UDC 624.131.3

V. V. CHESKIDOV, *Associate Professor, vcheskidov@misis.ru*
A. V. LIPINA, *Assistant*
I. A. MELNICHENKO, *Post-Graduate Student*

National University of Science and Technology — MISIS, Moscow, Russia

INTEGRATED MONITORING OF ENGINEERING STRUCTURES IN MINING*

Technological development in mining calls for accurate modeling and continuous awareness of the behavior of engineering objects in order to ensure mine safety. The information technologies and Big Data enable the next-level design, operation and management in the mining industry. The principal tool of acquisition of information on the parameters and behavior of basic production systems under operation is monitoring. Modern mines are the complex nature-and-technology systems, and their control is impossible without full and reliable information on the behavior of the components. The most hazardous structures in open pit mining are slopes of pit walls, dumps and hydraulic fill dams. The slope stability is governed by a set of factors (geology, hydrogeology, technology and other) which feature high variability in space and time. The ground water level monitoring in a slope structure allows interactive assessment of the slope behavior through calculation of safety factor using geomechanical models of the slope. In the course of time, as a result of variation in operating conditions in the mining waste storage areas, or due to environmental changes (extra moistening of clay rocks, thawing of frozen soil, etc.), physical and mechanical properties of stock piles and their bottoms alter. This fact dictates periodic determination of basic characteristics of slopes: density, cohesion and internal friction angle; the latter, together with the landslide body geometry and hydrogeological conditions govern the ratio of shearing and retaining forces. The optimized-rate measurement of water levels in an aquifer and adjustment of physical and mechanical properties of rocks by means of testing or statistical checking enables reduction in total operating cost and ensures ecological and production safety. Thus, monitoring of engineering objects in mining is the most critical Big Data tool in practical mining upon transition to the technologies of the Fourth Industrial Revolution.

Key words: *mineral mining, IT in mining, Big Data, monitoring, slope, information processing methods, neural networks*
DOI: 10.17580/em.2018.02.05

Introduction

The second half of the 20th century faced the tremendous growth in the science of information technologies. For the first time, scientists and engineers got an opportunity to process large arrays of data. By the early 1990s, the first powerful design-automation and production control systems were developed. Analytical calculations were totally computerized while earlier formula evaluations took much time both in engineering and economy. In its turn, the late decade of the 20th century and the first years of the 21 century became the period of overall spread of information technology. To date each large company has a mighty information technology department, while the market deals with the rivalry of program products being in charge for the implementation of all business-processes and flow charts.

History of development and application of information technologies in different branches of industry can be divided into two periods:

Period 1 — universal application of information technologies is restricted by the low power of computers;

Period 2 (modern) — with the high-power computers and super-computers available, information system designers run into the problem connected with the lack of the methods of collection, transmission and storage of information, as well as modeling techniques for different natural and technical objects, systems and their behavior in time and space.

Currently modeling starves basic knowledge in many sciences, particularly in operation with complex natural objects and processes, for instance, rock mass, aquifer, mineral deposit, etc. Mine-geological systems are extremely complex, and their behavior is governed by an abundance of factors which are impossible to embrace in full [1]. The analytical methods developed for the simulation of a geological medium in the 20th century, including mineral mining, allow highly accurate calculation of the behavior of a system under influence of a relatively small set of parameters. In most cases, this set includes not more than 5% of the total number of factors which affect the parameters and behavior of a system while the rest of the factors are either assumed as constants or neglected. Naturally, the withdrawn factors have no decisive influence on the result; nonetheless, in the modern conditions of high accuracy standards imposed on predictions and evaluations, such models can be inapplicable.

Main text

The present situation calls for new data processing algorithms based on nonanalytic techniques. In the last two decades, the methods rest upon neural networks [2, 3], theory of automata [4] and other have found wide application. On the other hand, a trainable system to be created needs learning data sets. Such sets of data are difficult to collect in practical geology and mining. First, geological objects feature wide variety and unequivalence. Second, total number of objects under development is comparatively small, and these data are mostly private to the effect of information security of a business. Another barrier for the wide introduction of information

*The study was supported by the Russian Foundation for Basic Research, Project No. 16-35-60116 mol_a_dk.

