Ensuring safe operation and assessing the condition underground structures by the method of acoustic resonance flaw detection

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Abstract. In the article the main results of theoretical and experimental research in the field of nondestructive testing and forecasting of the geomechanical state of the dome part of transport tunnels. It is shown that for this purpose it is possible to apply the acoustic resonance defectoscopy method. The method of mine measurements consisted in fixing the forced oscillations of a multilayer carbon-rock massif with the shock initiation of a seismoacoustic signal. The excitation and reception of acoustic standing waves were carried out in the lower rock layer. The actual characteristics of the efficiency of the acoustic assessment of the state of the geoenvironment provide the authors the opportunity to recommend the described methodology for mass practical application in the transport tunnels.

1. Introduction

The task of ensuring industrial safety in the conditions of the continuing physical and moral deterioration of underground structures and equipment at hazardous production facilities in Russia causes the increasing role of diagnostic methods and tools. Non-destructive testing is an instrument of industrial safety examination. The modern definition of technical diagnostics as an industry of scientific and technical knowledge, the essence of which is the theory, methods and means of detecting and searching for defects of objects of a technical nature, covers methods and means of nondestructive testing. Non-destructive testing is an instrument of industrial safety examination, therefore, the reliability of the assessment of the technical condition of structures and equipment is largely determined by the applicable non-destructive testing equipment. Preference should
be given to integrated systems that allow monitoring of several factors influencing the safe operation of a structure.

Great scientific and practical interest for specialists in the construction of transport tunnels is the assessment of the geomechanical state of the rock massif in their arch. As the practice of mining in mines and metro, reliable information on the geological environment in the construction area allows you to choose the optimal parameters for the fastening elements.

The existing geological control methods do not allow to solve with a sufficient degree of reliability the indicated problem, and drilling of exploratory holes and wells is a very costly technological production process.

At present, geophysical methods based on the difference in the physical parameters of rock mass objects are used widely and successfully to predict the continuity of the geological environment. Their

advantages over other methods of forecasting are: high reliability of results (up to 92%), work productivity, relatively low financial costs for the implementation of mine research [1].

Results of the introduction of geophysical evaluation of the structure of the massif in coal and ore deposits, and also experimentally established close correlation dependencies between the physico-mechanical parameters of the coal-bearing medium and the fixed current geophysical field values provide an opportunity to use the underground seismo-acoustic methods and technologies in order to predict the state of the mountain massif in the construction of tunnels [2].

Geophysical work on the estimation of the geomechanical state of the vaulted part of tunnels is proposed to be carried out using spectral geoacoustics. The main role is assigned to acoustic resonant fault detection (ARFD), which with the necessary and sufficient reliability for the justification and development of the technology of excavation allows you to determine the spatial location of the rock layers.

2. Materials and Methods

Analysis and generalization of the results of studying the physicomechanical properties of rocks in the free state and massif made it possible to draw a number of conclusions that were used as the basis for the physico-mathematical theory of monitoring the state of the geological environment using the acoustic defectoscopy method. The starting point is the fundamental thesis of geophysics, consisting in the fact that the response (response) of the rock to the artificially generated signal depends on the frequency of the signal, the physical and mechanical properties of the constituent elements: density, porosity, stressed state, acoustic and electrical resistance, moisture saturation. During the passage through a complex of rocks composing the array, the acoustic signal changes its shape in accordance with the properties of the rocks, as well as the quality of the mechanical contact between the rock layers and their geometric dimensions.

The geological environment within the Rostov region is composed of the following rocks: argillites, shale interlayers (clayey and sandy fractions), siltstones and sandstones. The listed rocks have a fairly high density (the average value is 2.7 g/cm^3), strength (up to 115 MPa), relatively low water saturation (the average value is 0.4 %) and porosity (3.4 %). In this case, there is a significant spread in the parameters of the rocks in the horizontal and vertical directions.

