ABOUT MECHANICAL-MATHEMATICAL MODELS FOR COMPUTER SYSTEMS OF INTELLIGENT AND SMART ANALYSIS OF GEOMECHANICAL PROCESSES

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1. General comments

At the present time Artificial Intelligence (AI) technologies play an important role in the development of computer technologies for mathematical modeling and computer simulation the state and behavior of physical and engineering objects of various nature.

Therefore, the actual task is to develop the “philosophy” and essence a new generation of application software and actually elaborate such software.

The application of approaches and methods of numerical (computer) analysis in performing research and solving applied problems of mechanics and engineering has an impressive history of development. But, before the advent of modern computers and computer technologies, the use of realistic mathematical models in performing complex fundamental and applied research and calculations was possible only in rather limited cases.

Today computer modeling capabilities are qualitatively changing and one of the essential new requirements to computer modeling technologies is the presence of artificial intelligence (AI) elements in such technologies, or, what seems to be more precise, the presence of such "skills" as "intelligence", "understanding", "insight", "ability to adequately predict on the basis of processing large sets of information and data (Big Data)" (which is the essence of the concept of "artificial intelligence").

Modern computer modeling systems should be “able” to give recommendations for setting model problems, be able to correct computational algorithms, interpret the results of calculations and give a person a possible plan of further actions (measures).

It can be stated that today computer technologies for modeling physical and production processes are: high-performance computing + knowledge and "Big Data" + mathematical models + elements of artificial intelligence technologies.

What are intelligent and intellectual systems?

While intellect and intelligence are related, they are not the same thing. A person can be highly intelligent but lack intellectual curiosity or the ability to think deeply about abstract ideas. Conversely, a person can have a high intellect but struggle with practical problem-solving or learning new skills.

May be say that: “Intelligent” is a quick learner of any task, and “Intellectual” is knowledgeable and would offer great solutions to an issue.

Therefore, let's assume that in decision-making technologies, *an intelligent system* is an information-computing system with intelligent support that solves problems mainly without human involvement, as opposed to *an intellectual system* in which an operator is present.

What are the concepts Modeling and Simulation?

Modeling and simulation are two closely related computer applications, which play a major role in science and engineering today.

Modeling is a way to create a virtual representation of a real-world system. Simulation is used to evaluate a new design, diagnose problems with an existing design, and test a system under conditions that are hard to reproduce in an actual system.

The key difference between modeling and simulation is that optimization modeling provides a definite recommendation for action in a specific situation, while simulation allows users to determine how a system responds to different inputs so as to better understand how it operates.

Modeling is the act of a model building. A simulation is the process of using a model to study the behavior and performance of an actual or theoretical system. While a model aims to be true to the system it represents, a simulation can use a model to explore states that would not be possible in the original system.

The model comes first. That model is then used to perform simulation studies. Typically, you are using a model to either reproduce a historical period (for validation purposes) or to extrapolate data to predict the future (for what-if studies).

Simulation modeling is the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world. Simulation modeling is used to help designers and engineers understand whether, under what conditions, and in which ways a part could fail and what loads it can withstand. So, for example, it is more correct to use the term “simulation” or “simulation modeling” for Digital Twin technologies.

2. Some strategic goals of development of mechanical-mathematical modeling systems with elements of AI.

It should be noted that at the current stage of AI technology development, we are talking about systems with human participation in the control of the AIsupported process. From this point of view and *building intellectual system of modelling, strategic goals of active development of AI systems are*:

- elaboration and development of mathematical foundations of data processing and intelligent data analysis methods for various application areas and directions;
- elaboration of mathematical foundations of systems for computer simulation, calculations and analysis of various physical processes;
- recommendations for setting model mathematical and computer problems for real processes and phenomena under analysis;
- intelligent interpretation
- transition to new intelligent CAD, CAE and CAM technologies.
- recommendations for setting model mathematical and computer problems for real processes and phenomena under analysis;
- intelligent interpretation and analysis of modeling and simulation results.

Expansion of AI applications, increasing complexity of the class of solving problems, range and volume of data used to create applied AI models and intelligent systems based on AI, requires a significant expansion of the theoretical and algorithmic base of AI, including the need to develop machine learning methods using mathematical and physical models of objects and phenomena, methods of multimodal data consolidation, methods of creating geometric and topological components of neural deep networks, methods of three-dimensional computer design and simulation of objects.

AI technologies are increasingly becoming full-fledged “co-authors” of algorithms for simulation mathematical and computer modeling of various physical and technological processes and phenomena.

