

Slope Monitoring Systems Design for Mining Enterprises

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Abstract. The fast development of technologies for the collection, processing and interpretation of information, as well as significant complication of mining natural-technical systems, leads to the emergence of a need to revise the principles of monitoring mining facilities. The operation of modern sloping structures in mining enterprises is associated with high industrial and environmental risks, since the possibility of emergencies remains, and the scope of the accident consequences can be continental. The current conditions of mining require the development of new principles to assess and forecast the status of dumps, open pit slopes, tailings dams, and hydraulic dumps. The developed typification of mining and geological phenomena and factors that affect the stability of sloping structures allows the design of monitoring systems of their state with consideration to each object's specifics. Besides, this approach is formalized and allows its implementation in conditions of digital technologies progress. The development of detailed models of slope structures, which should become their digital twins, at last, enables to evaluate the current state of the observed object at all stages of its life cycle, based on received surveying, engineering-geological and hydrogeological information, and predict the slope structure behavior in the short term and medium term. The main task to be solved is the creation of principles for the organization of monitoring at mining enterprises that will enhance environmental and industrial safety in conditions of significant complication of mining and geological conditions of operated mineral deposits.

1 Introduction

The annual gross volume of extracted minerals is continually growing throughout the development of industrial and post-industrial society. In the current century, the annual consumption of mineral resources continues to increase rapidly, despite the development of resource-saving technologies and large-scale involvement of waste in secondary use. The explanation of the consumption growth is the total population increase and rising per capita consumption of energy resources, metals, chemical raw materials, etc. At the same time, mineral deposits with simple structure, high content of valuable components, located in favorable climatic conditions, and at relatively shallow depths are currently fully developed in the territories of leading mining countries, or their reserves are significantly depleted. The increasing complexity of geological conditions leads, on the one hand, to increasing volumes of accumulated waste in the form of waste dumps and enormous tailings storage

facilities, and, on the other hand, to a significant complication of underground and open-pit mines configuration.

The situation leads to an increase in environmental and technological risks in the operation of modern mining natural-technical systems. On average, the number of accidents associated with the stability violation of dumps, open pit sides, and dams of hydraulic structures over the decade has not decreased; however, the scale of man-made disasters has become more abundant. For instance, the scale of the consequences of the destruction of the tailing dump that occurred on January 25, 2019, in the municipality of Bramadinho of the Minas Gerais state in southeast Brazil was tremendous. The current situation necessitates the development of new approaches in the assessment and medium- and long-term forecasting of the sloping mining structures state.

Ensuring industrial and environmental safety in the development of mineral deposits is one of the most important tasks in our time [1–3]. In the current century, with the rapid development of digital technologies, issues of monitoring the state of mining natural-technical systems have moved to another plane [4–6]. Two decades ago, hardware for collecting and transmitting real-time information was not available, and the cost was too high. Today, in the presence of many sensors, means, and methods of data transmission, the main tasks in the field of mining facilities monitoring are:

- Design of monitoring systems (structure justification, selection of methods to process, store, and analyze data);
- Object modeling;
- Accuracy increase in the forecast of the mining facilities state.

These issues are the basis for several solutions in North America, Europe, and Australia. With that, not only mining companies or scientific groups are involved in solving these tasks. Several software suppliers for subsoil users are involved in the same activity as well. A review of analytical reports by consulting companies (Deloitte, PricewaterhouseCoopers, KPMG, HATCH, etc.) shows that the most promising and demanded direction in the development of safety control systems is the creation of detailed digital models. Based on the digital models' reliable forecast of the rock massif state, depending on the change of environmental conditions and operational mode of objects, it becomes possible.