As part of the development of the method of spectral studies, the authors relied on the results of studies of specialists in the field of geomechanics, which are described in the special literature [3]. According to the indicated data, strength and physical and technical parameters of rocks were measured at presses of the VNIMI Institute: tensile and compressive strengths, and strengths. In accordance with the accepted lithological classification, rock samples amounted to approximately equal samples: 114 pieces - clay shale, 116 - sand shale, 120 - siltstones. The volume of the sandy-clay lithotype group included thirty samples.

On the basis of the results obtained, conclusions were reached that are of decisive importance in the complex estimation of electrical and acoustic characteristics of lithological differences for the formulation of the equations of the relationship between strength and physical parameters in the specific conditions of the geological environment. The compressive strength in the direction perpendicular to the rock layers was σ_c = 10 - 170 MPa. For a specific rock, the strength values occupy a certain length on the numerical axis. The minimum value is possessed by argillaceous and sandy-argillaceous lithotypes (σ_c = 10 - 90 MPa), and most of the values are in the range from 30 to 70 MPa. The strength of shale facies is characterized by the quantities 30 - 110 MPa (mainly 50 - 90 MPa). The maximum values are siltstones – 70-170 MPa, the overwhelming majority of the tested samples (92 pieces) have strength 91 - 170 MPa. Strength characteristics of samples of lithotypes, investigated for tension, are arranged in the same order σ_c – smaller values of the strength limits belong to clay and sandy-clay facies groups (from 1 to 3MPa), the average position (in the area 4-6 MPa) take samples of sand shales, the maximum values from 6 to 9 MPa belong to siltstones.

If there is a significant variation in the strength parameters of the same facies in different regions, the tendency is quite clearly seen that the limits of the strength of the samples of the same lithotypes taken in a normal geological environment (without discontinuities) and in disturbed areas differ by tens of percent. So the parameter σ_c of the sample from the disturbed massif has an average value of 37% less compared to a similar sample collected in the reference zone.

From the standpoint of geomechanics, the decrease in the strength characteristics of lithotypes located in the disturbed zone can be explained by the ability of rocks to deform under the influence of tectonic processes. When loading is applied, the structural and texture characteristics of the facies change, as does the fracturing. The classical theory of geoacoustics asserts that the velocity and dynamic characteristics of elastic oscillations depend on the strength parameters of rocks and are uniquely estimated by the corresponding elastic moduli entering into the so-called wave equation. The results of full-scale experiments provide an opportunity to understand the conditions for the occurrence and propagation of a seismic signal in a geological environment.

It is known from practice that the stability of the "roof" of development, i.e. of the tunnel part is determined by the geomechanical and geometric characteristics of the rock layers forming the mountain massif: the degree of stratification, the spatial position in the geo-environment of the planes of mechanical weakening (MIP), and the value of the coefficient of mechanical cohesion between adjacent rock layers. The actual stratification of the mountain mass is mainly observed in the MIP, and not between the surfaces that limit the distribution of geological lithotypes in this section.

Identification of the physical causes determining the separation of rocks into layers along the planes of mechanical attenuation and propagation of the seismic signal in the geospace while studying it with the geoacoustic spectral method (ARD) enabled the authors of the article to construct a model that is reasonably suggested to be used in interpreting the results of studies.

Interpretation model of the geological environment, which we called the vertical gradient physico-geomechanical model (VGFGM), represents in its essence the approximation of a part of the rock massif of the "roof" in which the seismic signal. The basis for the application of the ARD method is the closely-related experimentally established close correlation between the spectral response of the geomedium response and the thickness of the rock layer, taking into account the adhesion quality along the separation planes [4]. The position of the MIP on the vertical is determined on the basis of the total thickness of the rock layers enclosed between the exposure of the tunnel arch and the boundary of the stratification to be found. The variation in the thickness of the layers, which uniquely determines the frequencies of the resonance oscillations f_{res}, has a vertical vector (the vertical axis of symmetry of the development). The analysis of the actual materials of underground measurements made it possible to estimate the value of the so-called core of the mountain massif of the geoenvironment over the production of h, which is approximately 20 meters [5].

