

NEW SENSOR TECHNOLOGY FOR DETERMINING ROCK
PRE-DESTRUCTIVE STATES

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Abstract

Based on the experimentally discovered regularity – emission of micro-sized particles during monoaxial deformation of non-homogeneous structures, such as rocks and concretes, a sensor technology to identify their pre-destruction processes is proposed. At nearing the stressed state until the disintegration of the massifs, exponential increase of particles generation appears. The innovation is applicable to risky rock formations where vertical measurement boreholes are made, by which kernels are obtained. Using the specimens formed by the kernels, through monoaxial load by press in laboratory conditions and corresponding particle emissions, the reference pressure values for different stages of the pre-destructive state development are determined. The reference data from the pressure are compared with the results for the deformation loads in the rock structure, corresponding to the generated particles in a borehole model. The values of the stress determine the occurrence of critical states in the structure. This information is an integrated indicator for the timely identification of pre-destructive processes in rocks. The described system increases the accuracy of determining the appearance of failure conditions. One of the strategic applications of the new technology is in seismically active regions.

Key words: particles emission process, monoaxial deformation, rock structures, integrated indicator of failure events, seismically active regions

Introduction. Among the major problems at the extraction of energy resources and ore fossils using underground technologies are the rather complex

mining and geological conditions and the great depths. The anthropogenic activity results in material change of the natural tense state of the rock massifs and the underground horizons. During the design and use of the deposits, information about the level of the initial internal energy in rock structures and its change in the course of the exploitation process is required. The emerging static and dynamic loadings under the conditions of non-homogeneous stress generate crucial conditions in the massifs, and quite often – serious failure situations. Therefore, the non-destructive methods and devices assessing the stress-strain state of the rocks, construction equipment including, are particularly promising. Regardless of the diverse information which they present for some basic characteristics of these processes, the obtained data are differential. This means that each parameter is acquired individually by a specific method/regularity for which relevant equipment has been developed [1,2]. However, such approach complicates the control and the adequate metrology. Here are some of the most widely distributed technologies for the purpose. To forecast the destructive processes in mountainous massifs, electromagnetic and acoustic emissions from the rocks during their deformation, Fourier spectral analysis is used. The results thus obtained allow to make conclusions about the dynamics of the deformation state [3,4]. However, the drawback here is the low accuracy of the destruction forecast related with the dominating uncertainty in its occurrence from the chaotic electromagnetic and acoustic radiation. Another widely distributed approach, particularly important in seismology, which determines the distribution of the rocks' stress-strain state, is the release of the radioactive gas radon (Rn). It is registered by a series of specifically formed boreholes of various depths in the massif [4]. The problems here lie in the fact that the results are affected by the instability of radon release in the selected test area, as well as the difficulties in recording the variations of atmospheric pressure and precipitations. Optic systems are also used, which are positioned in some control points of the risky massif. The disadvantage here is again the low accuracy of the forecast due to the readings' errors, including a number of occasional processes, most often, landslide ones, as well as pollution of the optic devices [3].

Recently, a new effect has been experimentally observed. It lies in the generation of micro-size particles in structurally unordered solid body materials, such as rocks and concrete composites under the action of strong monoaxial deformations [3-9]. This regularity allows to use the emission of particles as an integrated sensor technology assessing the strained state of rocks. For the purpose, it is proposed to form in advance a measurement horizontal borehole in the rock massif [10]. An indicator for the occurrence of pre-destructive state in the structure is the abrupt increase of the amount of generated particles. The drawback of this solution is the low sensitivity resulting from the small quantity of emitted particles in such horizontal cylindrical boreholes. Therefore, the obtained data are unrepresentative of the geodynamic processes taking place in the depth of

the rock massif and the accuracy being low. The reason for this is the previously unknown range of deformation pressure, corresponding to the crucial values of the destruction process. In the article, this sensor approach has been further developed. An innovative technology for forecasting of catastrophic events and failure situations through monitoring of the microparticles in rock massifs has been proposed, whereat the drawbacks have been removed.

Structural implementation of the sensor technology. Description.