2 Results and Discussion

In Russia, over the past two decades, supervisory authorities have been continuously increasing safety requirements for hazardous facilities, including in mining enterprises. One of these tools becomes continuous, including automated monitoring of the facilities state and monitoring of compliance with the requirements for the operation of the facilities laid down in the project. The set of criteria for assessing the state of mining structures, developed by the authors, allows design data collection and analysis systems that meet the requirements of the Russian regulatory framework (Federal Law No. 294 of December 26, 2008, Order of the Ministry of Natural Resources of the Russian Federation of May 21, 2001 No. 433, Federal Law No. 68 of December 21, 1994), and also takes into account the leading international development trends and experience in this industry.

Due to the wide variety of mining structures, a single set of criteria cannot be directly used for all structures. The authors created a systematization of dangerous mining and geological phenomena characteristic of different types of sloping structures and natural slopes to solve this problem. The differentiation of mining and geological phenomena seems to be four-level: classes, subclasses, types, and factors, determining the development of critical geological processes are defined. Class identifies the phenomenon itself, indicates its belonging to a specific dangerous engineering-geological process (for example, landslides, filtering destruction of rocks, phenomena associated with consolidation), authors

identified eight classes. Subclass genetically classifies mining and geological phenomena (landslides of open-pits, external and internal dumps), a total of 48 subclasses were identified. Type details the subclass as much as possible. Engineering-geological, hydrogeological, and mining-geological features of their development were distinguished (landslides of external and internal dump are divided into supra-sole, plantar, subsoil, etc.), more than 100 types were identified. Factors of the development of geological phenomena are a set of engineering-geological, hydrogeological or mining-geological parameters, a combination of which is a prerequisite for the emergence and development of a process of a specific type (factors are: connectivity of rocks, water cut, physical and mechanical properties, a configuration of the slope structure, etc).

The approach used to systematize dangerous mining and geological phenomena allows us to build trees of possible outcomes for each object and assess the risks of a specific negative process caused by natural or man-caused factors. A risk-based approach in assessing industrial and environmental safety is a priority in Russia. The scope of its applicability is described in Article 8.1 of Federal Law dated 26.12.2008 No 294-FZ (as amended on 06.06.2019), and several state standards have also been developed.

In countries of Western Europe, North America, Australia, the risk-based approach has been used for a long time. It is fundamental in assessing the safety of the functioning of natural-technical systems. Today, there are several requirements, conducted a number of basic researches [7–12] (G. Taylor, R. Pastorok, G. Suter, J. Glasson) for various industries. Also, the selected formalized structure in the “Tree form” makes it easy to switch from a fundamental to a mathematical model, if necessary, apply various assessment methods and completely automate the calculation process. The designer can track all possible outcomes and assess the likelihood of their occurrence.

In addition to the phenomena systematization, monitoring systems' design requires an assessment of the degree of influence of a particular factor on the state of mining structures. The modeling and generalization of the experience of assessing the condition of sides of the open-pit, slopes of dumps and dams of hydraulic structures allowed us to make several conclusions:

- All factors affecting the stability of the rock mass can be divided into two categories in terms of the dynamics of change over time - rapidly changing and slowly changing; the numerical characteristics of the latter vary within 5-10% over several years;
- Characteristics of factors are strongly correlated;
- Modern geomechanical models used to assess the condition of sloping structures do not consider the spatial and temporal variability of rock properties.

Based on the identified factors affecting the condition of the slope structures, as well as the dynamics of their change over time, a generalized model for the organization of an integrated quality control system for the operation of mining structures was developed. It includes elements of data collection, transmission and accumulation, interpretation of the information received, analysis of the current state of the object based on integral indicators, their comparison with the required regulatory characteristics. The generated database occupies the key position in the developed system. All the necessary characteristics for assessing an object's state were divided into four types depending on the rate of change of their indicators over time.

1. Dynamic – parameter values are measured at least once a day; these characteristics include deformations of the sloping structure, levels of the technogenic aquifer in the body of the tailings dam, or dump. It should be noted, in current conditions, the collection of dynamic data at high levels of Spatio-temporal variability of the observed parameters is carried out mainly using autonomous sensors.

2. Relatively dynamic – parameter to ensure the accuracy of the information and the necessary accuracy, it is necessary to measure it from once a week to several times a year.

