Research methods for seismoacoustic monitoring of large underground facilities

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Abstract. Large underground mine workings of hydropower facilities created in complex engineering-geological and seismic conditions significantly differ from industrial underground facilities designed for different purpose in their construction, operation and operating conditions. This makes it extremely urgent to organize seismo-acoustic monitoring in order to ensure their safe and reliable operation and prediction of the status of the underground circuit. The solution of this problem requires the improvement of methods and techniques for field observations of the operation of underground structures during construction and operation. In this paper, we formulate the basic principles of the organization of seismo-acoustic monitoring of the rock mass state that contain mine workings. We propose system of seismo-acoustic monitoring of a complex of underground structures, for example, the underground circuit of the Rogun HPP, which is under construction. The paper presents the field observation technique using seismoacoustic methods: seismic transmission and profiling, seismic well logging, acoustic emission method for concrete and boreholes, dynamic response method for assessing the quality of concrete-rock contact, ultrasonic well logging, ultrasonic studies of rock samples and concrete structures. Effective qualitative and quantitative parameters have been determined, which make it possible to assess the degree of change in physical parameters in the internal parts of rock massifs that occurs under the influence of natural and technogenic factors. This is done in order to assess ultimate strain levels and to find indicators of the critical state of the geological environment in problem areas.

1. Introduction

The basic principles of the organization of geodynamic monitoring of the state of massifs and the main structures of the underground complex should be based, first of all, on systemic principles, since these structures form specific techno-natural systems “structure - massif” [1-3].

A peculiarity of these systems is a special responsibility in terms of ensuring trouble-free operation facilities during the long period of their operation. When considering the organization of geodynamic monitoring of structures in complex engineering - geological and tectonic conditions, it is necessary to further increase the degree of reliability of the measures being developed to prevent possible accidents.
Moreover, the development of the structure of geodynamic monitoring systems in the general case should include the following steps [4,5]: creating geomechanical models of controlled mining systems and structures, including the assessment of geodynamic risk; selection, justification and assessment of the possible values of priority controlled parameters; equipment for observation posts; taking measurements of controlled parameters in the field; creation of databases of field observations, as well as design parameters and evaluation criteria; verification of geomechanical models by comparing the measured controlled parameters and the corresponding calculated values; establishment of normative or obtained by numerical simulation of forecast-critical parameters corresponding to a virtual catastrophic situation; comparison of the measured values with the normative and calculated forecast-critical values; assessment of the current and forecast of the further state of controlled objects; making managerial decisions and developing preventive measures; monitoring the effectiveness of the implementation of preventive measures.

As follows from the principles of the organization of geodynamic monitoring, full-scale (field) measurements and observations constitute a very substantial part of the total work. Moreover, taking into account the modern understanding of the rock mass as a medium of hierarchical-block structure, the main information that should be obtained, first of all during field observations, is the presence of decompression, displacement, and deformation zones of the enclosing mass [6].

Various geophysical methods can be used to obtain this information, since they make it possible to assess the degree of change in physical parameters in the interior of rock massifs under natural occurrence under the influence of natural and technogenic factors, to assess ultimate strain levels and to find indicators of the critical state of the geological environment in problem areas [7,8].

2. Seismoacoustic research methods

In principle, for monitoring purposes, the use of various geophysical methods is possible: acoustic, thermophysical, radiometric, electromagnetic. However, among the various geophysical methods, seismoacoustic methods are noticeably distinguished by the degree of development and the level of information content [9-11].

The main methods of seismic-acoustic monitoring are seismic profiling along the well and production walls, seismic logging and ultrasonic logging of wells, seismic tomography of the pillars between the workings and wells, ultrasonic examination of concrete and samples, as well as acoustic emission studies on the surface of concrete lining or lining, as well as in the internal parts array using wells.

Seismic scanning and profiling is carried out according to standard methods [7,12], using geophones with a natural frequency of 10-20 Hz. The vibrations are excited by striking a sledgehammer on the floor and walls of the mine workings, or by explosions of small (50-200 grams) explosive charges. To register the signal, digital computerized equipment is used, for example, the Lakkolit 24-M1 seismic station manufactured by LOGIS (Russia). The measured values for these types of seismic operations are the propagation times of elastic waves from the source to the receiver.

During profiling, the excitation of oscillations and the reception of signals are carried out along one line (profile). As a rule, a “heel and-” or “seven-point” observation system is used. Moreover, with a “five-point” observation system, the excitation of vibrations is performed at five different points: along the edges of the arrangement, in the middle of the arrangement and at a distance from the extreme geophones, equal to its length. One arrangement includes 24 geophones located at an equal distance from each other along the profile. The detail of the studies is determined by the placement step, that is, the distance between the receivers is 1-2 m.