One of the important problems today is the development of modern advanced approaches and methods of reliable and adequate mathematical modeling and computer simulation for various classes of problems with elements of intelligent analysis.

Any model is accurate for some classes/types of problems and inaccurate for others. In addition, you need to know at which stages it is most effective to use and which model to use in order to avoid errors or minimize inaccuracies. Thus, the same object of applied mechanics can be described by different mechanical-mathematical models, based on the goal set by the researcher. It is reasonable to note that when constructing a mathematical model of the applied mechanics problem under consideration and choosing a method for its solution, it is necessary to be guided not only by the accepted mechanical model of the object behavior, but also by the ultimate goal of solving the problem.

The use of AI technologies is effective practically at all stages of mechanical-mathematical modeling of processes and phenomena of applied mechanics. Among them, for example, intellectual processing, interpretation and analysis of large volumes of knowledge and data on the basis of mathematical models of studied objects, processes or phenomena; development of knowledge bases on various directions and subject branches of mechanics; development of systems for analyzing the results of modeling and decision-making and others.

3. Elaboration of Intelligent and Intellectual computer simulation systems in geomechanics. Actual problems

Let us now consider some of the main directions in the development and construction of new geomechanical models.

Intensive excavation of underground space leads to quantitative and qualitative changes in geomechanical processes and phenomena and even to new, previously non-existent phenomenon. In this regard, at present, sometimes even radically changing ideas about the nature of geomechanical phenomena and processes.

Therefore, there are a number of new scientific problems and questions associated, on the one hand, with the study of the influence of man-made factors on the geophysical environment, and, on the other hand, with the study of the behavior of rock strata and the ability to manage natural processes in the new changed conditions.

Deepening and expansion of fundamental knowledge about the behavior of rock masses with underground workings, constructions.

One of the most important fundamental task of geomechanics at the present stage is the construction and developing models of the rock masses behavior with underground constructions, which most adequately describe rock masses' condition and behavior, taking into account the new facts and ideas about the behavior of rock masses accumulated to date. In turn, this general problem includes many internal problems. Among them, for example.

A. It is very difficult to correctly account for the variability in time of stress fields in the massif around of underground structures due to the wide variety of influencing factors. The main difficulty is caused by the structurally inhomogeneous structure of rock massif. In addition, in the rock massifs with mines (the undermined rock massifs) in general, areas are formed that are in different structural-mechanical states. In this regard, mathematical formulations of model problems for the study of geomechanical processes in the selected characteristic zones of the mined rock strata should be different.

Therefore, the problem of constructing mechanical-mathematical models to study the stress-strain state of the rock massif from the depths of underground mining operations to the Earth's surface is an urgent and very complex.

B. It is well known, that for rocks and rock masses, as a rule, the mechanical properties of rock samples, rock mass samples and mechanical properties of the rock mass on the whole are different and in some cases significantly. There are a lot of works related to the determination of the properties of rock masses, and significant progress has been made in this direction. But, there are still a lot of unresolved questions in the problem of determining the physical&mechanical properties of rock masses. Currently, a new scientific direction is developing – breed science, associated with the construction of classifications of rocks and massifs according to physical and mechanical properties in canonical scales. A cluster approach based on the existence of canonical series of structural separations and associated amplitude-period spectra of geophysical and geomechanical fields is developed for the quantitative description of the block-hierarchical structure.

C. It should be noted an actual problems associated with modeling of geophysical processes in the rock mass as multilayer media (taking into account the presence of gas fraction and liquid). For their reliable solution, it is necessary to construct conjugate mechanical&mathematical models. On their basis, such important tasks as the elaboration of measures to prevent sudden emissions of rock and gas in mines, prevention of flooding of mines etc. are solved, in particular.

D. Despite the significant numbers of research work carried out, the problem of forecasting and describing such a dangerous phenomenon as dynamic phenomena in mining operations has not yet been studied and solved.

E. It is experimentally confirmed and theoretically justified that rock masses before destruction are divided into parts, while the continuity of the massif as a whole can be preserved. As a result, a block structure appears in the massif. It is obvious that when a block structure occurs, the resistance of the rock to deformation decreases, but still remains finite. This phenomenon is characterized by the appearance of a "descending branch" on the stress-strain diagram. Obviously, in this new state of the massif, the relationship between stresses and strains is different from the standard one. Therefore, it is necessary to expand the "standard" approaches and schemes for the construction of mechanical-mathematical models of geomechanics problems. We should investigate the behavior of rock massifs when we "get" on the deformation diagram to the stage of post-peak development of deformation processes.