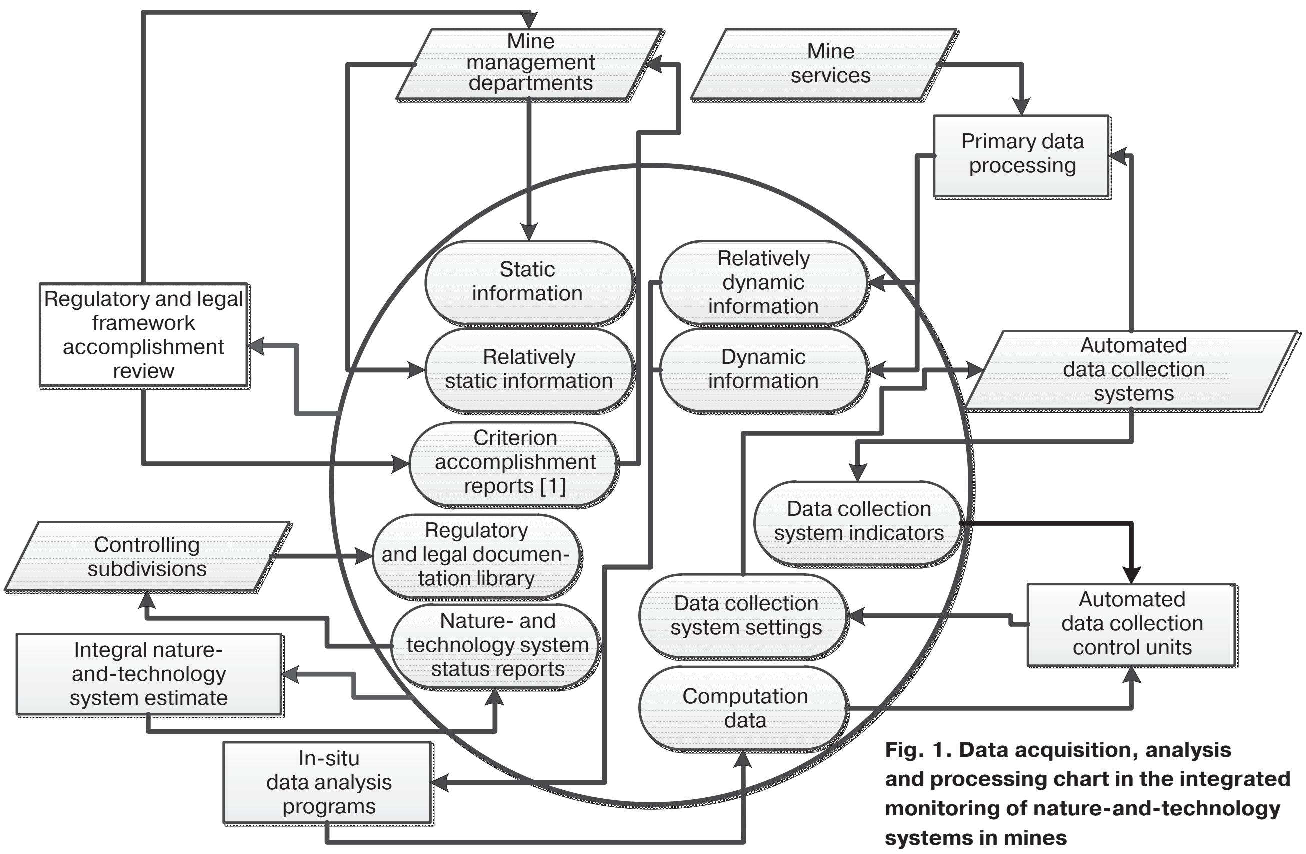

Fig. 1. Data acquisition, analysis and processing chart in the integrated monitoring of nature-and-technology systems in mines

systems based on machine intelligence is the absence of data structuring and distinct division of a mining process into stages and steps. A storage device for the information collected at different stages of mineral mining in the 20th century as mostly paper. Digitization of such data will enable their integrated analysis. In the meanwhile, in recent years, Russian and foreign companies are attempting to introduce complex systems designed for the next-level data flow control and meant for the large data base generation in mining and metallurgy [5, 6] for the analysis of behavior of systems and processes as well as for learning intelligent systems.

Using Blockchain tools, it is possible to secure information from industrial espionage by data decentralization, on the one hand, and, on the other hand, to cluster data for learning neural networks and artificial intelligence systems. In the long run, unobvious patterns and new solutions will be revealed for the mining industry. The Internet of Things (IoT) can enable all-inclusive analysis of equipment and personnel required for optimizing productions.