The proposed sensor technology to identify the pre-destructive state of rock structures requires to form in advance vertically in the rock massif a measurement borehole 3 in the absence of water horizon (Fig. 1). From the zone of greatest depth within this capacity 3, a cylindrical rock kernel is taken out and from it, a body with fixed length is cut out. The opening of the borehole 3 is then closed hermetically with a stopper 4, through which two air-conductors 5 and 6 are laid. The external part of the first air conductor 5 is connected to the atmosphere by a highly effective air particles filter 7, and the internal part of it is placed in the measurement capacity 3. This filter 7 is needed to isolate the volume from the particles of the surrounding medium. In this way, no fractions greater than 10 μm which are not related with the emission effect would be let through. The internal part of the second air conductor 6 is positioned in the borehole 3, close to its

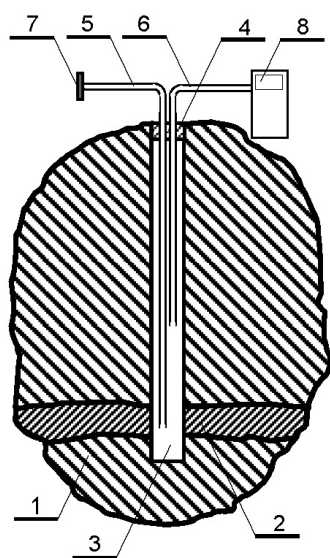


Fig. 1. Schematic configuration of measurement borehole for determining the deformation state: rock massif 1; tectonic plate 2; vertical borehole 3; hermetic stopper 4; air conductors 5 and 6; air filter 7; aerosol particles' laser counter 8

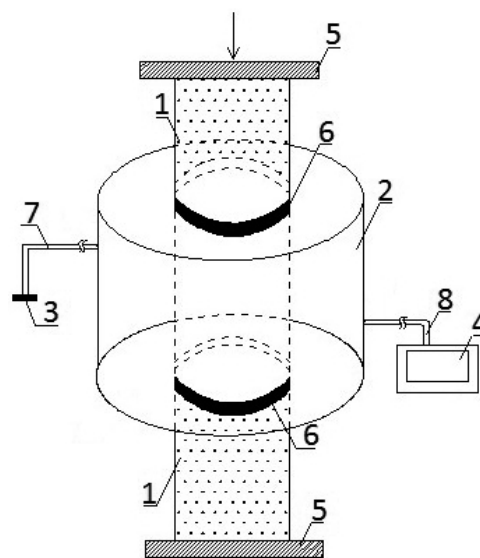


Fig. 2. Sketch of arrangement for laboratory microparticles detection: rock test specimen 1; box 2; air filter 3; electronic laser counter 4; press 5; flexible muffs 6; air conductors 7 and 8. The cylindrical samples are subjected to uniaxial loading

bottom, and the external one is connected to the first laser counter 8 of micro- and nanosized particles. This electronic device records periodically on its monitor as sensor information the quantity and size of the dispersed fractions which are released in the measurement volume 3.

The cylindrical body 1 from the rock kernel is placed in a hollow bottomless cylinder 2 made of solid material whose height is smaller than the height of the specimen 1, and whose diameter is greater than the diameter of the sample. Onto both bottom zones of the cylinder, elastic muffs 5 are fixed, enclosing tightly the rock body 1 (Fig. 2). On each of the opposite sides of the hollow cylinder 2, one opening is formed, to each of which another air conductor 7 and 8 is fixed.