In the region after the “peak” behavior of rock, in addition to general deformations, shear deformations develop and slip sites appear. As a result, there is a dilatancy effect (volume change due to stress changes and due to shear). In turn, the appearance of slip areas and associated dilatancy is important for the study of a wide range of processes, for example, geofiltration in the rock massif.

F. Among the important tasks is the problem of development and adaptation of modern approaches and methods of mathematical modeling to perform computer modeling and simulation of a wide range of applied geomechanical processes. At the same time, the main emphasis should be placed on the study of physical processes, the modeling of which is very time-consuming or almost impossible to execute with the help of other approaches.

G. As a special important problem I would single out the problem “Construction of geomechanical models of rock massifs behavior take into account of their complex structure”

Among the most “science-intensive” are such areas as the construction of mechanical-mathematical and computer digital geomechanical models of rock masses, taking into account their structural-mechanical features and with an extensive system of underground structures. And as well as the study and prediction of physical processes in rock masses under the influence of natural and man-made sources of disturbances on the basis of these models.

Studies of the material behavior and properties at the pre-limit stage of deformation were carried out quite a lot. Similar studies for the “over-limit deformation section” are single. However, the practical importance and relevance of these studies are evident. In an over-limit deformation branch, a solid takes on a block structure.

Therefore, to account for the behavior of the rock massif at all stages, models are needed not only in the framework of continuum mechanics, but also in the framework of discrete media mechanics.

H. Intellectual systems for the formulation of boundary value problems and the construction of numerical computational models.

So, we talked about the urgency of the development of adequate mechanical-mathematical models to describe geomechanical processes. It was about the importance of using AI-technologies in modern systems of computer modeling and simulation of various classes of applied geomechanical processes. And now I would like to provide information about such direction of our research as the development of Intellectual systems for formulation of boundary value problems, the construction of numerical computational models and solution applied problems on their base.

Despite the fact that the general algorithm for solving such problems as study of strength and stability of geotechnical underground structures (such as mining excavations, underground cavities and chambers) for a given period of time for mining excavations was developed long time ago, the solution of this problem is still widely discussed in the scientific publications.

There are some of important problems related to the common relevant problem of the development of computer-aided technologies for describe the behavior of rock masses with underground structures at various depths.

One of the main our points is that the calculation schemes for the study of stress-strain state of rock masses in the vicinity of underground structures at great, moderate and small depths should significantly differ.

I. Our experience in solving problems of stability and strength of geotechnical structures located at different depths inside the rock strata with significantly different mechanical properties allows to clarify and expand the classification of depths in geomechanics. We propose the classification of mining depths based on the level of rock pressure and mechanical properties of the rock strata at the considered depth:

Small depths at which the ratio of cohesion coefficient to lithostatic pressure is greater than unity ($C/\rho gH>1$).

Moderate depths at which the ratio of cohesion coefficient to lithostatic pressure is less than or equal to one ($C/\rho gH\leq 1$), but this ratio does not exceed the effective ultimate compressive strength of the correspondent rock strata ($\rho gH\leq\sigma_c$).

Significant depths at which lithostatic pressure exceeds the effective ultimate compressive strength of the rock strata ($\rho gH>\sigma_c$).

As follows from the introduced classification, the understanding of “significant depth” depends not only on the absolute value of the vertical component of the lithostatic pressure, but mainly on the value of the effective ultimate compressive strength of the rock mass σ_c in the considered strata.

J. One of the difficult problem of rock mechanics is: “what is the limit state of the rock mass in the vicinity of the underground structure (mining, goaf), what is the criteria for the limit state of the rock massif”?

The problems of strength and stability of underground structures and undermined rock masses are among the most important problems of rock mechanics.

To date, researchers have clearly established that to assess the strength of undermined rock masses, one should use not classical strength theories and corresponding strength criteria, but limit state criteria instead. This is because rock fracture or crack propagation in some area of the rock mass does not necessarily lead to its complete failure or to the critical impact of the rock mass on underground structures.

Nowadays, a number of limit state criteria are suggested for the evolution of the rock mass limit state in various conditions. However, the correct choice of the limit state criteria for applied engineering problems is still an open issue.

Limit state (LS) of the rock mass and geotechnical structures, in turn, is a condition at which the considered rock mass and/or elements of geotechnical structure experience significant violation of LS criteria (zones discontinuity, failure, fracture or crack propagation occur) and this leads to complete destruction of the rock mas, loss of stability of the whole geotechnical system or transition of the rock strata into a new structural state.

