Automated system for stability diagnosis of hydro technical structures

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SUMMARY

The influence of dangerous geological and man-made processes on the real geological environment leads to scattered destruction, which in turn causes the degradation of deformation properties, the reduction of effective elastic properties, and the change in the structure of the fracture-pore space and, accordingly, the change in filtration properties and pore pressure. A characteristic feature of the mechanical behavior of the geological environment is the possibility of accumulating mechanical damage even under small quasi-static loads, not only under the action of shear stresses, but also under tension and compression. The generation of cracks is inevitably accompanied by the absorption of energy owing to the growth of cracks and the corresponding change in the structure of the geological environment in the vicinity of crack banks. Military operations are a source of man-made cracks. Consequently, a significant number of hydro technical structures in Ukraine were damaged and destroyed. This makes it necessary to diagnose the stability of hydro technical structures. For this purpose, an appropriate automated system was developed. The adequacy of its results was verified through experiments using the acoustic emission method.

Keywords: automated system, microcracks, deformations, acoustic emission, stability diagnosis, hydro technical structures
Introduction

The study of the stress state of the geological environment for diagnosing the stability of hydro technical structures should be conducted together with the study of physical processes in places of destruction, because these phenomena are cyclically interconnected (Gomelya et al., 2020). Because of military operations, a significant number of hydro technical structures in Ukraine have been damaged and destroyed (Kuzmych & Voropai, 2023). Explosions of different types of ammunition cause damage (destruction) to the integrity of the environment, which can occur in two scenarios: the activation of old fractures and cracks that already exist in the geological environment, and the emergence of new breaks and chips (Ivanik et al., 2022).

High- and medium-magnitude earthquakes can be considered to be analogous to the influence of military operations on the technical condition of hydro technical structures (Ivanik et al., 2022). A model of brittle destruction of the geological environment is generally accepted (Rokochinskiy et al., 2023). Under the breaking and fragmentation conditions of the geological environment, plastic deformation occurs during the destruction process, which is associated with the friction of the formed fragments (Halysh et al., 2020). This process is accompanied by an intensive transformation of elastic energy into heat (Turcheniuk et al., 2022).

Method and Theory

The receiving sensor was attached to the test sample using rigid gluing. The receiving sensor was connected to the AF-15 device through a blocking filter and pre-amplifier (with $K_0 = 40 \text{ dB}$, $F = 200–1000 \text{ kHz}$) (Onanko et al., 2021). The AF-15 acoustic emission (AE) device provides reception of AE signals on two channels and simultaneous registration of at least four informative parameters: amplitude, counting rate, shape and duration of AE pulses, sum of oscillations, and registration of AE parameters on a computer, as shown in Figure 1 and Figure 2. The rejection filter in the AE signal path provided suppression of voltages in the range of 1.0...3.0 MHz (range of excitation frequencies of the tested samples) by at least 50 dB. The amplitude of the AE signals exceeded the noise level in the experiment up to 50 times.

![Figure 1. AE-control equipment technique (left) and formed pulse after the peak detector (right).](image)

![Figure 2. Block-diagram of AE-control registration technique.](image)

1 – radio pulse generator, 2 – rock, 3 – acoustic emission sensor, 4 – blocking filter, 5 – preamplifier, 6 – acoustic emission signal processing device AF-15, 7 – oscilloscope, 8 – personal computer
Results

If a plane monochromatic elastic wave propagates in a geological environment with an initial uniform stress, the generalized Green–Christoffel equation can be constructed using the linearized elasticity ratio of the theory of finite initial strains (Vyzhva et al., 2011):

\[ (B_{ij} - \rho \dot{\epsilon}_{ij} \dot{\varepsilon}^0)(U_j) = 0. \]  \hspace{1cm} (1)

where \( B_{ij} = \frac{C^{ijkl} \lambda_i \lambda_j \lambda_l \lambda_m \eta_{im} \eta_{lj}}{2(\eta_{im} + \eta_{lj})} \), \( \dot{\epsilon}_{ij} \) is the strain rate tensor, \( \dot{\varepsilon}^0 \) is the initial strain rate tensor, \( \rho \) is the density of the geological environment; \( U_j \) is the effective density of the geological environment; \( \dot{\varepsilon}^0 \) is the effective density of the elastic wave. It follows from the solution of Equation (1) that three-phase velocities with orthogonal polarization vectors propagate in any direction of the wave normal to the geological environment (Bohaienko et al., 2023).

