma
GT software developed at the Mining Institute Kola Science Center of the Russian Academy of Sciences (Apatity, Russia).

The use of geomechanical forecasting systems directly at mining companies for more than 10 years has shown their high efficiency, associated, first of all, with the promptness of calculating the stress-strain state during exacerbation of the geodynamic situation and the possibility of considering various options for mining operations in order to reduce the stress concentration and issue recommendations and unloading activities in mine workings. In addition, the Sigma GT software is used for annual and long-term planning of mining operations [7-8].

Initially, such systems were developed for individual rockburst hazardous mining blocks, and their efficient operation time was limited to a 3-5 year period, that is, the block mining time. Further on, taking into account the demands of the companies, systems began to include a whole deposit or even several deposits. Being applied, a system is constantly developed and advanced and adapted to specific conditions and tasks.

2. General methodology of geomechanical forecasting using the Sigma GT software

The successive approximation method is the basis for the prediction of the stress-strain state of a rock mass section. In accordance with this method, first of all, a number of 3D small-scale tasks reflecting the main mining-geological and mining-engineering features of the simulated space is formulated and solved. The sequence of operations at the first stage (small-scale modeling) is as follows:

- determination of the parameters of a small-scale computational domain corresponding to a lithological block;
- development of an engineering-geological and numerical model;
- substantiation of the boundary conditions and the sequence of solving a number of 3D tasks of rock mechanics to determine the main factors influencing the regularities of the primary stress field formation in the rock mass including the mineral deposits;
- comparison of the calculation results with the data of other (direct or indirect) methods for assessing the initial stress state of the rock mass;
- study of the regularities of the secondary stress field formation in the vicinity of previously worked out and designed for mining excavations included in the modeling area;
- carrying out, if necessary, the correction of the model and repetition of calculations.

The second stage (large-scale modeling) includes:

- determination of the influence area of the maximum achievable volumes of excavations both by underground and open mining methods when comparing the corresponding variants of small-scale modeling;
- determination of the size of the next computational domain;
- setting on the boundaries of the computational domain of nodal displacements obtained at the previous stage;
- carrying out calculations to simulate sequential extraction of reserves;
- analysis of calculated data and determination of safe parameters of the mining methods used or planned for use on the deposit.

If more detailed calculations are required, it is possible to refine the mesh of finite elements by inserting additional sections in any of the three planes or to form a new modeling area with setting of boundary displacements from the model of the second stage.

At the third stage, more accurate calculation of the stress-strain state is carried out in the vicinity of a single or several excavations, taking into account the stress field formed at certain geometry of the working excavations by setting boundary displacements from the corresponding variant and then modeling the excavation driving. Thus, in the large-scale modeling schemes of the second and third stages, the main factors influencing the stress state of the rock mass are taken into account.
3. Use of geomechanical forecasting data to determine the safety parameters of the development of deposits in difficult geological and mining engineering conditions

As an example of the implementation of the proposed approach, let us consider the stress-strain state of the rock mass in the vicinity of the section of the Khibiny apatite arc, which is being mined by JSC Apatit (figure 1).

Initially, geomechanical models of individual sections of a deposit were developed to forecast the stress-strain state of the rock mass. After that, forecasting systems began to include a whole deposit or even several deposits.

So, for example, to substantiate the order of excavation works at the exploited (+320, +250, +170, +90m) and planned for mining (+10m) levels, a 3D geomechanical model of the Kirovsky mine was developed, which includes the Kukisvumchorr and Yukspor deposits (figure 2).

![Figure 1. Scheme of the location of the Khibiny apatite arc deposits.](image1)

![Figure 2. General view of the volumetric finite element model of the Kirovsky mine.](image2)
The geomechanical forecasting system based on such a model made it possible to determine the optimal mining procedure, the location and size of block-pillars and joining sections, as well as the parameters of regional protective measures when developing the reserves of the +170m level of the Kirovsky mine under conditions of mutual influence and subsequent joining of three working excavations: underground – the Yukspor, Kukisvumchorr and an open-pit – the Saamsky open pit, with an additional factor complicating mining operations: a thick geodynamically active structure of the Saamsky fault (figure 3).

Figure 3. Distribution of stresses $\sigma_{\text{max}}$ on the +236 m sublevel (+170 m level) in the zone where the Kukisvumchorr and Yukspor deposits join with the Saamsky open pit.

As a result, the authors have proposed a procedure for conducting mining operations at each sublevel, taking into account the need to minimize the driving of excavations in the body of the Saamsky fault and assuming the breaking by bulk explosions of both the joining sections located on the upper sublevel on both sides of the Saamsky open pit, and a certain part of the hanging wall reserves in the Saamsky fault on the lower sublevels with subsequent breaking of the joining sections at the Kukisvumchorr deposit.

