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Acoustic emission response of rocks to electric power action as seismic-electric effect manifestation

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Abstract
Two parts of the research are distinguished in this paper. The first part is devoted to the structure of signals of Acoustic Emission (AE) and electromagnetic emission (EME) which accompany the inelastic straining of terrestrial materials. Special attention is paid to the similarity of waveform of EME signals at various scale lengths. The second (and main) part of the work involves the investigation of AE responses to the action of additional power fields over strained rocks. Our experimental investigations have revealed the interrelation of acoustic emission activity to power actions applied externally (impacts of electromagnetic field). Different modes of responses to electromagnetic impact have been specified. The characteristics of such responses and their variations depending on the material of specimens tested and of electric parameters of external pulses during power impacts have been considered. A general conclusion on possible electromagnetic triggering of AE has been drawn, the prospects of further studies being outlined.

Key words *acoustic emission activity – energy impact – rock*

1. Introduction

At the close of the XXth century, the progress of science and technology pointed out new possible ways to approach the problem of how to reduce the hazard of strong earthquakes. This unexpected way is related to power physical fields, which may influence the structures in the terrestrial crust to induce tectonic overstress unloading and thus reduce seismic hazard. Initially, the effects allowing us to control deformation processes in seismogenerating zones manifested itself as induced seismicity, which results from underground nuclear explosions, or from fluid industrial waste injection into boreholes located in a seismic area, or from variations in water level in large water reservoirs, or from mining operations, etc. Thereafter it was revealed that dynamic actions redistribute the seismicity in the following manner. They decrease the number of major events due to a growth of energy released by weak earthquakes.

There are some ways, which are the most acceptable from an ecological viewpoint, for man-made relaxation of tectonic stress in the terrestrial crust. One of them is electromagnetic action by electric current flashing. Pioneer results on the effect of power electromagnetic pulses produced by magnetohydrodynamic (MHD) generators to test the seismic activity in regions of

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Bishkek and Garm testing fields were obtained in Russia and Kyrgyzstan (UIPE, OIVTRAN) (Tarasov *et al.*, 2001). It is very important that such external impacts always trigger seismic events of minor magnitude ($M < 6$). Such power actions are adequate for civil and scientific purposes only.

This paper is related to the concept of seismicity control by means of technological power actions (so-called Energy Impacts, EI). The phenomenon of acoustic and electromagnetic energy release during the process of structural defects formation and fracture of terrestrial materials is well-known (Nitsam, 1977; Gokhberg *et al.*, 1982; Warwick *et al.*, 1982; Kurlenya *et al.*, 2000; Manzhikov *et al.*, 2001). It is a reasonable assumption that the effect of electromagnetic impacts over defects accumulation processes (microcracking and so on) in loaded rock specimens is to occur as well. The manifestation of such inverse energy conversion is that the acoustic emission and the rate of rock straining are influenced by electromagnetic impacts excited externally. The aim of our investigations is to study the responses of terrestrial material specimens to electric power actions.

The investigation of AE and EME structure based on waveform analysis is significant to reveal the physical origin of emission pulse. Besides, the results of structural studies give essential information on the kinetics of fault formation process in a loaded solid. So, for example, the emergence of the second spectral maximum of acoustic signal whose frequency is lower than that of the main maximum implies the microcracking transition from the stage of diffusive accumulation of defects to cluster stage of defects growth (Trapeznikov *et al.*, 1997). The experience has demonstrated that the combined analysis of statistic and structural data on AE yields more reliable results and facilitates results interpretation. Our studies have been oriented to the works on statistical characteristics of AE and EME events occurrence.

2. Experimental results

AE is a good indicator of inelastic straining processes and microfracture. So during experiments we focused the measurement system on recording the AE of loaded specimens of terrestrial materials. Some characteristics of AE turn out to be keyword parameters revealing correlations between the rate of straining processes up to specimen fracture and power impacts supplied externally. The work on modeling above inverse processes involves the creep test of specimens of rocks and of artificial heterogeneous materials overburdened by uniaxial compression. The experiments were performed on spring rheological installation UDI with a maximum compressive load of 100 tons (designed by A.N. Stavrogin, VNIMI, St. Petersburg). We tested a number of samples manufactured from granodiorite, quartzite, granite and halite. Some concrete specimens which were prepared by Stavrogin routine (Stavrogin and Protosenya, 1979) and have the sizes of $100 \times 120 \times 250$ mm^3 were tested as well. Additional electric power impacts produced by external sources took place during a deformation session with constant level of compressive load. The sources of additional power action were as follows:

i) Square-wave generator G5-54 giving square-wave signals, whose amplitude was close to 50 V and duration was around 5-50 μs, the frequency being 1-3 kHz.

ii) 10 kV generator of sparks (without wave form control).

iii) Capacitor discharges supplying electric pulses with parameters: the time of voltage ramping was about 1 μs and the peak voltage was around 1 kV.