When conducting multi-point seismic transmission (seismic tomography), the sources and receivers are located on opposite sides of the studied rock pillar. In this case, the arrangement may include any desired number of receivers. The resolution of the models is determined by the density of seismic rays. The term beam means an imaginary line connecting the source and receiver. Seismic receivers are placed with a constant step of 1-2 meters. Excitation of oscillations is carried out after 2-4 meters.
Seismic logging of wells. In all well logging, receivers are located inside the well. Excitation of vibrations is performed by a shock near the wellhead. In this case, a seismic streamer consisting of 6 (12 or 24) geophones is used. The step between the geophones is 1-2 m. The spit moves along the wellbore in increments of 5 (11 or 23) m. When a shock is initiated at the wellhead, elastic waves propagate along the wellbore in the near-wellbore space and provide information about the properties and structure of the enclosing array. The measured parameter is the travel time of elastic waves from the point of excitation to the geophones. Based on the totality of measurements for each well, graphs of changes in the speed of their waves elastic with depth are constructed [13,14].

Acoustic emission method. The acoustic emission method (AE) is based on the study of acoustic emission of rocks. Studying the parameters of acoustic emission, it is possible to quickly and reliably solve a number of important practical problems related to both studying the dynamics of landslide and deformation processes, assessing the stress-strain state of rock massifs, and identifying active tectonic disturbances, contouring weakened zones around mine workings and other special issues.

Field measurements, as a rule, are carried out according to the profiling technique in holes, wells and along the walls of tunnels [15].

Acoustic emission profiling in tunnels includes the production of measurements of acoustic emission along the walls of tunnels. The experience of such works indicates that, as a first approximation, the following measurement conditions can be taken: measurement step, i.e. the distance between the measurement points along the axis of the tunnel, equal to 10 m for “calm” sections and 1-2 m for “active” zones; registration time at one point $\Delta t$ for at least 15 minutes; oscillation frequency recorded $f \approx 10 \text{ kHz}$ (at a frequency controlled acoustic emission of thicker lining).

Dynamic response method. One of the main tasks of the non-destructive testing method in hydraulic engineering is to assess the quality of the “concrete-rock” contact behind the lining of underground structures and to localize areas of lack of contact [16,17].

The dynamic response method (DRM) is based on the difference in the dynamics of the reaction of the medium to pulsed action in the presence or absence of a concrete-rock contact. The dynamics of the reaction and the environment are understood as the frequency composition, duration, and other characteristics of the time variation of the surface displacement caused by a pulsed, that is, short-term, force (mechanical shock, explosion, electromagnetic pulse, etc.). Short-term effort is compared with the period of natural vibrations of the investigated section of the structure. Vibrations of the lining are recorded using displacement velocity sensors (geophones) located on its surface.

Ultrasonic logging of wells, ultrasonic studies of rock samples and concrete structures. Ultrasonic logging of wells is carried out using a seven-element borehole probe with a step of 10 cm between the sensors. The recording of ultrasonic vibrations is performed by each sensor during radiation in series with the first, seventh and fourth sensors. The pitch of the probe along the well is 0.5 m.

Ultrasonic examinations of the samples include measuring the propagation velocity of P-waves during transillumination of the samples in three mutually perpendicular directions: along the axis of the sample (X), and in two directions normal to the axis of the well ($Y_1$ and $Y_2$). For these measurements, the same set of equipment is used as with ultrasonic testing, only remote piezoelectric sensors with a natural frequency $f = 60 \text{ kHz}$ are used instead of the probe.

Ultrasonic inspection of concrete is carried out according to the standard method [12,18] of longitudinal profiling at measuring sites located on the walls of the machine room, transformer room, or construction tunnels.

3. Research results and discussion
The seismic-acoustic monitoring will result in seismograms along 24 channels (primary document); reference model of the propagation of elastic waves (partial processing); distribution curves and cumulative distribution curves of P-wave velocities (output document).
As an example, we consider the output document of seismic-acoustic studies conducted in the engine room of the Rogun HPP [19-21]. According to these measurements, the modal value of the velocity of P-waves of the seismic range in the sandstones of the Obigarm Formation is 3.8 km/s. Nizhneobigarm'skije argillite and siltstone from approaching gallery P-25 (elev. 982) characterized speed $V_p = 3.2-3.4$ km / s, and at 967 ~ elevations velocities 3.4-3.8 km / s. From the side of the engine room to a depth of 15 m, the influence area of the engine room output is clearly traced in the form of a zone of increased speed dispersion - from 3 km / s to 4.5 km / s. It can be assumed that the high-speed intervals adjacent to the mine working contour are associated with overvoltage’s arising from the interaction of the array with the wall of the turbine hall, anchors and supports supported in the whole workings (for example, current lead galleries).

