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THE INVARIANT KINETIC APPROACH TO THE STUDY OF STRUCTURE AND ENERGY DISTRIBUTIONS IN ROCKS

Summary. The paper proposes a kinetic approach to study of structure and energy inhomogenieties in rocks masses as well as their transformation in a real time. The laboratory and field experiments show a good agreement with the proposed theoretical model. A transfer from 3-D to 2-D model is discussed as a way of forecasting the time of rock failure at different scale levels.

NIEZMIENNICZE PODEJŚCIE KINETYCZNE DO BADANIA STRUKTURALNO-ENERGETYCZNYCH ROZKŁADÓW W GÓROTWORZE

Streszczenie. W artykule przedstawiono podejście kinetyczne do badania niejednorodności strukturalno-energetycznych w górotworze, a także ich transformacji w czasie rzeczywistym. Wyniki eksperymentów laboratoryjnych i polowych dobrze zgadzają się z zaproponowanym modelem teoretycznym. Omówiona jest możliwość prognozowania chwili początku zniszczenia bloku skalnego jako przejście od modelu przestrzennego do modelu płaskiego w różnej skali.

ИНВАРИАНТНЫЙ КИНЕТИЧЕСКИЙ ПОДХОД К ИЗУЧЕНИЮ СТРУКТУРНО-ЭНЕРГЕТИЧЕСКИХ РАСПРЕДЕЛЕНИЙ В ГОРНЫХ ПОРОДАХ

Резюме. В работе предложен кинетический подход к изучению структурно - энергетических неоднородностей в горных породах, а также их трансформации в реальном времени. Результаты лабораторных и полевых экспериментов хорошо согласуются с предложенной теоретической моделью. Обсуждается возможность прогнозирования момента начала разрушения блока горной породы как переход от трехмерной к двумерной модели на различных масштабных уровнях.

1. INTRODUCTION

Practical needs of mining industries and geotechnique, including the burying of radioactive wastes, put forward the problem of long-term monitoring of stressed state in rock massifs to prevent emergencies which may be caused by rockbursts, earthquakes, landslides etc. In many cases, dense instrumental network capable of registering excessive local stresses or deformations in rock massifs could be replaced or supported by relatively simple registration systems which can detect trends in stressed media for sufficiently long time. However, their use demands a better understanding of the rheological properties and physical mechanisms of rock failure process.

It is believed that this problem can be reduced to defining quantitative physical criteria of the stability loss by a rock massif, in other words, to finding earthquake or rockburst predecessors which are understood as anomalities of a certain measured physical field observed during a relatively long time before the seismic event. However, the existence of a large number of predecessors which do not often co-relate with one another and are local in space and time shows inefficiency of this approach for the prediction of failure of geophysical media because here the process of the preparation of strong seismic events is exluded from consideration. It is clear that the final stage of the event can develop in different ways due to its highly stochastic nature.

This paper is an attempt to study the process of rock massif failure preparation as a whole applying the theory of physical kinetics. The kinetic approach to the description of failure process was first formulated by Zhurkov (1957) for polymeres and was later developed by Regel et al (1974), Petrov (1981) and others for rocks. This approach has been also successfully used by Mikhailov (1972), Anikolenko and Mikhailov (1976) in solid state physics and chemistry.

2. FORMULATION OF THE PROBLEM AND PHYSICAL MODEL

As it is known, the crucial role in the failure process belongs to microstresses which exist a priori in all kinds of rocks due to the microheterogeneity and microanisotropy of the geophysical media. The presence of such powerful energy concentrators causes microcracks which grow in number and size as the deformation develops. This process involves the overcoming of a set of potential barriers caused by interatomic interactions. A kinetic equation describing crack accumulation process should at least take into account the heterogenic nature of potential barriers (activation energy distribution). In this case, the statistic ensemble is described as a whole on the basis of the generalized energy parametres rather than individual cracks. An equation describing the kinetics of defect accumulation with time can be written as in the work by Anikolenko and Mikhailov (1976):

$$N(t)= f(E)\{1-\exp[-k(E)t]\}dE \qquad (1)$$

where f(E) is the potential barriers energy distribution and k(E) is the rate constant for the joining of two separate defects which for a thermoactivating process may be written as follows:

$$k(E)=k_o\exp(-E/kT)$$

where k_o is a constant factor independent of the energy, k - Boltzmann constant, T - temperature.

f(E) can be obtained from the solution of an inverse problem for the equation (1). It allows one to describe the process in terms of energy distribution and, finally, obtain information about the elementary act of the mechano-chemical reaction on the molecular level. The presence of various additional chemical factors in the geophysical media which affect k(E), e.g. fluids, makes this problem a very compicated one.

