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Method of seismoacoustic evaluation of stability and strength of rocky objects and constructions

Calculation models of stability and strength adopted for substantiation of reliability of civil engineering designs and determination of the state of operated facilities with structure including rock (geostructural) mass are recognized even by their authors as approximated, sometimes conventional and, in general, suitable more likely for "qualitative analysis" [Gaziev], rather than for accurate solutions.

Application of arbitrary complex tools of mathematical apparatus detailing calculated environment and pretending to a precision does not compensate for a priori lack of source perceptions and data on properties of an object activated by its natural-technogenic situation. Unfortunate situation is evidenced by repeated crushes, emergency deformations of mining edges, underground structures, etc., including ones during usage of applicable normative or scientific-calculated grounds.

In-situ control over hidden processes forming stability (strength) conditions could become the most prospective way out of principal contradiction between requirements to reliability and restricted possibilities of its scientific support. In order to introduce such control into the practice of designing and construction, it is necessary to elaborate physically adequate criterion for evaluation of environment state corresponding with method of control.

Analysis of theories (criteria) concerning strength of sophistically arranged poly-component environments like rocks demonstrates that their (theories) multiplicity (not exhausting real features of environment behavior under load) manifests common characteristics. Stressed-strained state (SSS) is correlated with form alteration of a material during successive reaction to impact.

With known conventionality, main stages of deformational manifestations are described as elastic, elasto-plastic (and/or viscous) destructive associated with signs of the increased volume of area of deformation, expansion of flaws (cracks) and accompanied by reduction or stabilization of effective stresses.

In most cases, discussed environments are defined as rheologic ones deforming at final stages in conditions of relaxation and dilatancy.

Unless marking recognition properties, such a process must possess with at least signs of occurrence of boundary (transition) states, including ones preceding critical development of events.

In order to study possibility of tracing SSS dynamics and searching for precursors or accompanying indices of rocky environment destruction, researches were performed with rock samples and directly in geostructures (underground workings and construction site trenches).

Semi-hard (low-strength eroded sandstones) and hard (up to high-strength massive crystalline schist) were subjected to tests. Samples – core and individual natural pieces – were loaded in conditions of uniaxial compression – tension and compression (unloading) with side support (for core, in metal cartridge with adjustable counter-pressure). The following was measured: deformations and propagation velocities of longitudinal and transverse elastic waves with two-four cycles of loading-unloading and with maximal compression of samples up to 80-95% of the average value of strength limit for uniaxial compression (up to 70% of actual strength of tested sample).

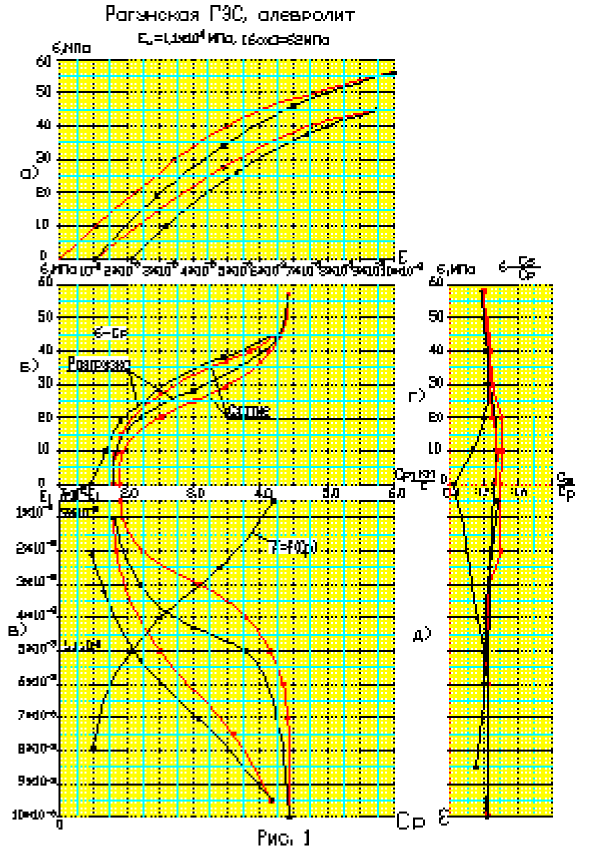

Рис. 1

Диаграммы данных испытания пород:
а) напряжение–деформация; б) напряжение–скорость УЗВ;
в) деформация (относительное перемещение, λ)–скорость УЗВ;
г) напряжение–отношение скоростей поперечной и продольной (Cs/Cp) УЗВ;
д) деформация (относительное перемещение)–Cs/Cp. Пунктиром–данные по породному массиву, остальное–по образцам пород