3. Results
Taking into account these data, a representative volume of experimental studies was made, in the course of which the conditions and physical characteristics of the propagation of acoustic vibrations in the roof and tunnel soil along the vertical to bedding.

When pulsed signals are excited in an array on the surface of the MIP (in the boundary zone between rock layers), so-called forced "thick" oscillations are formed. The amplitude of the inherent acoustic oscillations of the response of the rock structure in the case of the presence of an attenuation plane significantly (several times) exceeds the amplitude of the response under normal conditions, i.e. in the absence of MIP.

The method of carrying out the experiment consisted in periodic instrumental recording of forced oscillations of a mountain massif representing, in the first approximation, a layered plane-parallel structure, with shock initiation of seismic acoustic signals. Excitation and recording of geoacoustic pulses were carried out in the lower rock layer. The distance between the points of excitation and recording of the signal was 1 to 5 m. The signal was recorded on a recording device (Figure 1).
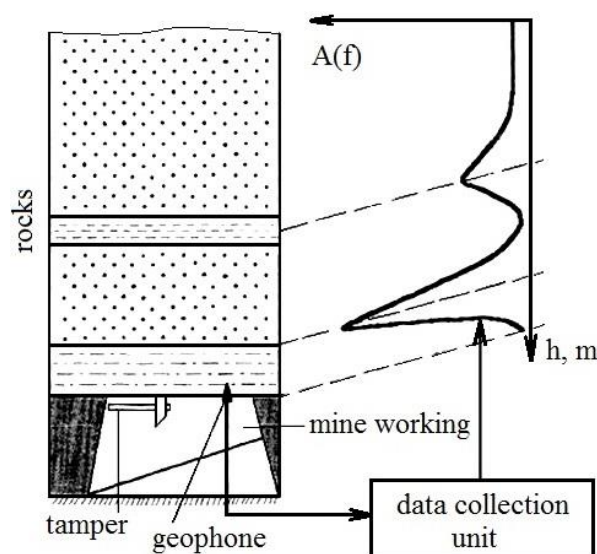
Figure 1. Testing scheme

The received seismograms were processed on a personal computer. Typical experimental records of rock mass responses contain a sequence of resonant extrema in the form of maximum values of amplitudes, which, according to the theory of geoacoustics, are due to the presence in the geological environment of fiber bundles along the planes of mechanical attenuation. The distance from the arched part of the development to the lower boundary of the desired rock interlayer uniquely determines the resonant frequency f_{res}, and the value of the amplitude maximum allows to estimate the quality of adhesion between layers. Comparative analysis of the results of studies by ARD and the characteristics of geological sections on reference holes confirmed the correctness of the proposed assumptions. It was found that the detected signal is stably determined by the physico-mechanical state of the geological medium at the point of measurement of the point and changes its amplitude-frequency characteristic in accordance with the variation in the geometry of the rock layers and the quality of the MIP [6-11].

The value of the distance from the output to the boundary K of the rock layer is calculated from formula

$$h = \frac{V}{2f} ,$$ (1)

where V – is the average speed of propagation of elastic vibrations in the geo-environment along the vertical, m/s; f – is the average speed of propagation of elastic vibrations in the geo-environment along the vertical.

Speed on different sections is 4000 - 5000 m/s. The amplitude of the spectral components of the seismic signal is inversely proportional to the quality of the mechanical cohesion between the rock layers.