However, new information about the physics of the process can be obtained by analyzing the formal kinetics of rock fracture without complicated calculations. Let us assume, in the same manner as Chehdze (1987), that the rate constant of the interaction between defects i and j has the following form:

$$k(r)=k_o\exp(-2r_{ij}/a) \tag{2}$$

where r is the distance between these defects and k and a are constants. Normally the value of a is of the order of several Angstroms or tens of Angstroms and could be considered as a minimal initial cluster size for a given kind of rock. Such a form of the rate constant does not contradict the assumptions about the k(E) form in equation (1), because it is clear that at a constant temperature a higher activation energy is needed to overcome a wider barrier. So the equation (1) can be replaced with a kinetic equation which takes into account the barrier width distribution:

$$N(t)= f(r)\{1-\exp[-k(r)t]\}dr \tag{3}$$

where the so-called distribution of free (from cluster) volumes (see Mikhailov and Anikolenko (1977) and Anikolenko (1993) may be used as f(r):

$$f(r)dr = \frac{4\ r^2dr}{4/3\ r_3} \exp(-r^3/r^3\ ) \tag{4}$$

where $r_o = (3C/4\ \ )^{1/3}$ is the mean distance between the defects existing at the beginning of the observations, with the defect concentration equal to C. Then, substituting (2) and (4) into (3) we shall obtain:

$$\ln[N(t)/N(t^o) = a/2r_o[\ln^3(k_ot) - \ln^3(k_ot_o)] \tag{5}$$

where t_o is the time of beginning the observations. The physical meaning of the right side of the equation (5) consists in the decrease of free volumes at the rate proportional to $\ln^3 t$.
In case of uniform distribution

$$f(r)dr = \frac{dr}{2(r_{max} - r_{min})} \qquad (6)$$

instead of equation (5) we shall obtain the following equation:

$$N(t)/N(t_o = a/2(r_{max} - r_{min})\ln(t/t_o) \quad (t \;\; t_o) \qquad (7)$$

which describes defect concentration as a linear function of the logarithm of time. This situation corresponds to the case when the distance between two interacting defects is considerably shorter than the distance to another pair of interacting defects (the so-called kinetics of pair interactions).

The equations (5) and (7) have been obtained with the assumption of the Markov process of crack formation by the joining of two separate defects into a long chain. This means that the final result is independent of the manner of the crack generation.

It follows from the above that by solving the inverse problem for equations (5) and (7) we can obtain the parameters of the distribution f(r), as well as on the parameter a responsible for the elementary act of the mechano-chemical reaction. This problem demands a separate and more detailed study. However, useful information on the rock fracture process can be obtained even by analyzing kinetic dependences.

3. COMPARISON WITH THE EXPERIMENTAL RESULTS

With this purpose, let us consider the results of several laboratory experiments for rock failure. The forming defecrs were registered by acoustic emission. Fig. 1a shows a typical differential spectrum of acoustic emission with uniaxial loads acting for a long time until the sample failed because of the formation of a major crack. Consequently, Fig.1b shows an integral curve describing the total number of acoustic emission events versus time t for the same experiment. Such curves are very smooth and demonstrate an initial slow growth followed by a more intensive growth and, finally, a plato.

Fig.2 shows the same curve plotted in the coordi- nates N(t) versus lg t, where practically 85 per cent of its length is in good agreement with the linear dependence given by the equation (7). The linear part of the kinetic curve is assumed to be due to interpair interaction of clusters under the load. So the initial nonlinear part of the kinetic curve evidently corresponds to the stage of formation of primary (noninteracting) clusters and the final (also nonlinear) part corresponds to the process of formation of the major crack which interferes with the process of interpair interactions throughout the crack's surface.

The above considerations are in good agreement with the mechanical theory of rock failure of Sadovsky (1984). From the physical point of view this means that with time the system has to overcome potential barriers of larger widths, the average waiting time for higher energy elementary interactions increases and the process (Fig. 1b) seems to slow down.