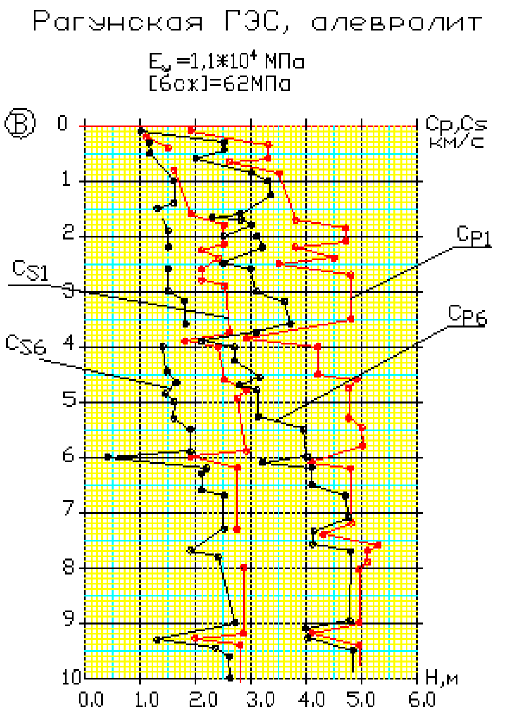

Рис. 2

Распределение скоростей УЗВ по глубине массива в 1-ом и 6-ом циклах нагружения (этапах разработки машзала)

Results of tests of rocks (preliminarily compressed in order to remove natural unloading of samples) are presented in Figs.1, 3, 4, 5.

Сангтудинская ГЭС, песчаник

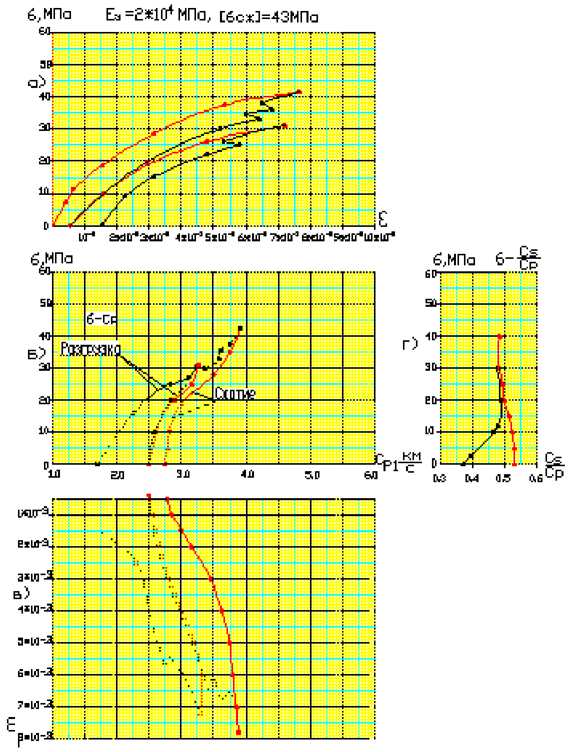

Рис. 3

Диаграммы данных испытании пород
(обозначения см. рис. 1)

Саянская ГЭС, кристаллический сланец

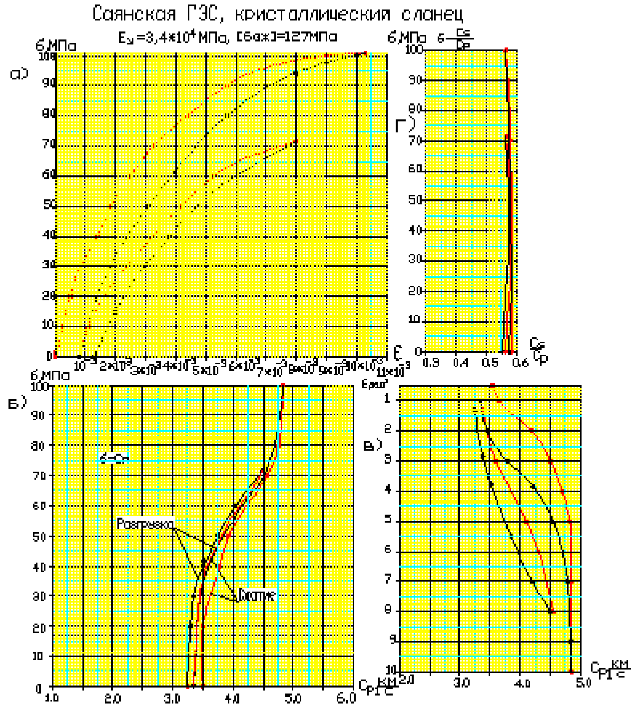

Рис. 4

Диаграммы по данным испытании пород
а) напряжение-деформация; б) напряжение-скорость УЗВ;
в) деформация-скорость УЗВ; г) напряжение-отношение скоростей
поперечной и продольной (Cs/Cp) УЗВ;

As can be seen, “stress-strain” diagrams confirm typical nature of tested material behavior within the wide range of its strength properties (initial compressive resistance of rocks is within 40 to 130 MPa). Above noted differences in the state of a material in the process of loading are revealed in this case as well; however, boundaries of alterations are not fixed, as a rule, and possibilities of destruction (formation of macro-cracks) prediction by the test data in parameters directly describing SSS appear to be restricted. For example, displacement (in the result of shift along surface of weakening or expansion of micro-cracks), which is interpreted uniquely as local one and being the symptom of the beginning of destabilization of sample stability, was observed with poorly cemented sandstones only (Fig.3) during unloading of stresses being limit ones for them.