To estimate the values of microstresses at which destruction of the geological environment occurs, it is necessary to determine the dependence of the average stress components on the macrostresses and temperature:

\[ C_1 \left( \sigma^{(1)}_{ij} \right) = \left( S_{ijkl} - S^{(2)}_{ijkl} \right)^{-1} \left[ \left( S_{ijkl} - S^{(3)}_{ijkl} \right) \left( \sigma_{pq} \right) + \left( \alpha_{ij} - \alpha_{ij} \right) \right]; \]  \hspace{1cm} (2)

\[ C_2 \left( \sigma^{(2)}_{ij} \right) = \left( S_{ijkl} - S^{(2)}_{ijkl} \right)^{-1} \left[ \left( S_{ijkl} - S^{(4)}_{ijkl} \right) \left( \sigma_{pq} \right) + \left( \alpha_{ij} - \alpha_{ij} \right) \right]; \]  \hspace{1cm} (3)

where \( S^{(1)}_{ijkl} \) - elastic compliance of the component; \( S^{(2)}_{ijkl} \) - effective elastic compliance of the geological environment. Similarly, expressions for the average deformation components can be obtained (Romashchenko et al., 2022).

Because of the current impossibility of conducting experimental research directly on damaged hydro technical structures, the parameters of the theoretical model of SiO\(_2\) fracture-pore geological environment \((-\varphi_1^0 \neq -\varphi_2^0 \neq -\varphi_3^0)\) were entered at the input of the automated system. The horizontal compressive stresses were assumed to be unequal, that is, \( \sigma_2^0 = \frac{\xi}{4} (\sigma_1 + \sigma_3) \) and \( \sigma_3^0 = \frac{\xi}{4} (\sigma_1 + \sigma_2) \), and the vertical component of the stress tensor \( \varphi_3^0 = \sigma_3 \). Numerical calculations of the acoustoelastic effects of SiO\(_2\) modules with chaotically oriented “disk-like” microcracks (with microcrack density \( \xi = 0.05 \)) were performed under the conditions of a spatial stress state \((-\varphi_1^0 \neq -\varphi_2^0 \neq -\varphi_3^0)\) in the form of stereographic projection of isolines of characteristic surfaces, as shown in Figure 3.

The symmetry of the stereographic projections of the characteristic surface of the isolines with equal values of the anisotropy coefficient \( A_2 \) turned out to be rhombic, that is, it coincided with the symmetry of the stress tensor. The extreme values of the phase velocities of the longitudinal waves are collinear with the directions of action of the principal stresses. The maximum value of the quasi-longitudinal waves coincided with the direction of the action of the maximum compressive stresses. The obtained quantitative estimates of the coefficients of elastic anisotropy can be considered as the minimum possible, because the processes of closing and opening of microcracks depend on their orientation to the direction of action of the principal stresses, and the possibility of generating new microcracks under the conditions of thermal stresses was not considered during the modeling. Figure 4 (left) shows the acoustic response after laser irradiation by a ruby laser with an intensity of \( I \approx 300 \text{ MW/cm}^2 \) into SiO\(_2\), which was accompanied by the creation of inhomogeneous thermomechanical stresses with the melting of the crater and release of the melted sample onto the surface. The temperature-pressure dependence (directional surface of the elastic body) of SiO\(_2\) elastic module \( B_{001} = \mu V_{010}^2 \) \( = \mu V_{200}^2 \left[ 3 + \frac{1}{1 - \left( \frac{V_{100}}{V_{200}} \right)^2} \right] \) (Onanko et al., 2012) is shown in Figure 4.
**Figure 3.** Stereographic projection of the isolines of the coefficient of differential elastic anisotropy of the SiO₂ model for the stressed state \((-v_2^0 = -v_3^0 = -v_4^0)\) (isolines in %) (left) and stereographic projection of isolines of the wave phase velocities longitudinal polarization of the same model (isolines in km×s⁻¹) (right)

**Figure 4.** AE signal in SiO₂ by a ruby laser intensity \(I \approx 300\, \text{MW/cm}^2\); 2 V/div., 250 μs/div. (left) and temperature-pressure dependence (directional surface of elasticity body) of SiO₂ elastic modulus \(E_{001}\) (right)

The numerical results obtained were in good agreement with the experimental data obtained using the AE method and indicated the existence of intense acoustoelastic effects under the influence of the stress state in fractured rocks.

**Conclusions**

1. Based on the results of seismoacoustic research, an automated system for stability diagnosis of hydro technical structures was developed using a model of a discrete nonlinear multicomponent fracture-pore geological environment with initial pore pressure.

2. Owing to the evaluation of the microstresses and deformations in the components, it is possible to forecast the dependence of the phase velocities of the geological environment on changes in the stress state, temperature, and pore pressure. Determination of fracture-pore zones using seismoacoustic methods is of great interest for diagnosing the stability of hydro technical structures.

3. In this study, a new discrete nonlinear multi-component crack-pore model with intrapore pressure is proposed, which is influenced by a complex stress state and temperature. This model can be used to diagnose the impact of military operations on the technical condition of a hydro technical structure.

**References**


