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Methodological aspects of studying the parameters of elastic waves and controlling the standard form of acoustic emission in the field

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To measure the energy of the source of acoustic pulses in the absolute scale of units (J) from the registered pulses, an analysis of the energy balance „source of pulses"– „transmitting medium"– „receiver of pulses"was carried out using a spectral analysis device. Comparison of two independent methods for determining the energy of elastic interaction (capacitive method and photoelasticity method) gave a discrepancy between the results of less than 12%. The spectral composition of the interaction energy is determined. The results make it possible to determine both the parameters of the signal source and the structure of the transmitting average signal conversion. To measure stresses in an elastic wave, a piezoelectric receiver, in which a piezofilm served as a sensitive element. This receiver differs from receivers made on the basis of piezoceramic elements, has a significantly lower non-linearity of the amplitude-frequency characteristic, since it has only two natural frequencies.

Keywords: photoelasticity, elastic wave velocity, rock mass, concrete, acoustic emission.

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Introduction

The real geophysical environment has a complex structure and consists of blocks and layers. Equally oriented faults create the anisotropy of the medium, while microcracks form a network of small heterogeneities, determining the absorbing properties of the medium. The assessment of the geomechanical stability [1–3] and the safety of operation of various large-scale underground structures [4–6], such as tunnels and liquefied gas tanks, remains relevant [7,8], since the conclusions about the current geomechanical and geodynamic problems provided by mining research institutes state [9–11]that the tasks of ensuring safety and timely detection of critical situations that arise during the development of deposits and underground spaces remain not fully resolved. New methods and computer technologies make it possible to assess the stress-strain state in rock masses [12–14], but one of the widely used methods for such assessment is the acoustic emission (AE) method [15–17] , which studies the process of the initial stages of destruction (initiation and accumulation of microscopic cracks) [18] in various materials, such as rocks [19,20], building materials [21], composites [22]. Unlike homogeneous materials — glasses, single crystals, which are destroyed according to a quasi-critical scenario due to the growth of a localized center with the energy release from a limited number of simultaneously growing cracks, the development of damage under mechanical loading of brittle heterogeneous bodies occurs through a gradual accumulation of microcracks, since such materials have many „weak points", primarily in intergranular interlayers [23–25]. This paper discusses some important methodological aspects of studying the acoustic pulse (AP) propagation in rocks and concrete in the field conditions [26–28], and proposes solutions that reduce the error in calculating and measuring the parameters of elastic waves. Also, a method was developed, and the calculation of the coordinates of the AS source for media with a variable speed field was optimized, and its adaptation (implementation [26]) began [27] for the conditions of rock mass and concrete lining in some underground structures of State Corporation „Rosatom". The manual for large underground facilities under construction was developed, and new methods for studying destruction processes and optimizing calculations for filtering man-made AE noise were proposed as a reliable diagnostic method for AE monitoring of the stable operation of underground facilities [16]. The method for determining the amplitude-frequency characteristics of AE sensors, the method for calibrating a piezo-film sensor and low-frequency „mine" sensors (for installation and calibration in boreholes) without a preamplifier [27] were improved. A method was developed for serviceability test of acoustic sensors in natural conditions of the rock mass with concrete lining in underground structures of the State Corporation „Rosatom".

1. Basic method and monitoring acoustic wave reference form

To test the correct operation of the AE monitoring system a sensor based on a piezofilm (PFS) was manufactured and calibrated for measuring stresses in the elastic wave. This sensor, unlike the piezoceramic ones, has a linear amplitude-frequency characteristic (AFC) in the range up to 20 kHz. FPS was calibrated on a special stand-up to determine the sensitivity in units μV/Pa. In the performed preliminary studies the shape of the acoustic wave with FPS was monitored by the reference photoelasticity method, which is inertialess and makes it possible to measure the magnitude of stresses in the elastic wave and, accordingly, calculate its energy. This method is patented [29].