Their ends are connected accordingly with the second particles air filter 3 and the input of a second laser counter 4. Then, the cylindrical specimen 1 is placed between the two operating plates 5 of a laboratory press. The sensor information about the amount N and the size of the particles released by the monoaxially deformed body 1 is recorded on the monitor of the second counter 4. The obtained data are used to determine the regularity of distribution of the quantity of released particles N as a function of the pressure \mathbf{F} , $N(\mathbf{F})$. By this procedure, the crucial value \mathbf{F}_0 of the destruction deformation of the rock body simultaneously with the number N and size of its respective particles is established, too. The data about the pressure \mathbf{F} obtained by tensosensor assembled in the press and the respective released particles for the specimen are used as reference data, including the destruction value \mathbf{F}_0 . An indicator for the occurrence of pre-destructive state of the rock body (specimen) 1, (Fig. 2), or the macro-destruction of the rock mass is the abrupt increase of the quantity of generated particles N prior to the occurrence of the reference value \mathbf{F}_0 . The exponential curves $N \sim \exp \mathbf{F}$ have the same nature, regardless of whether the data are from the real measurement borehole or have been obtained by a laboratory press setup. The quantity of emitted particles N and their corresponding monoaxial pressure \mathbf{F} are mutually supplementing parameters in the proposed sensor technology. Hence, this sensor approach is an integrated indicator for pre-emergency conditions. In seismology, the new solution can provide permanent control over the folding of tectonic plates in risk zones (Fig. 1).

Laboratory verification. The purpose of the verification of the sensor technology in laboratory conditions is to juxtapose the values of the deformation pressure \mathbf{F} with the quantity of emitted particles N both in the cylindrical body from the rock kernel and a borehole model from the same rock structure. The need of this solution is the following. The implementation of the innovative configuration and the determination of reference values, in particular, of the crucial deformation \mathbf{F}_0 of the macro-destruction in real conditions require nature experiments. At this stage, their realization faces logistic difficulties. The formation of boreholes is routine and practically no future problems are expected. The experimental results with rock specimens prove consistently that, at nearing

deformations F , close to the limit state F_0 , abrupt exponential increase of the microparticles emissions is observed. The ultimate objective of this algorithm, proposed by us, is in both cases – a rock cylindrical specimen and a borehole model to determine, through the generation of dispersed fractions and the relationships $N \sim \exp F$, fixed reference values for the parameter F , and the value F_0 , too.

The experimental accomplishment is as follows. From a large piece of granite supplied from the Rhodope mountains two kinds of samples are formed. The first type are cubes with dimensions $12.0 \times 12.0 \times 12.0$ cm, on which in the middle of one of the sides an opening is made with diameters $d = 3.0$ cm; 4.0 cm; and 5.0 cm. The depth of the borehole model is $h = 8.0$ cm. The second specimen is a cylinder with diameter $d = 10.0$ cm and effective height $h \approx 12.0$ cm. With the first type of specimen, the borehole model is formed. The stopper, through which the two air conductors are laid, is made of silicon material. The cubic specimen is positioned between the plates of the press in such a way that the pressure F is exercised on the opposite sides which do not contain the cylindrical opening. Actually, the borehole is perpendicular to the force F and is subject to pressure. The experimental setup with the second kind of specimen corresponds to Fig. 2. The two muffs are made of silicon material. Detailed information about the press and the measurement equipment is contained in [8,9].

Figures 3 and 4 present the deformation dependencies of the particles emissions obtained from experiments with five rock structures each for each of the two types of specimen. The data have been averaged. The combined error of compression load cell (tensosensor), constitutes no more than $\pm 0.05\%$. The error in the particles measurement is no more than 5% . According to the obtained data in the two cases, regardless that the quantity of emitted particles is different, the load forces F , in first approximation (Fig. 3, 4) are close in value. For example, the critical load F_0 for the cylindrical structure is $F_0 \approx 51$ MPa and for the cube with borehole model is $F_0 \approx 48$ MPa.

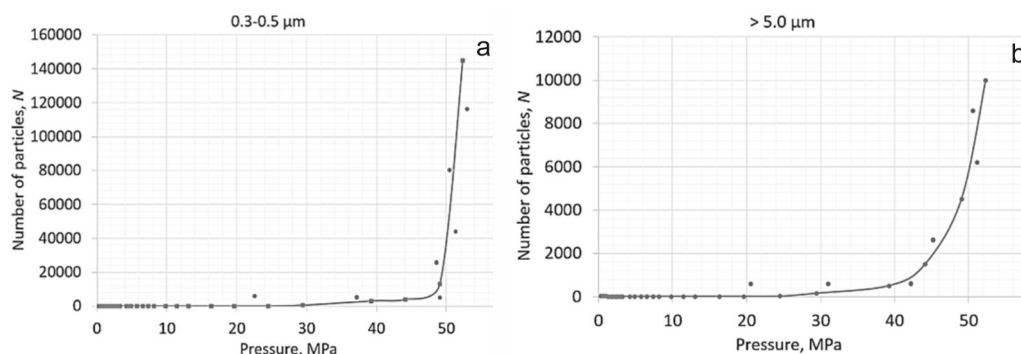


Fig. 3. (a) Intensity of particles emission on uniaxial pressure for granite cylindrical samples in the range: $0.3-0.5 \mu\text{m}$; (b) Particles emission $> 5.0 \mu\text{m}$ for granite cylindrical body