3. Relatively static – values must be measured once every several years. This group includes the physicochemical properties of technogenic deposits and their bases.

4. Static – this is a facility location, climatic conditions of the territory, and operational characteristics provided by the project.

The given systematization allows determining the measurement frequency and methodology when developing programs for organizing the collection of information. Justification of the frequency of obtaining data on the state of objects and the values of individual parameters is one of the main tasks in the design of modern monitoring systems for mining facilities [13-16]. For the most part, the frequency of measurements is determined based on the experience and expert opinion of the specialist who is responsible for this issue at the enterprise.

The developed system for monitoring the state of mining facilities was considered as an element of the enterprise's integrated digitalization. In particular, the possibilities of accumulation and application as a training set for artificial intelligence systems of Big Data, which can be generated in hydrogeomechanical monitoring of the status of sloping structures, are considered. Today, the digitalization of industrial facilities, the formation of Big Data and the creation of artificial intelligence systems are advanced issues in most scientific areas around the world. In the past two decades, a number of foreign and domestic companies (Google, Microsoft, Alibaba group, Yandex, United States Geological Survey, NASA, etc.) in the framework of its activities, have been implementing software based on image recognition methods and machine learning using an artificial neural network device, cluster and analysis of variance, theory of automata, etc.

In the field of Earth Sciences, the formation of Big Data today is constrained mainly by the lack of developed methods and tools, as well as due to the confidentiality of information, which is often a commercial secret. However, today, scientists systematically accumulate data on weather conditions, the results of aerial surveys, satellite surveys, as well as geophysical and geodynamic measurements. At the same time, these projects are implemented mainly by organizations and companies from USA, Japan and some other western countries: the United States Geological Survey (USGS), the Geodetic laboratory of Nevada, the Geological Survey of Japan, the International Council for Science World Data System, other state and commercial organizations, international and regional scales (the International GNSS Service, NASA, Scripps Orbit and Permanent Array Center, etc.).

In the mining and primary processing of minerals, the accumulation and manipulation of Big Data is a new type of activity. In recent years, in foreign countries (primarily Australia, USA, and Canada), systems have been introduced that allow automated planning and design of mining operations, optimization of rock mass flows, control of all types of mining transport, and interactively evaluate the quality of the extracted raw materials. It should be noted that even in these countries, in the process of analyzing the operation efficiency of facilities or assessing their condition, no more than a third of the information collected is used, and in most cases, this indicator is a few percent.

At the beginning of the XXI century, as a result of a significant increase in computing power, as well as the formation of databases with digitized experience in operating industrial facilities, attempts were made to apply artificial neural network methods to make managerial decisions and assess the state of production systems and their elements. For example, many companies, including SAP, Google, Micromine, and Yandex, use the tools of artificial intelligence systems, including those based on neural networks, to solve the problems of the industrial sector. At the same time, introducing such systems into the real sector of the economy is gaining significant turnover, including Russia. In 2018, in comparison with 2017, the number of such systems in our country increased several times. The most widely used artificial intelligence systems are found in the banking sector;

however, energy and mining (oil and gas) companies have also begun introducing similar technologies over the past year.

3 Conclusion

Thus, in the modern data processing industry, the gradual rejection of classical analytical estimation and transition to new methods, based on the principles of trained artificial intelligence systems, is observed. The authors of this work attempted to apply similar solutions to the issues of assessing the state of mining structures. In particular, the necessity to revise existing geomechanical models is substantiated, and the possibility of using neural networks to assess the stability of enclosing dams is considered with specific examples. The developed principles for design and organization of monitoring systems at mining enterprises have a few distinctive features:

- Upon receipt of new data on the properties and condition of the observed object or changes in the conditions of its operation, the digital model can be adjusted; this is achieved using neural network methods;
- Rejection of analytical models that have significant limitations on accuracy is due to the large number of factors affecting the formation and current state of sloping structures;
- Status monitoring in the proposed approach acts as a regulator of the developed digital model.

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