The study of the AP spectra from shock in laboratory and natural conditions showed that the signal can be characterized by a superposition of normal modes of propagating bulk waves in a solid body. The interpretation of AP spectra and the method for estimating acoustic energy are based on the fact that any object has certain geometric dimensions and can be represented as a half-wave oscillatory system. When excited by a pulsed source with a wide spectrum such object will generate a process with a narrow-band spectrum. The frequency of this oscillatory process depends on the following parameters: *1* — geometric dimensions of the object; *2* — propagation speeds of one or another type of waves. The quality factor of the oscillatory process (the value reciprocal of the wave attenuation coefficient in the medium) is determined by: *1* — the degree of object disturbance; *2* — boundary conditions at the object contacts with the environment; *3* — the duration of the impact of the pulsed source. Therefore, for a correct assessment of the source energy of elastic oscillations, it is necessary to know not only the amplitude-time parameters of the AP, but also the amplitude-frequency parameters. In the experiment, we measured the fraction of mechanical energy used by the source on the elastic wave excitation during the elastic collision of a steel ball (source) with a glass prism (transmitting medium), and independently measured the stress in the elastic wave by the photoelasticity method (receiver), which was excited by the source, from which the wave energy was calculated (Fig. 1).

For the model case, virtually all the energy of elastic impact was converted into the energy of elastic oscillations of the prism, which, in turn, has an almost ideal transfer function due to the homogeneity of the sample, the absence of any absorption mechanisms, and the observance of ideal boundary conditions (three stress components on the faces are equal to zero, i. e. there is no re-radiation to the external environment).

An estimate was made of the energy balance between the source and the oscillatory process in the sample. The evaluation was carried out on the basis that in a solid body of finite dimensions, a pulsed source of a single mechanical action generates an acoustic process representing the process of propagation of bulk longitudinal P- and shear S-waves, which, in turn, at the boundaries generate a secondary process of sample natural oscillations [28].

The energy of traveling bulk waves was calculated as the energy flux through the contact surface of the sensor with a prism:

$$E_b = S_t \cdot 1/\rho c \cdot \int_{t_1}^{t_2} \sigma^2(t)dt, \qquad (1)$$

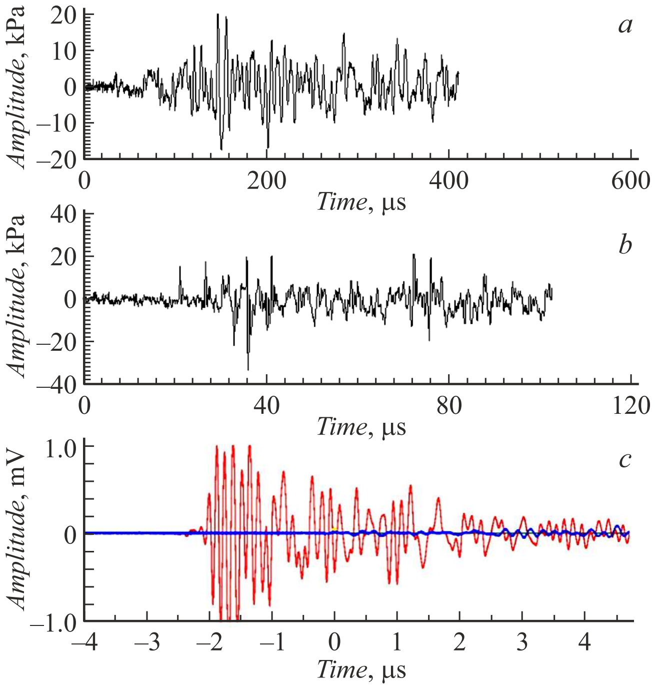

Figure 1. AE wave pattern: *a* — in glass prism from ball impact; *b* — in glass plate when crack occurs; *c* — in granite sample during the crack formation.

where the time interval $t_1 - t_2$ is the duration of the process of multiple re-reflection of bulk waves, σ is the stress in the wave measured by the photoelasticity method at each moment of time, S_t — sensor-sample contact surface area, ρc — material impedance.