At the same time, test results verified additionally by sample insonification with determination of ultrasonic wave (USW) propagation velocity provide exhibit of stage-by-stage alterations in the state of rocky material in the process of its loading (Figs.1-5). This phenomenon is conditioned by the nature of target value – wave propagation velocity depending simultaneously on both variation of insonification base dimensions (in the result of deformation) and the yield of a material with internal transformation of its microstructure.

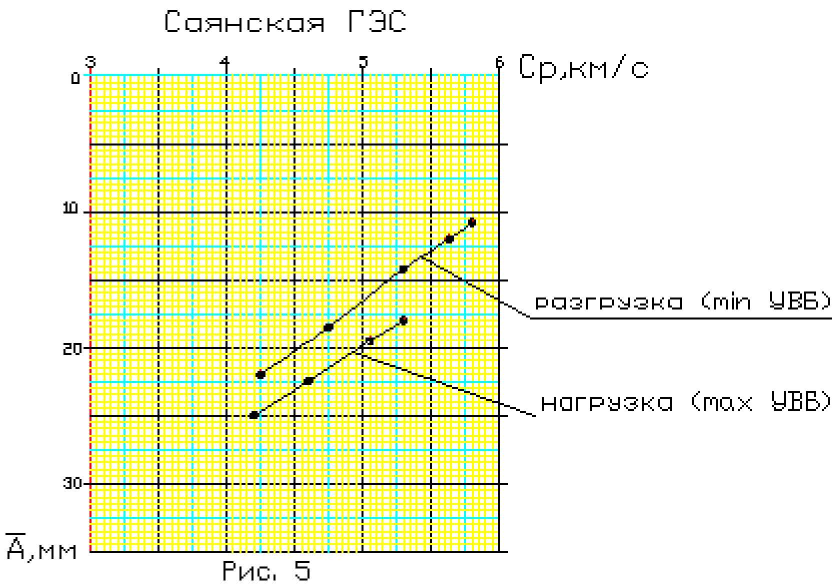

Рис. 5
График связи :
Скорость упругих волн (Ср)-перемещение
(осадка) поверхности основания плотины

Increase of “sensitivity” of the state testing by insonification as compared with method of direct measurement of macro-manifestations is revealed already at the stage of elastic (quasi-elastic) loading of a sample. For example, in Fig.1, constant inclination angle (elasticity modulus within limits of measurement accuracy) on the “stress-strain” graph in compression cycle at press pressure of up to 20 MPa is accompanied by noticeable rise of USW velocities emphasizing effect of movements in the loaded rock.

Indicating motion as a factor of alteration of the environment form defining eventually stability (strength) of an object, velocity of elastic waves appears to be the working index of the dynamics of its state. In particular, with deformation level exceeding elasto-plastic resistance of rock, USW velocity approaches asymptotically to some minimum decreasing drastically previous rate of its trend. Obviously, this circumstance is related with beginning and development of microstructural rearrangement of environment, which can be considered as a state of destruction precursor.

Alteration trends in the environment are demonstrated even more radically by the measurement data represented in the form of ratios of velocities of transverse (Cs) and longitudinal (Cp) waves. Being the dynamic equivalent of the Poisson’s coefficient, this index of shaping fixes rise of transverse displacements during longitudinal loading-unloading by sharp variation of Cs/Cp values (Figs.1 d, e; 3 d).

Ultrasonic and seismic (hereinafter, common term “seismoacoustic” is adopted) observations performed in the rock mass in parallel with geodetic measurements of surface movements confirm results obtained with rock samples. Masses brought into active state by stage-by-stage drifting of underground chambers like machinery halls (Rogunskaya

HPS) and constituting dam foundations during filling and activation of a reservoir (Sayanskaya HPS) were adopted as an objects for observation and analysis.

Propagation velocities of elastic waves and movements (in the course of convergence and setting) of the foundation contour of objects were the measurable parameter of the mass properties.