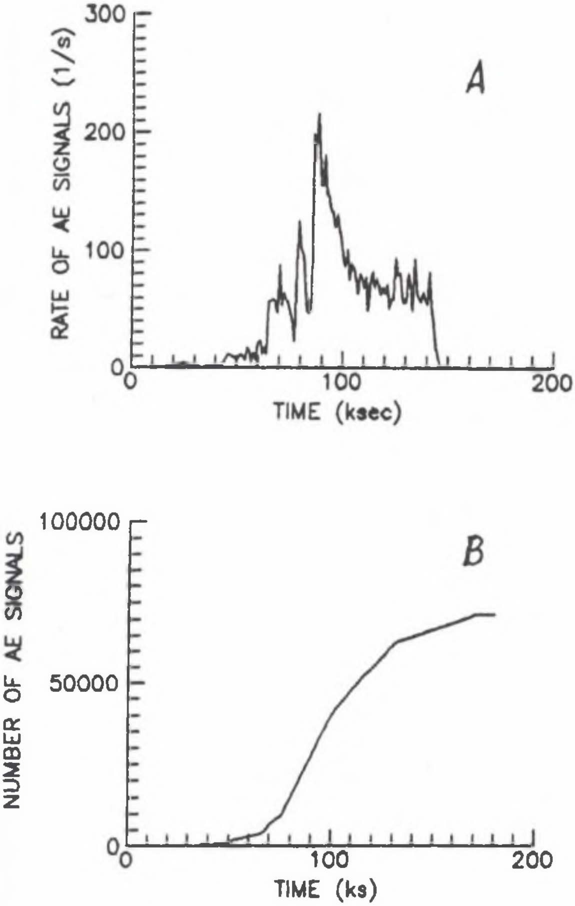

Fig. 1. Failure of a sandstone specimen in a test maschine :
(a) - rate of acoustic emission (AE) signals vs time,
(b) - cumulative number of AE signals vs time
Rys. 1. Zniszczenie próbki piaskowca w maszynie wytrzymałościowej :
(a) - zależność pomiędzy tempem emisji akustycznej i czasem,
(b) - zależność pomiędzy skumulowaną liczbą sygnałów emisji akustycznej (AE) i czasem

As follows from equations (5) and (7), the average widths of the overcome barriers increase proportionally to the logarithm of time. So the distribution f(r) as well as the parameter a can be obtained from the equation (7). However to avoid the external factors affecting the sample one should carry out a series of experiments at various loading rates using the specimens of the same kind of rocks.

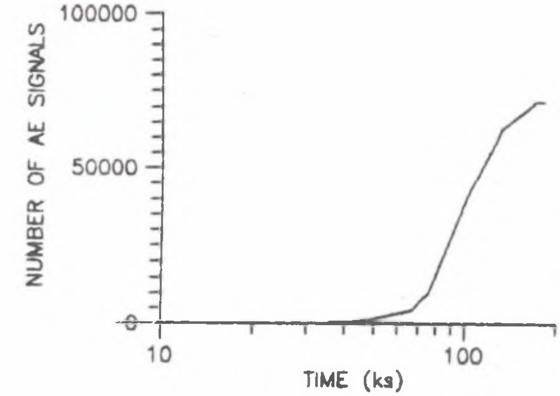

Fig. 2. Fig. 1b plotted as a function of logarithm of time

Rys.2. Wykres 1b wykreślony w układzie współrzędnych z osią odciętych (czas) w skali logarytmicznej

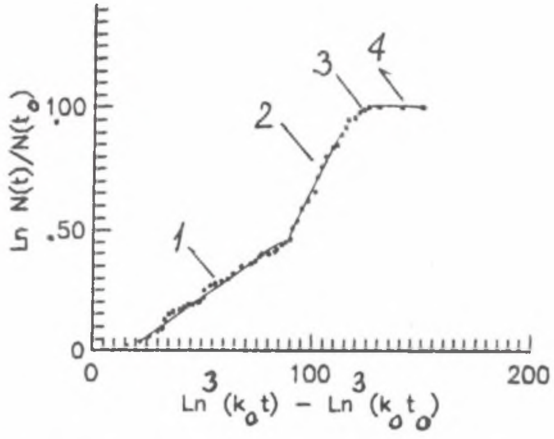

Fig. 3. Kinetics of failure of a granite specimen in a test machine plotted in the coordinates from equation (5), where k=1 1/s, and t is measured in ksec : 1 - generation of initial defects ; 2 - generation of cracks due to the combining of lower scale defects ; 3 - formation of a major crack ; 4 - failure of the specimen

Rys.3. Kinetyka zniszczenia próbki granitu w maszynie wytrzymałościowej wykreślona we współrzędnych z równania (5), gdzie k=1 1/s, a t jest mierzone w ks; 1 - powstanie defektów początkowych; 2 - powstanie pęknięć w wyniku łączenia się defektów niższej skali; 3 - formowanie się pęknięcia głównego; 4 - zniszczenie próbki

Fig.3 shows three separate linear segments the first two of which can be defined, according to Kuksenko (1984), as a stage of accumulation of initial defects followed by their interpair interaction. The third segment of the curve evidently corresponds to the generation of a quasiplane major prefailure crack, i.e. transition from the 3-D to the 2-D solution of the equation (3).