Intensification of mining activities and complication of mining conditions in view of the current ecological and production safety standards dictates continuous monitoring of constituents of nature-and-technology systems (an integer, ordered in time and space combination of interacting components, including tools, natural or man-altered natural bodies as well as natural and artificial fields of physical magnitudes). One of the critical points of efficient monitoring process is optimized collection, transmission, processing and storage of geo-data [7] which feature weak structuredness. Parameters of a nature-and-technology system are highly variable in time and space, and possess strong correlation bonds which are often impossible to reveal and assess. Incidentally, modern mine monitoring systems collect redundant data. Proper distribution of communication flows will ensure maximum utility of information, reduce expenditures and improve efficiency of interactive estimation of nature-and-technology system elements.

Development and active introduction of robotics and automation in the mineral mining and processing industry in the years to come will call for the methods and means for geo-medium information acquisition and data flow control. In this respect, the top-priority objectives to be reached in mining this day is development of reliable models of rock mass under mining and key layouts (surface and underground mines, transport systems, concentration mills, complex mechanisms, power transmission lines, etc.) [7]. Such models will enable operational managerial decision-making towards sustainable production performance.

Based on the analysis of the international experience gained in the area of integrated monitoring in mineral mining, as well as the structure of modern mines and architecture of information systems, a chart of acquisition, analysis and processing of data on mine's nature-and-technology system has been constructed (**Fig. 1**).

A critical component of the systems is the data base on engineering geology, hydrogeology, geomechanics and other behavior of rock mass, mines, dumps, waterworks, etc., as well as on operating personnel, normative legal documents, performance of automated data acquisition systems and other. Each mine data base is conditioned by a mining technology in use, presence of unique and complex nature-and-technology systems (e.g., a truck dump placed on a hydraulic fill, or a pit wall under loading by a dump, etc.); at the same time, the structure of the data base should make it possible to analyze the behavior of the nature-and-technology system components and to pinpoint areas with high risk of events and phenomena with negative after-effects.

The information processing blocks are boxed in Fig. 1. The In-Situ Data Analysis Programs detect in real time ill-measured and incorrectly calculated characteristics of a nature-and-technology system (slope safety factor, load-bearing capacity of bottoms) to assess the system performance safety on that ground. When calculations are completed and the results are analyzed, the information is stored in the data base; upon tracing ill measurements, the system notifies on additional measurements to be carried out. Based on the calculations, the rate of dynamic data interrogation, which is directly proportional to gauging speed, is set.

This system will ensure mining control at modern safety standards. The Regulatory and Legal Framework Accomplishment Review block provides mine divisions with regular relevant reposts on the behavior of the nature-and-technology systems, required personnel instructing, personnel development, etc., which favors minimization of violations and improvement of quality of the mine nature-and-technology system operation.

General assessment of the mine safety behavior is carried out by the Integral Nature-and-Technology System Estimate block. As a result, off-normal situation probability is determined from the theory of risk. To this end in view, threshold values are set for the quality and quantity figures to indicate the line of change in the integral estimate of a nature-and-technology system component.

In surface mining, the scope of the detailed study encompasses slopes (pit walls, dumps, waterwork embankments, etc.) [8]. Slope instability is confirmed by many landslide events in many mines within the late ten years: Zarechny open pit mine dump (Kuznetsk Coal Basin, Russia); tailings pond at Ajkai Timfoldgyar Zrt Alumina Plant (Hungary); dump at Mikhailovsky Mining and Processing Works (Belgorod Region, Russia); Kennecott Copper Mine pit wall (Utah, USA) and so on. Numerical characteristics of slope parameters are governed by: physico-geographical, natural geological, hydrogeological, geotechnical and technological groups of factors. Each group has specific time history [9].

Prediction of the behavior of large mining waste accumulations (refuse heaps, tailings ponds, etc.) in the last 50 years is is complicated as there was no experience of dumping earlier on. Eventually, it is required to carry out continuous monitoring of geological, hydrogeological and geomechanical behavior in order to estimate effect of natural and geotechnical factors on slope stability.

Based on the long-term observations and generalized experience of slope assessment [10, 11], some conclusions have been drawn, namely:

- All factors that influence rock mass stability can be divided into two categories with respect to the rate of time change — quickly and slowly changing factors; in the latter case, the numerical values vary within 5–10% for a few years;
- The characteristics of the factors obey a strong correlation bond;
- The modern geomechanical models of slopes inadequately account for the spatial and time variation in properties of rocks.

As a test, the integrated monitoring chart is proposed to be used within a single mine division.

The team of the Chair of Mining and Surveying at NUST MISIS has long-term been supporting hydro-geomechanical monitoring of hydraulic fill structures at mining and processing plants in the area of the Kursk Magnetic Anomalies (Lebedinsky, Mikhailovsky, Stoilensky) with a view to estimating stability of waterworks (dams), internal tailings ponds and hydraulic fills [10, 11].