Determinations were performed in wells, on surface and in measurement galleries in the foundation of mass. The set of methods of seismoacoustic profiling and insonification was applied. Example of distribution of velocity values across the depth of mass at various stages of its loading-unloading is presented in Fig.2 (data on 1 and 6 stages of descend of machinery hall at Rogunskaya HPS). Diagrams in Fig.2 evidences significant dynamics of the environment reaction to transformation of internal stress tensor in process of the release of energy of drilled in mass. It is seen that up to analyzed depth of 10 m, mass responds actively to the opening of free movement surface in the result of exploitation of machinery hall cavity. Under data of parallel geodetic measurements, these processes in mass are accompanied by displacement of machinery hall walls resulting in internal effects of unloading.

Relationship of phenomena observed in environment and on its surface is established by diagrams in Figs.1 c, e and Fig. 5. Moreover, such interconditionality of various behavioral indices of loaded semi-space does not differ in principle from one defined by testing of rock samples simulating such effects.

Analysis of correlation between seismoacoustic indices of the state of deformed environment and characteristics of stressed-strained conditions in it makes it possible to mark out unambiguously signs of occurrence (preparation, more precisely) of material disintegration stage.

Index of slope (rate) of the velocity value variation and the ratio of velocities of longitudinal and transverse waves by values of movements of the rocky object surface is recommended to be adopted as recognition criterion for precursor of conditions being critical for stability (strength) of rock mass. Herewith, criterion parameter – inclination angle of curves A=f(Cp), A=f(Cs/Cp) increases toward axis Cp and decreases toward axis Cs/Cp tending to some constant values. For example, for curve A=f(Cs /Cp), this limit angle is defined by condition (Cs/Cp) → 0 (Poisson's coefficient tends to 0.5) for the case of marginal state of rock, i.e. its destruction, complete loss of cohesion in a material, which is not implemented practically due to preservation of residual strength (but, not stability obligatorily) of shifted mass.

In principle, lack of stability and subsequent caving can occur also without destruction of shifting object material, but in result of formation of the shear surface (layer, more precisely) only (collapse of so-called "absolute rigid body"). However, even in this case, shear is preceded by destructions on displacement surface in the form of opening of cracks and shear-bearing of their walls. Seismoacoustic observations monitor these events with fixup to the place of manifestations. Process of their preparation must not differ from above described one.

Volumetric expansion at the stage of pre-destruction – dilatancy – as a result of non-uniformity of shear strength and local discreteness of this multi-component environment of complex structure is the common feature of rock mass deformation. In order to provide efficiency of seismoacoustic monitoring, this factor of stability upset associated with possibility of the object free movement creates accenting prerequisites. Dilatancy changes sharply steepness of the drop of velocities and ratios of the transverse and longitudinal wave velocities (*see,* for instance, Fig.3b, c, d) with preservation of the sample residual strength, as shown in Fig.3a, but with signs of movement along newly formed flaws (Fig.3b, c). Displacement of an object noted in observations must be related, obviously, with reduction of stability margin: in assessment of risks, special cases of temporary recovery of stability following displacement cannot be considered.

In either case, i.e. with or without dilatancy, relationship of seismoacoustic and kinematic indices of mass properties and state proposed as a criterion provides possibility of prediction of critical conditions prior occurrence of the collapse danger.

It is recommended to perform control observations over potentially instable (subjected to destruction) rocky object in the mode of monitoring with minimal, as far as possible, interval between measurements, including automated version.

Results of performed observations over the mass are presented in Figs.1c, 5 in the form of A=f(Cp) graphs. Despite of known data fragmentariness and absence of the actual event (collapse), variation of steepness of the graph in its upper part (with $A>=7.5\cdot10^{-3}$) in Fig.1c is interpreted as a primary sign of block displacement in the wall of machinery hall at Rogunskaya HPS. Materials of tests of samples of rocks of the same mass performed in parallel and presented in Fig.1 provide basis for such interpretation.

Conclusions

1. Analysis of strength theories, results of tests of samples of rocks considered as a behavioral model of the loaded rock mass, as well as results of paired geodetic and geophysical measurements on surface and inside the mass had made it possible to establish suitable for measurement criterion of evaluation and prediction of the rocky object stability.

2. Direct observations in the monitoring mode confirm efficiency of method of object seismoacoustic studies performed in parallel with measurements of object surface movements during tracing of dynamics of the stressed-strained state of rocky mass this object is composed of.

3. As an indices of preparation of conditions within a mass being critical for stability (by the reduction of resistance), it is recommended to adopt parameters in the form of the variation rate elastic wave propagation velocity and/or ratios of longitudinal and transverse waves velocities per unit of variations of values of the object surface movements.

Accenting influence of dilatancy process in the crevassed hard (semi-hard) rock mass on the recommended criterion is noted.

4. Made conclusions and recommendations are confirmed by the results of simulation tests and in-situ observations over rock mass presented in this paper.

References:

E.G. Gaziev. Rocky foundations of concrete dams. Moscow, Printing House of the Association of Civil Engineering Institutions, 2005.