4. The concept of the organization of a geomechanical forecast on the basis of a hierarchical system of interconnected models

Further advancing of mining operations within the Khibiny apatite arc and other ore fields predetermines the convergence of open pit and underground excavation works and the need to carry out the mining operations under mutual influence conditions [9]. Therefore, the situation mentioned above can occur in several areas at the same time. These areas require particularly detailed forecasting of the geomechanical and geodynamic situation when choosing the optimal option for the mining technique and its parameters.

From our point of view, the necessary consideration of the mutual influence of mining in adjacent deposits can be provided by creating a hierarchical system of interconnected volumetric models. Figure 4 shows a schematic example of a similar system for the Kirovsky mine.
A feature of this system is the modeling of the rock mass stress-strain state in the conditions of a specific deposit (section of deposit) with automatic changes in neighboring areas and in the general small-scale model of the 1st level. That means, for a user, a reduction in the volume and time of editing a variant, and a reduction in the calculation time. After logging into the system, the user can select the most convenient site for making configuration changes, and the system itself will decide in which of the models these changes should be reflected in terms of the impact on the rock mass stress-strain state. Moreover, each of the 2nd level models (the Kukisvumchorr, Yukspor, Saamsky and Gakman sections) can have an unlimited number of submodels of various detail, generated automatically both by "cutting" and thickening the finite element mesh, and by using a library of models of mining technology elements.

This approach will allow:

- using mining plans for each of the sections, working in a local coordinate system;
- predicting the impact of the development (change in configuration) of mining operations in neighboring deposits;
- reducing the size of tasks to be solved by calculating for individual large-scale models and taking into account changes of the stress-strain state in the entire system;
- taking into account adjacent areas, in particular the Saamsky fault zone;
- obtaining a complete picture of the distribution of stress fields for all the system’s deposits in each calculation variant.

5. **Additional advancement courses of the Sigma GT geomechanical forecasting system**

While being used, the system constantly develops and can be modernized, as well as adapted to specific conditions and tasks. The main directions of further advancing of the geomechanical forecasting system are:

- modernization of a unit for calculating and interpreting shear stresses with the development of an interface for visualizing areas with critical parameters of shear planes near structural faults;
- introduction of contact elements;
• development of a module for the prediction of underworked rock mass caving with the identification of potential areas of partial and complete caving of the overlying strata;
• development of a module for calculating the rock mass stress-strain state in blocks with the ability to simulate the driving of mine workings;
• expanding the library of single mine workings to various sections (horizontal, inclined and vertical), their interfaces and working tools;
• supplementing the models and algorithms for calculating the stress-strain state with tectonic faults near the contour of mine workings, options for unloading measures and supporting;
• development of a 3D representation of stress fields calculated in a block and vector form in the Sigma GT software.

To improve the accuracy of geomechanical forecasting, an important condition is the integration of modeling results with seismic and geological data. For example, [10] presents the integration of the results of cluster analysis of seismic events and the results of numerical modeling of the rock mass stress-strain state during the development of rockburst-hazardous deposits. The use of the seismic method for monitoring the processes of changes in the stress-strain state makes it possible to trace the behavior of the geological environment in all conditions and stages of its evolution, including in mining natural-engineering systems. The advantage of an integrated approach is a potential more detailed study of mining-induced seismicity and a more accurate assessment of the rock mass stress-strain state. In the future, such an approach to data analysis will improve the quality of rockburst hazard forecast.

6. Conclusions
The long-term application of the geomechanical forecasting system based on the numerical modeling of the stress-strain state has shown its effectiveness to substantiate the optimal parameters of mining operations and the development of regional and local unloading measures. At the same time, promising directions for the development of such complexes were identified as follows:
• combination of single different-scaled geomechanical models of deposits and separate sections of a deposit or the ore field into a single hierarchical system of interconnected models;
• generation of additional models of sections with a perspective convergence of mining operations and the mutual influence of open pit and underground mining excavations;
• development of a library of typical models of mining blocks and elements of mining technology for the quick assessment of the stress-strain state and rockburst hazard at the actual and predicted state of mining operations with varying degrees of detail;
• development of modules for assessing the processes of tensile cracking and shear, taking into account structural failures;
• integration of stress and strain field transformation data as mining develops with seismic and geophysical monitoring data and following access to a comprehensive assessment and forecast of the geodynamic hazard of separate areas of mining-engineering systems.

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