The effect of flooding on the velocity of P-waves in an array consists of three main effects: filling of cracks and pores with liquid, hydrostatic pressure, and chemical exposure. In the course of the research, measurements were made both for the waterlogged (sources at a depth of 16.5 m) and for the waterless (from the crane beam mark) areas of the pillar. As a result, it was found that the values of the velocities of the array drained as a result of pumping decreased by 0.5 km / s, while in the irrigated area they remained the same. From these data it can be seen that, while maintaining local features of the change in $V_p$, the pillar under study, the overall level of velocities during drainage of the pillar decreased on average by 0.5-0.7 m / s. Since these changes occurred in a short period of time, in a few weeks, and the change in hydrostatic pressure was insignificant, it should be assumed that the observed decrease in velocities is mainly associated with the replacement of open fracturing by air instead of water flowing out.

A statistical analysis of the values of $V_p$ measured in the studied massif at different water levels in the turbine room indicates that the most significant changes in $V_p$ occurred in the siltstone massif, while for sandstones these changes are less significant.

The main objective of the ultrasound studies in this area was to study changes in the characteristics of the discharge zone around the mine for the period from 1991 to 2005. The measurements were mainly performed in the same wells in which regime ultrasound and seismic observations were previously carried out. You can also note a slight decrease in the average values of the velocities of P-waves in the "unchanged" array from 4.8 to 4.6 km /s (Figure 1).

![Figure 1. Comparison of distribution curves and cumulative distribution curves of P-wave velocities according to ultrasonic testing for the machine room section: 1 - 1990 data; 2 - 2005 data.](image)

At the same time, no such decrease was observed for S-waves; the value $V_s = 2.3$ km/s remained unchanged. In general, the results of observations indicate that the processes of changing properties within the unloading zone, noted in the 90s, continue. Moreover, in the near part of the zone, especially at the level of 977 m, the opening of the fracture is observed, which is characteristic of the early stages of the formation of the zone. At a depth of 1-3 m, a subzone with a thickness of 1-2 m is distinguished, characterized by lower speeds by 0.30-0.50 km / s and increased attenuation of ultrasonic signals.
4. Conclusions
   1. Based on many years of research of underground structures of the Rogun HPP with means of complex seismic-acoustic techniques a seismic-acoustic system for monitoring the geological environment of the medium hosting the underground structures has been developed.
   2. Analysis of the research data for the period 1990 - 2005 allows us to compare with the data of the works at the design stage and evaluate the changes that have occurred in the array containing the Rogun HPP engine room compared to the distribution curves and cumulative distribution curves of P and S wave velocities according to seismic and ultrasonic data for section of the machine room, as a quality parameter:
      • the elastic properties of the rock mass beyond the influence of mine workings over the past period have not undergone any significant changes and are characterized by the same level of elastic wave velocities as at the stages of research until 1992. Taking into account the close correlation relations between the velocities of elastic waves and the main geomechanical indicators (modulus of elasticity and deformation, strength indicators, etc.) for the rocks of the engine room of the Rogun HPP, it can be argued that for the internal (outside the influence of the mine workings) parts of the massif, their physical and mechanical properties from 1990-1992 have not changed;
      • for rocks within the zones of influence of mine workings, a slight deterioration of their elastic properties is noted, which is confirmed by a decrease in the average values of the P wave velocities of the ultrasonic frequency range in the vicinity of the machine hall by 9-10%. Along with the general deterioration of the physicomechanical properties of the rocks in the contact zone, they level out in the deep part. A comparison of the data of ultrasonic and seismic studies indicates that these changes in the properties of the rocks in the vicinity of the workings occur mainly due to the opening of small cracks and some additional compression of larger fracture faults. Significant changes in the power of the zones of influence of the workings have not been established;
      • there is a slight general deterioration in the elastic properties of the entire rock between the machine room and the transformer room. Here, the average velocity of P-waves for an irrigated massif decreased from 3.8 km / s to 3.45-3.5 km / s, i.e. approximately 9%. This decrease corresponds to a decrease in the elastic modulus and deformation modulus by approximately 15–20%. The reason for this phenomenon lies in the additional unloading of this pillar under the influence of a combination of factors caused by the creation of a network of various mine workings in the vicinity of the machine room, their long standing time and the influence of non-design flooding of the massif.

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