In case of tailings storage area monitoring at a mining and processing plant, it is required that the data base stores four time-spaced kinds of geotechnical, hydrogeological and geomechanical information.

The Static Information includes project documents on operation of tailings storage, including data on land lease, legal bodies, etc. The Relatively Static Information is the parameters of hydro-fill material, physical and mechanical properties of rocks in the body and at the bottom of the dam within the engineering blocks delineated for the estimation. As a result of long-team soaking, high moisture content and variable external load, the physical and mechanical properties of rocks (density, porosity, internal friction angle, cohesion) can change within wide ranges, which demands geological surveying during operation of tailings storage. The additional exploration of the body and bottom of slopes under increasing external load is governed by the Morh–Coulomb soil model ($\tau = \sigma_n \mathrm{tg}(\varphi) + C$) accepted in the majority of methods of slope stability estimation. The discrepancies are particularly high in case when the failure envelope is plotted for relatively low loads (to 1 MPa) while the calculations should use values of internal friction angle and cohesion cased by the loading up to 1.5–4 MPa [12].

The Relatively Dynamic Information is the data on the behavior of nature-and technology systems within the tailing storage, which are measured once a month; as a rule, these are unautomated measurements (geodetic surveying, water line in check water wells, visual observations, etc.). It is worth mentioning that this kind data are highly subjective though can be used to validate automated-received information from sensors.

The Dynamic Information is the data received more often than once a month (mostly, a few times a day). The short-term estimate of the slope behavior needs monitoring variation in hydrogeological conditions of the slope operation. The hydrogeological conditions can change after heavy atmospheric precipitation, heavy snow melting, or redistribution of pulp discharge during hydraulic fill construction. The listed factors have the highest effect on stability of sandstone–clay slopes. Mechanical properties of soil in slip zone change much slower. A jump in the internal friction angle and cohesion of clayey rocks can result from high moistening; however, much portion of rocks experiencing structural failure and displacement of blocks is in full water flooded and show no signs of jump-wise change of mechanical properties. The data on water lines in wells (**Fig. 2**) drilled in the dams of the tailings pond at Stoilensky Mining and Processing Plant are taken from sensors each 6 hours a day (given standard situation) in the mode of automated measurement and data collection. In this case, it is required to provide automated validation of data in order to eliminate false values of parameters in the data base and to reveal errors due to the human factor.

In the discussed system for Stoilensky MPP, the performance criteria of the tailings storage sites is the safety factor of dams. These safety factors are calculated using the software developed at the Chair of Geology and Surveying (**Fig. 3**). The work-back calculations produce the

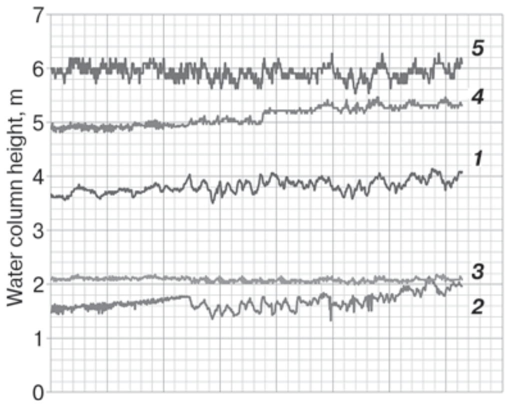

Fig. 2. Water column height history in checking automated profile ZP wells in the head dam at the tailings pond between 1 Sep 2015 and 29 Feb 2016:
***1* — well ZP-01; *2* — well ZP-02; *3* — well ZP-03; *4* — well ZO-05; *5* — well ZP-06**

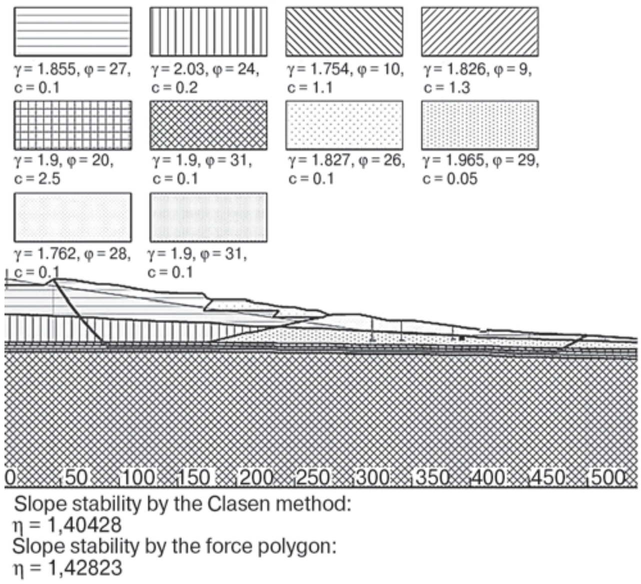

Fig. 3. Calculation of safety factor for head dam of tailings pond using evidence from automated checking profile P-3