The energy of natural oscillations of the sample was calculated as the sum of the energies of the normal modes of the sample:

$$E_{nm} = \sum_{i,n} (nS\sigma_0^2/8\rho c f_n), \qquad (2)$$

where $n = 1, 2, \ldots$ — mode number, index i denotes mode type, S — area of sample surfaces, which correspond to stress nodes in a standing wave, σ_0 — maximum voltage amplitude in a standing wave, f_n — frequency of the n-th mode of the i-th type. The energy values obtained by formulas (1) and (2) were compared with the measurements of mechanical energy loss of the ball as a result of collision with glass. To accurately measure the lost energy, the experiments were carried out in vacuum 10^{-3} mm Hg. Mechanical energy was calculated from potential energy:

$$\Delta E = mg(h_1 - h_2), \qquad (3)$$

where m — the weight of the ball, h_1 — the fall height of the ball, h_2 — the rebound height of the ball.

In elastic collision the mechanical energy of the ball is approximately 5% of the potential energy of the ball [30].

The elastic wave velocities in the concrete layer were measured on the basis of 988 mm. The time moments

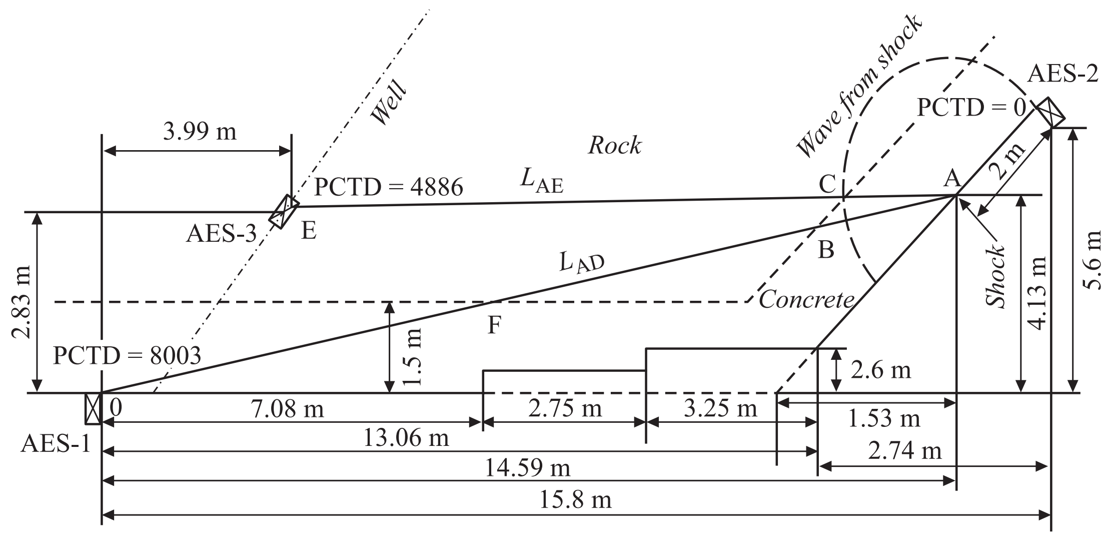

Figure 2. Layout of AE sensors and wave propagation from ball impact. LAD = 15.16 m — distance from point A to point D, LAB ≈ 2.0 m — distance from point A to point B), LBD = 13.16 m — distance from point B to point D; PCTD (pulse coming time difference) — time difference (in μs) of AP arrival to the sensors AES1 and AES-3 with respect to AES-2.

of wave arrival were registered by the first arrival of signals. According to these measurements, the velocity in the concrete layer is $V_{concrete} = 3920$ m/s [20].

The wave velocity in concrete was estimated by calculation using the modulus of elasticity E_{eff} for a plane wave:

$$E_{\text{eff}} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}, \tag{4}$$

where E — Young's modulus (for concrete it is 36.1 GPa), ν — Poisson's ratio (0.22). We obtain

$$E_{\text{eff}} = \frac{28.2 \cdot 10^9}{0.68} = 41.5 \cdot 10^9 \text{ Pa}.$$

The velocity of plane longitudinal wave C_L is equal to

$$C_L = \sqrt{E_{\text{eff}}/\rho}, \tag{5}$$

where ρ — concrete density (2200 kg/m^3).