Experimental studies of the wave pattern confirmed the following conclusions from the results of model studies and theoretical studies: relative to the form of seismograms, regression links between resonance frequencies and the thickness of rock layers, the interrelationship between the amplitudes of the spectral components of the seismic signal and the quality of the rocks. In this case, the spectrograms were classified according to the characteristic of the tunnel roof. In the presence of a stable direct "roof" of the mine workings, the high-frequency region of the seismogram has resonant maxima in the number from two to three units, otherwise (unstable state) – 5-6. The main overlying part of the array, heavy in loading properties, does not have fiber bundles and is characterized by the absence of spectral components in the low-frequency range (Figure 2).
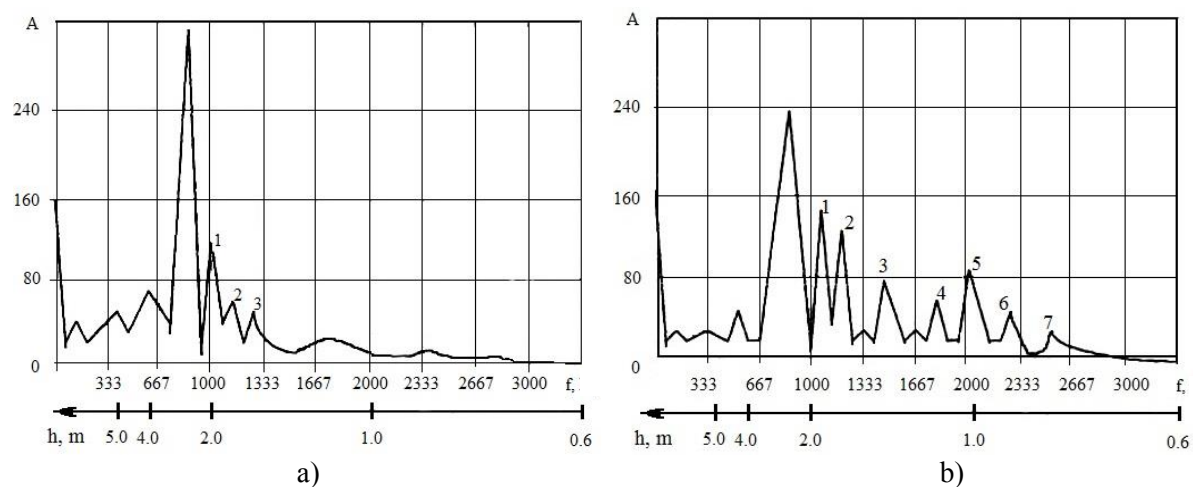
Figure 2. Typical experimental seismograms for the main types of the "roof" of the tunnel: a - for a stable immediate "roof"; b - for an unstable immediate "roof"; 1,2,3, ... n are resonance extrema

4. Conclusions

Practical confirmation of the scientific validity and effectiveness of the recommendations outlined in this article are the results of testing the methodology in the mine environment. Experimental work on the assessment of the physical and mechanical state of the roof rocks of mine workings with the use of the ARD method was carried out for twenty-five years at the mines of Donbass. The volume of tests was 137 profiles in various mine workings, which cover all typical mining and geological conditions. Comparison of the forecast data with the results of well logging, exploratory drilling and other actual materials of mining allowed:

   a) to evaluate the possibility of practical implementation of theoretical developments;

   b) to develop the methodology of mine measurements;

   c) determine quantitative criteria for assessing the condition of rocks.

   By results of tests the geoacoustic spectral method of an estimation of a physical and mechanical condition of breeds of a roof is characterized by following indicators:

   a) reliability of determining the number of OMC surfaces – 90 %;

   b) range of research (on the vertical axis) -15 - 20 m;

   c) resolution (the minimum distance between two neighboring planes) is 0.2 m;

   d) error in determining the distance to OMC – 10 %;

   e) reliability of forecasting of a condition of a roof by stability criterion – 90 %.

   The obtained technical and economic parameters of the geophysical forecasting of the structure of the roof rocks during the preparatory mine workings in the mines of Donbass, taking into account the analysis of specific mining and geological conditions, allow us to recommend the described underground geophysical methods for wide industrial use in the transport tunnels, which is currently very relevant.

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