AE and EME signals were recorded on a wide frequency region 80 kHz-5 MHz. This allows signals waveform control. The measuring system operates in a waiting mode. Figure 1 shows the experimental set up.

We also focused on electromagnetic emission induced by inelastic straining of terrestrial materials. EME from loaded rocks was recorded on the laboratory studies simultaneously with acoustic emission. EME was caused by the conversion of elastic to electromagnetic energy during microcracking or other fast processes on micro- and mesostructural levels. The comparison of the experimental EME signal recorded during our experiment with the seismic signal is shown in fig. 2a,b. The signal shown in fig. 2a

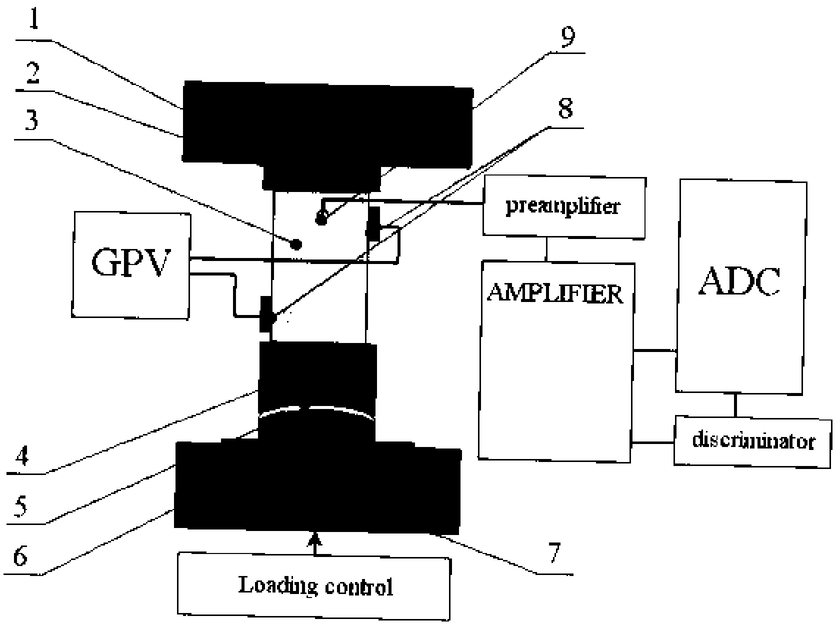

Fig. 1. The sketch of the experimental set up: 1 – upper cross arm; 2 – upper platen; 3 – specimen; 4 – lower platen with 5 embedded AE sensors; 5 – hemispherical bearing; 6 – insulating base; 7 – lower cross arm; 8 – electrods; 9 – piezotransducer; ADC – Analog-to-Digital Converter; GPV – Generator of Pulced Voltage.