Then we obtain the velocity of plane longitudinal wave in concrete $C_L = 4343$ m/s.

The measured velocity along the layer turns out to be less than the calculated velocity of plane waves C_L.

Fig. 2 shows the measurement scheme for determining the velocity of elastic wave propagation in the rock from the source of excitation of AE signal by impact by the ball with weight of 4.68 kg on a concrete lining at a distance of 2 m from the AES2 (AES — acoustic emission sensor).

An algorithm for calculating coordinates based on the Nelder-Mead method (simplex method) of finding the local minimum of a function of several variables was developed and is used. For two variables the simplex is a triangle, and the method is a search scheme that compares the function values at the three vertices of the triangle. The worst vertex (with the highest function values) is discarded and replaced with a new vertex, and the search continues. After determining the best approximation (X, Y, Z) for a given set of arrival time differences (ATDs) (Fig. 2), based on the obtained (X, Y, Z) the corresponding set of ATDs is calculated, and the discrepancy in determining the coordinates is determined. This method also makes it possible to consider the speed of sound as an unknown (adjustable) value. AE source coordinates are determined based on the system of nonlinear equations

$$\sqrt{(X-X_i)^2 + (Y-Y_i)^2 + (Z-Z_I)^2} - R_0 - V \cdot t_i = 0, \tag{6}$$

where $R_0\sqrt{(X-X_0)^2 + (Y-Y_0)^2 + (Z-Z_0)\{2\}}$ — distance from the source to the sensor closest to it, t_i — delay times for the i-th sensor, measured in the experiment, X, Y, Z — source coordinates, X_i, Y_i, Z_i — sensor coordinates, V — sound velocity in the medium. To solve the system (6) three sensors (AES) are required, and there are zones for which there are two solutions. However, the greatest difficulty is that the actual delay times are measured with a certain error, often significant. Therefore, one should strive to use a larger number of sensors (AEA) $N > 3$, especially with a large monitoring area. On a concrete sample the sound attenuation is higher, so the location error is greater, but the algorithm is quite efficient in this case as well.

The measured value of the propagation velocity of longitudinal elastic wave in the rock was $V_{rock} = 5320$ m/s.

The calculation of the propagation velocity of the longitudinal elastic wave in the rock according to the above formulas of the theory of elasticity gave a value of 5250 m/s, which is close to the measured value.

The stresses in the elastic wave were measured with a piezofilm sensor. It studied the spectral composition of

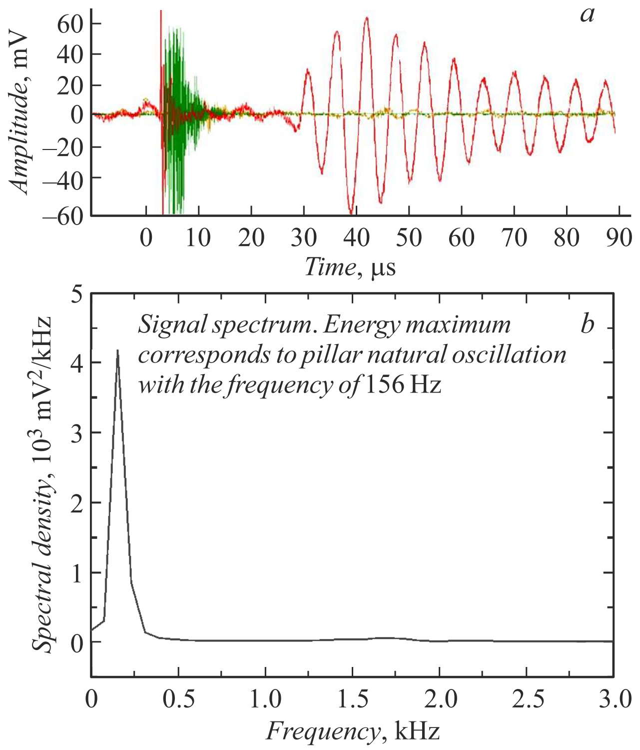

Figure 3. Signal from AES1 and AES3 with respect to AES2 (*a*) and signal spectrum (*b*) from structural element of the rock mass when it is excited by the impact of a steel ball with weight $m = 4.684$ kg.

the rock mass response to its excitation by the impact of steel ball with weight of $m = 4.684$ kg, and also energy of the elastic wave formed from the impact by the ball was estimated. The research results showed that at the location of the sensor installation the compression-tension oscillations were recorded through the thickness of the structural element of the rock mass in the form of a plate [20]. The signal and spectrum of the oscillation signal are shown in Fig. 3.