limit water lines of hazard to continue operation of the tailings storage area. Upon reaching the safety factor of 1.30, an appropriate division is warned to intensify observations. The other thresholds and prevention activities include: 1.20 — it is required to ensure higher safety factor, to stop cold operation; 1.05 — pre-emergency, insignificant structural deformations are possible; 1.00 — equilibrium state, high accident probability.

Conclusion

The analysis of the experience of the slope behavior modeling shows that it is most reasonable to estimate rock slope transition to instability using the method of determining limit values for individual critical variables. In this case, for each slope, the critical variables (hydrogeological, geotechnical and other) should be calculated in a certain sequence:

– Rated safety factor is determined on the basic of the criticality of a structure and process requirements;
– Engineering geological model is constructed for a certain time point with the indication of physical and mechanical parameters of rocks in the defined geological elements and with the marking of induced (natural) aquifer;
– Hydrogeological model is constructed with regard to permeability of enclosing rocks and mining waste;
– Geomechanical model with the indication of spatial position of landslide block and slip curve is built;
– Critical ranges of water level such that the safety factor is between standard and 1.0 are calculated for the aquifer for the short-term prediction of slope behavior;
– Patterns of temporal and spatial variability of the slope material and the intensity of change in the physical and mechanical characteristics under the variation in the hydrological regime and man-made load are determined;
– Critical ranges of water level in an induced aquifer are calculated with regard to the changed physical and mechanical properties of rocks.

Prediction of the behavior of slopes using the proposed scheme ensures reliable assessment of rock mass condition. The constructed models should be validated and adjusted based on additional engineering geologic exploration.

References

1. Galperin A. M., Kirichenko Yu. V., Kutepov Yu. I. Integrated approach to eco-friendly mining waste management. *Gornaya promyshlennost.* 2011. No. 5(99). pp. 22–23.
2. Hamza G., Ergun E. A neural network approach for attenuation relationships: An application using strong ground motion data from Turkey. *Engineering Geology*. 2007. Vol. 93, No. 3–4. pp. 65–81.
3. Manevich A. I., Tatarinov V. N. Application of artificial neural networks to predict modern movements of the Earth's crust. *Issled. Geoinform.: Trudy Geofiz Tsentra RAN*. 2017. Vol. 5, No. 2. pp. 37–48. DOI: 10.2205/2017BS045.
4. Corominas J. et al. Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment*. 2014. Vol. 74, No. 2. pp. 209–263.
5. Osipov V. L. Delineation of ore occurrence in ore reserves appraisal with MicroMine package. *Gornyy Zhurnal*. 2015. No. 4. pp. 82–87. DOI: 10.17580/gzh.2015.04.15.
6. Benni T., Rainer B., Thomas G., Stefan J., Malcolm A., Liz H., A WebGIS decision-support system for slope stability based on limit-equilibrium modeling. *Engineering Geology*. 2013. Vol. 158. pp. 109–118.
7. Cheskidov V. V. Prospects of cad using at engineering-geological pioneering at open cutting. *Gornyy informatsionno-analiticheskii byulleten.* 2011. No. 11. pp. 355–361.
8. Galperin A. M., Punevskii S. A., Borodina Yu. V., Zung B. K. Development of methods and means for hydro–geomechanical monitoring of slopes. *Marksheideriya i nedropollzovanie.* 2015. No. 3(77). pp. 22–30.
9. Wang Y., Cao Z., Li D. Bayesian perspective on geotechnical variability and site characterization. *Engineering Geology*. 2016. Vol. 203. pp. 117–125.
10. Napolskikh S. A., Kryuchkov A. V., Andrievskii A. I., Cheskidov V. V. Remote stability control of hydraulic inwash structures at Stoilensky Mining and Processing Plant. *Gornyy Zhurnal.* 2017. No. 10. pp. 52–55. DOI: 10.17580/gzh.2017.10.11.
11. Cheskidov V. V., Hydro–geomechanical monitoring of slope structures. *Gornaya promyshlennost.* 2017. No. 4 (134). 78 p.
12. Behnam Y. B., Danial J. A., Mohd For M. A. Strength characterisation of shale using Mohr–Coulomb and Hoek–Brown criteria. *Measurement*. 2015. Vol. 63. pp. 269–281.