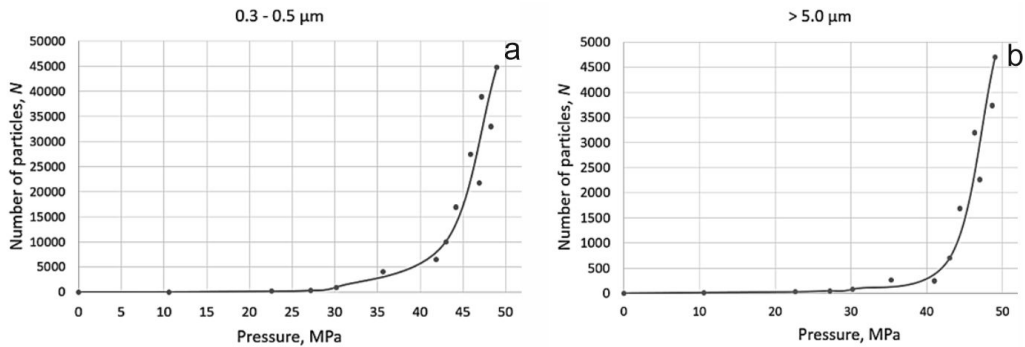


Fig. 4. (a) Particles emission for borehole model in the range 0.3–0.5 μm (cube granite samples); (b): for cube granite samples in the range $> 5.0 \mu\text{m}$. The capacity diameter is $d = 4.0 \text{ cm}$; Samples Nos 7, 8, 9, 10, 11

According to the results, the amount of emitted particles N_b in the different ranges of borehole models with a distinctive generating surface S , is directly proportional to the area, $N_b \sim S$. If a coefficient $K = N_b/N_c$ is introduced, at load $\mathbf{F} = \text{const}$, where N_c are the particles emitted from the cylindrical body, for the three measuring capacities it constitutes: $K(d = 3 \text{ cm}) \sim 0.22$; $K(d = 4 \text{ cm}) \sim 0.30$ and $K(d = 5 \text{ cm}) \sim 0.40$. This coefficient allows to be built for a specific rock structure the exponential dependencies for borehole models based on data on the emission and pressures of the cylindrical core, i.e. according to its exponential dependency obtained in the laboratory. This approach is also for real boreholes as follows. The reference sample is cut from the core extracted from the rock massif. Its effective emitting area S and the exponential dependencies $N \sim \exp(\mathbf{F})$ for the corresponding particle ranges are determined experimentally. In the bottom zone of the actual borehole, a measuring capacity with a fixed generating area S is formed. Then the particles N emitted from the rock structure are measured there (Fig. 1). According to the obtained exponential dependencies for the core, the corresponding exponential curve for a given range is scaled/reconstructed by the amount of particles from the real borehole with coefficient K , too. When changes occur in the particles generated at the bottom of the borehole, it will be possible to assess the occurrence of a pre-destructive state.

Specifics of the sensor technology. The new technology places some specific requirements. The electronic counter Haltech Hal-HPC601–USA based on laser spectrometry is constructively equipped with a pump sucking-in the air with the generated particles from the measurement volume. For a real borehole, the device will have to be assisted with a suitable external compressor. Therefore, the solution with the information obtained by reference is correct. Adequate corrections will be necessary, which is indispensable minding the material difference in the size of the actual rock capacity and its experimental version. Practice shows

that, within the measurement volume, the moisture is relatively high, regardless of the lack of a water horizon. This problem is removed by an appropriate amount of industrial silica gel, placed at a fixed depth in the borehole. Apart from this, there exist the dangers that, in the course of time and under the action of moisture, the borehole's wall may start disrupting, filling-up the effective volume of the measurement capacity [11]. This drawback is overcome by strengthening the cylindrical volume during its construction using a metal pipe. The practical application of the new sensor solution may be accelerated, if the deep caves, in which the country abounds, are used. The configuration from Fig. 1 in its form is suitable for processes control in tectonic plates at seismically active regions. That is why the new solution becomes a strategically important technology.