It is shown that to evaluation of the limit state of the rock masses in the vicinity of underground structures it is efficient to use the complex limit state criterion which is a specific system of failure criteria. The application of this criteria depends on the type of the stress-strain state at a particular point of the rock mass. The complex limit state criterion includes the most common and effective criteria used in the practice of geotechnical calculations. These common criteria are applied for each particular point of the rock mass depending on the value of the Nadai-Lode parameter, which defines the type of the stress-strain state. In addition to that it is shown that the system of failure criteria can be expanded if specific data of mechanical properties of the rock mass is available. In particular, this data should include the information on specific parameters used for other failure criteria used in geomechanics and geotechnics.

So, we proposed to evaluate limit states of rock masses based on a complex criterion. *The main idea of this evaluation is that before one evaluates the state of the rock mass it is needed to determine the type of stress state in each area of the considered rock mass*. After that, rock mass state evaluation should be performed by those limit state criteria, which are based on the same physical processes as occur in the evaluated area of the rock mass.

We propose to use the Discrete Element Method (DEM) or Block Element Method (BEM) to simulate the behavior of the rock mass beyond the limit state. To understand which areas can potentially go beyond the limit state, Finite Element Method (FEM) simulations may be used.

K. The algorithm of simulation the undermined rock mass behavior in the vicinity of excavations or underground structures is a complicated coupled technique (FEM + DEM + analytical methods). Such approach is almost the only one today, which can be used for adequate solution of applied engineering problems taking every significant factor into account.

The construction of a computer (digital) geomechanical model (DGM) of the rock massif with geotechnical structures for modelling of various geomechanical processes is a non-trivial, very difficult task. When constructing such model, it is necessary to generalize a huge quantity of multidisciplinary data and knowledge accumulated both in science and in practice. An important condition for the construction of an adequate reliable complex three-dimensional geomechanical model of rock strata is the use of the whole set of geological, mining and geomechanical data, their structure and consistency.

Numerical Modeling and Computer Simulation of geomechanical processes in rock massif with large-scale excavation of mineral resources.

The main directions of our research on the development of numerical models and computer models of various geomechanical processes can be grouped into several groups: (they are shown on the slide)

- stress-strain state in vicinity of underground geotechnical building/goafs;
- stability and measures of safeguard of underground goafs;
- stress-strain state in rock massif with large-scale underground mining works from Earth Surface to large depths;
- deforming processes on Earth Surface and undersurface regions;
- geomechanics of open mining operations, pits;
- stability of engineering buildings on Earth Surface and undersurface regions;
- couple (conjugate) problems of geomechanics (hydrogeomechanics, gasgeomechanics, thermogeomechanics and others);
- couple (conjugate) of rock mechanics and mechanics of rock equipment.

I would also like to separate the following problem into a separate class:

Stability of underground structures and rock massifs with a large-scale network of underground structures. Technogenic accidents.

At present, such a scientific direction of fundamental research in geomechanics and geophysics as “The elaboration of theoretical foundations of the theories of dynamic deformation of geomedia under powerful natural and man-made impacts” is actively developing.

Block-hierarchical structure of rock masses plays a significant role in the formation of specific dynamic processes in the undermined rock massifs. Today, it is indisputable that for the correct description of the behavior of rock masses and their responses to external influences, it is necessary to take into account the complex structure of masses, dissected by surfaces and weakening zones into separate blocks of different scale levels.

One of the important task is a reliable forecast of the long-term stability of the rock mass both in the vicinity of a complex system of underground workings, and the stability of the considered area of the rock strata as a whole.

Changes accumulate in the massif under the influence of technogenic factors can cause catastrophic consequences not only for an individual underground structure, but also for the mining region as a whole. The result can be a large-scale man-made accident, manifested in various forms (which depends on a set of factors). In accordance with the basic laws of the theory of catastrophes, to initiate the process of release of potential energy accumulated in the contour zone under certain conditions, a slight external influence is sufficient.

Conclusion

Unfortunately, the report does not cover the whole range of actual tasks and problems of modern geomechanics.

It should be emphasized that geomechanics contains tasks that require an excellent knowledge and skills from various fields of modern theoretical and applied mechanics, fundamental and applied mathematics and a number of special disciplines.

Successful solution of geomechanics problems requires the construction of specialized models and algorithms based on the methods of continuum mechanics, mechanics of discrete bodies and the mechanics of bulk media.