4.DISCUSSION

Finally, let us discuss the experiment in which samples were loaded by a test-machine together with iron parts or cylindric form which increased the stifness of the machine. This allows one to smooth out the dynamics of the sample failure during the final stage and thus obtain more detailed data.

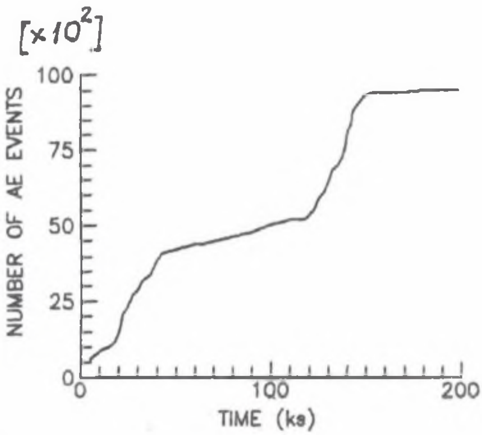

Fig. 4. Cumulative number of AE signals versus time (two-stage failure of a marble specimen)
Rys.4. Skumulowana liczba sygnałów AE w funkcji czasu (dwuetapowe zniszczenie próbki marmuru)

Fig.4 shows a typical kinetic dependence for experiments of this kind. It consists of two segments, each of them similar to the curve in Fig.1b. The beginning of each segment demonstrates an active growth of the number of acoustic emission signals, then a "quiet" period follows, then the sequence repeats. The experiments show that every new rise of the kinetic curve is preceded by the formation of a major crack splitting the sample into separate fragments. So every next step of the kinetic curve corresponds to the process of the failure of its separate fragments.

Fig.5 presents a long-term kinetic dependence for an experiment of this type plotted in the coordinates of the equation (7). In the course of this experiment the sample was completely unloaded and then loaded again. As seen from Fig.5, the kinetic curve falls into five linear segments and this dependence is also observed after the unload/load cycle.

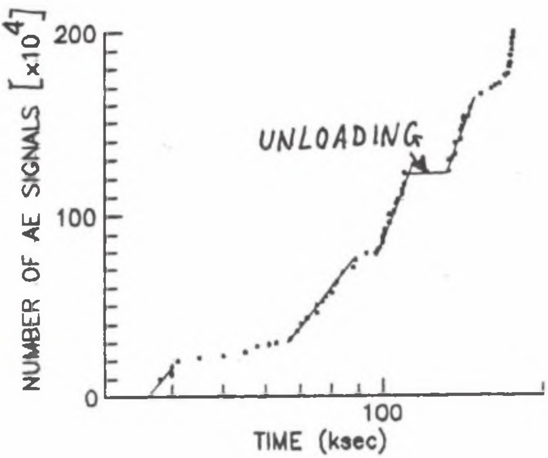

Fig.5. Cumulative number of AE signals versus time (log scale)
Rys.5. Skumulowana liczba sygnałów AE w funkcji czasu (w skali logarytmicznej)

This proves that the principle of self-reproduction is maintained with the transition to a new level of volume hierarchy.

Taking into account the self-reproductive nature of the failure process one can suppose that such well-known phenomena as seismic gap can be described by the kinetic dependence when an integral number of earthquakes registered comes to the plato, as e.g. in Fig.1b. At the same time it is clear that seismic gap does not correspond to a real decrease in seismic activity as it seems, because it is not observed in the N(t) vs Log t graph. Moreover, the probability of high-energy events (rupture) increases as most of the low-energy events already happened. From the point of view of earthquake prediction this means that a seismic gap is really an efficient predecessor of a strong rock burst or earthquake wherever it is caused by the formation of a rupture crack. This is accompanied by a full or partial energy release and reproduction of the kinetic dependence similar to Fig.5. However in case the energy release as a result of a powerful earthquake is caused by faulting due to techtonic processes, seismic gap may not be observed at all, because such events may occur within the rising segments of the kinetic curve, ref. (Fig.1b), i.e. before it has reached the plato.

Thus the analysis of integral kinetic curves obtained as a result of laboratory and field experiments provides new data on the mechanism, structure and kinetics of the process of the failure of geophysical media and makes it possible to give a physical interpretation to the phenomenon of seismic gap as well as to explain the earthquake frequency graph.

5. CONCLUSION

The results of model and field experiments are in good agreement with theoretical equations based on kinetic approach. The proposed kinetic model can be used for long-term forecasting of strong seismic events and rockbursts in mines and deep burials of radioactive wastes. It can also explain the nature of well-known seismic phenomena such as seismic gap.

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