On the origin of the emission of microparticles in rock structures.

The new sensor technology most probably includes the following physical-mechanical processes in rock structures. The origin of emission process is based on the fact that rocks are non-homogeneous systems. Therefore, they differ in their behaviour from metals which feature a regular crystal lattice. So far, a consistent quantum-mechanical interpretation of rock characteristics under deformation impact is absent [8,9]. Electromagnetic and acoustic radiation within wide frequency range in rock and mining structures at high monoaxial pressure is further observed [3,4]. The origin of this process is related with the shifting of dislocations containing electric charges in the field of strong mechanical strains. Another emission source is the thermal electrons flying out of the material through the formed surface nano-cracks and realizing charge mosaic. The acoustic spectrum is generated by increasing the breaking of the mechanical bonds between the individual clusters. The intensity of the emission is related with the value of the acting load. In the ends of the cracks in the material where the local strained state is most strongly expressed, electrons, neutral and electrically charged atoms, molecules, nano- and micro-particles are generated.

The emission of the particles may be explained by the fact that, in the specimens, in the pre-destructive state, micro-cracks in some individual near-to-surface zones are formed which, with increase of the pressure, increase greatly their amount. This behaviour results from the non-homogeneity of the structure, accompanied by chaotic distribution of the strain forces and the local exceeding of strength limit. At high monoaxial pressure, the anisotropy of interaction between the cluster formations, ion linkage configurations and the molecules in the rock formations increases even more. The change in the position of the electrostatic bonds is irreversible in contrast to the situation in metals. This modifies the arrangement between positively and negatively charged groups of particles. If the electric reflexive behaviour at monoaxial pressure in metals results from the fixed and regular arrangement of the atoms in the crystal lattice, with rocks the restoration of the state upon deformation is impossible. Their "memory" or "elasticity" of the initial state is lacking. The development of this irreversible process

results in the emergence of micro-cracks in the rock structure. The micro-defects in the bulk or on the surface of the specimen form a “case” of chaotically dislocated electrically charged nano-areas. The released potential energy polarizes additionally the neighbouring molecule groups. According to the experimental results, at reaching a load close to the structure’s destruction limit, exponential increase of the particles emission is observed. The finely dispersed mineral particles initially leave the near-to-surface areas of the specimen. In the process of the carried out laboratory studies, it has been established that the maximal amount of particles is observed precisely at the moment of the loading’s increase. This is related with the time of redistribution of the strains in the sample, as a result the intensive particles emission from the surface takes place.

The micro-fractions released in the rock are not of arbitrary size. The quantitative assessments of their characteristics, dominating within the range 0.3–10.0 μm , have been determined experimentally. The specific disperse composition of the emitted particles is a function of the properties of the rocks and ore fossils and the degree of pressure. The essential feature of the proposed model is its so-called “unidirectionality” – the irreversible exhaustion of the particles’ generation process.

Conclusion. The proposed innovative sensor system features the following advantages. The required sensitivity should increase due to substantial amount of particles in the vertical boreholes. It is representative of the information about the crucial deformation processes taking place in the depth of the rock massif and often resulting in its catastrophic destruction. An advantage is the increased measurement accuracy of the forecast for the occurrence of pre-destructive state. This important result follows from the reference information obtained initially from the kernel in laboratory conditions for reference values of the pressure in the different development stages of the strain-deformation process. Moreover, in the measurements, the subjective factor in the assessment for the occurrence of catastrophic states is removed, whereas the obtained information may be automated. The obtained results are an integrated indicator for pre-emergency and emergency conditions in mountain massifs. One of the strategic applications of the new sensor technology is in seismically active regions.

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