Based on this signal the energy in the elastic wave was estimated using formulas (1), (2), which was equal to approximately 0.12 J. And the measured value of mechanical energy loss during the ball collision with the rock was about 6 J. This difference is due, firstly, to the fact that when elastic wave is excited by ball hitting the rock, the collision is not purely elastic, since the rock near the surface of the working is strongly destroyed and absorbs a significant fraction of the ball mechanical energy at the point of contact. On the other hand, it is possible to estimate the fraction of energy spent on the formation of the field of elastic oscillations in the mass during purely elastic collision, using laboratory data obtained for the value of the potential energy loss of steel ball as a result of purely elastic collision with glass, which was approximately 5% of the potential energy of the ball. It was considered, as already mentioned above, that all the lost energy was spent for the formation of the field of elastic oscillations, and the elastic characteristics of the rock that constitutes the rock mass, and of the glass can be considered close, since the densities and propagation velocities of bulk waves are approximately the same. This value was approximately 0.58 J, which is comparable to the previously indicated values of the energy of elastic oscillations 0.12 J. The initiation of initial cracks corresponds to the energy release (reflecting the level of stresses, the size of the cracks, and the elasticity of the material). At the first stage this value is approximately the same for all cracks. At the second stage, increased stresses act in the fracture center, which, when new cracks are generated, leads to energy release, the value of which continuously increases. Thus, registration of the energy release (its change) makes it possible to fix the change of stages and detect the transition to the pre-rapture state, and the linear extrapolation of the measured dependence to zero time gives a lower estimate of the residual life time resource.

2. Discussion

To adapt the described method to work on underground structures a piezoelectric receiver [26,27] with a linear frequency response in the range up to 20 kHz was developed, manufactured and calibrated to measure the elastic wave stresses. It measured the spectral composition of the rock mass response to its excitation by the impact of ball with weight of $m = 4.684$ kg, and also energy of the elastic wave formed from the impact by the ball was estimated. Comparison of the estimate of the elastic energy (about 0.3 J) with the loss of mechanical energy upon impact by the ball (about 6 J) is very approximate [31]. This is mainly due to the fact that when the elastic wave is excited by a ball hitting the surface of working, the collision is not purely elastic, but is accompanied by the destruction of the rock at the point of contact, to which a significant proportion of the mechanical energy of the ball lost during the collision is used. The approximate estimate of this phenomenon makes it possible to correct the value of the elastic energy to about 0.58 J, with which the value of the energy of elastic oscillations, the calculated value of 0.12 J, is in acceptable agreement. Therefore, in order to correctly estimate the energy, it is necessary to eliminate the mass destruction when it is excited by the ball impact, for example, by embedded parts installation [20].

Conclusions

To monitor the reference form of the acoustic wave and to calibrate field AESs the methodological recommendations were developed and implemented. The importance of calibration is confirmed by the comparison of the recorded signals of the piezoelectric sensor with the reference signals obtained by the photoelasticity method for the same conditions of the field excitation of elastic oscillations in the reference sample. This made it possible to substantiate the choice of the frequency range and the manufacture of special AESs for use in selected wells, as well as to calibrate them in natural field conditions. Data on the mechanisms of elastic waves and their analysis during energy dissipation in stressed heterogeneous materials can be used for practical purposes in the development of methods for determining the AP source parameters, in particular, its energy and location, as well as the structure of the transmission medium, which will increase the reliability and information content of methods for monitoring the latent processes that pose a danger to various underground structures.

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Conflict of interest

The author declares that he has no conflict of interest.

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