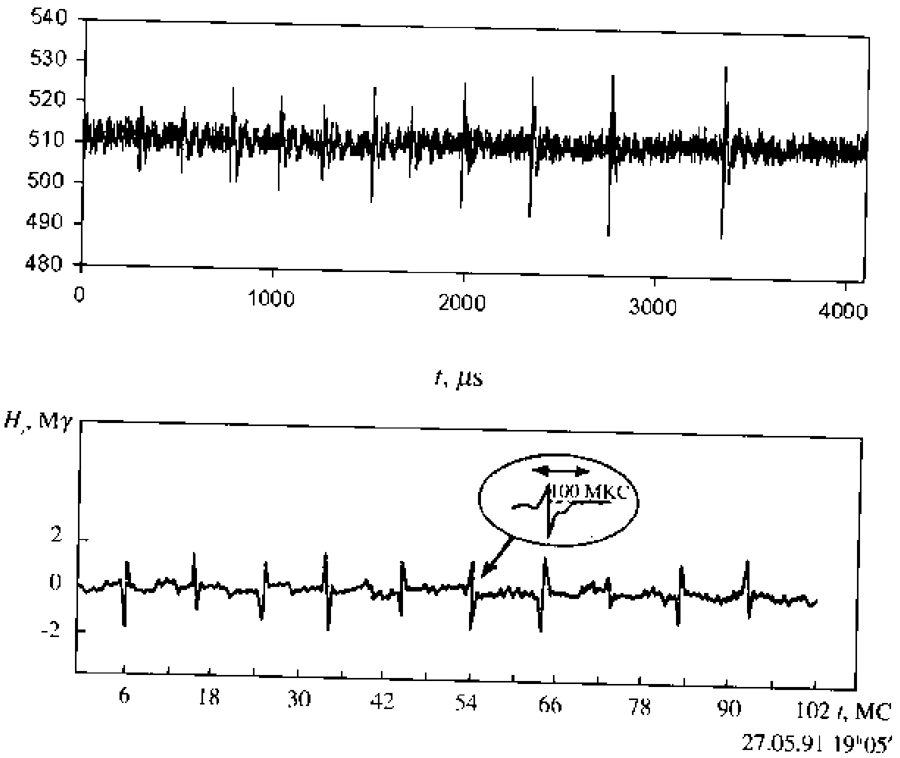

Fig. 2a,b. a) EME signal of granite sample; b) series of EME impulses recorded before the aftershock 27.05.1991 during the period of aftershocks activity of Dzhva-Rachin earthquake, 29.04.1991 (Morgunov, 1994).

was recorded during the experiment with pristine cylindrical sample from Kainda granite deposit (Kyrgyz Republic) with the help of an electrical capacitive sensor sensitive to EME. The sample was examined at «creep test» conditions with fixed uniaxial compression load. According to Kuksenko (1997), the origin of signals on capacitive sensors during such experiment is related to the change in specimen polarization due to the straining process. Figure 2b demonstrates the series of EME impulse recorded during the period of aftershocks activity after Dzhva-Rachin earthquake, 29.04.199 (Morgunov, 1994). The waveform of EME signals from specimen (fig. 2a) appears to be similar to that of EME (fig. 2b) accompanying coseismic crust deformation with possible change in rock polarization. This is a specific manifestation of such a distinctive feature of stressed-strained state of terrestrial materials as its simi-

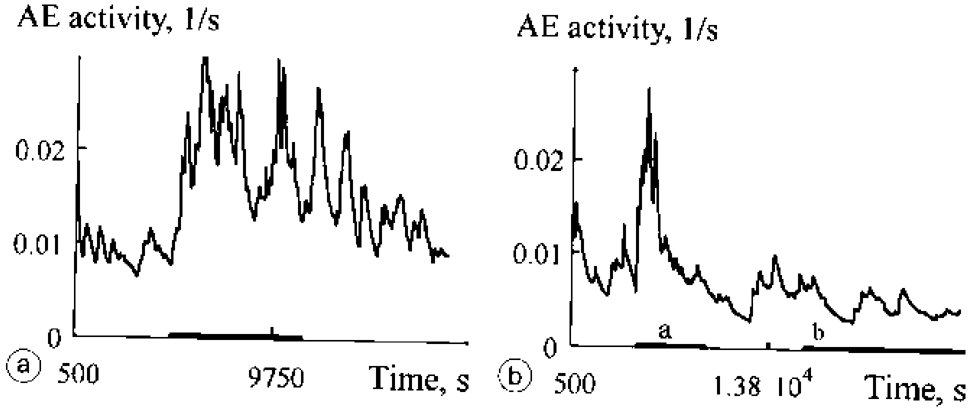

Fig. 3a,b. a) AE activity of halite sample *versus* time. Electric actions took place during time interval 4800-10800 s; the parameters of periodic pulses produced by the G5-54 generator were 2 kHz, 5 mks, 60 V. b) AE activity of concrete sample *versus* time. Electric actions of periodic electric pulses took place during time intervals: a) 4800-9600 s, b) 15000-27000 s; the parameters of pulses produced by rectangular generator G5-54 were respectively: a) 2 kHz, 5 mks, 60 V; and b) – 1 kHz, 10 mks, 60 V.

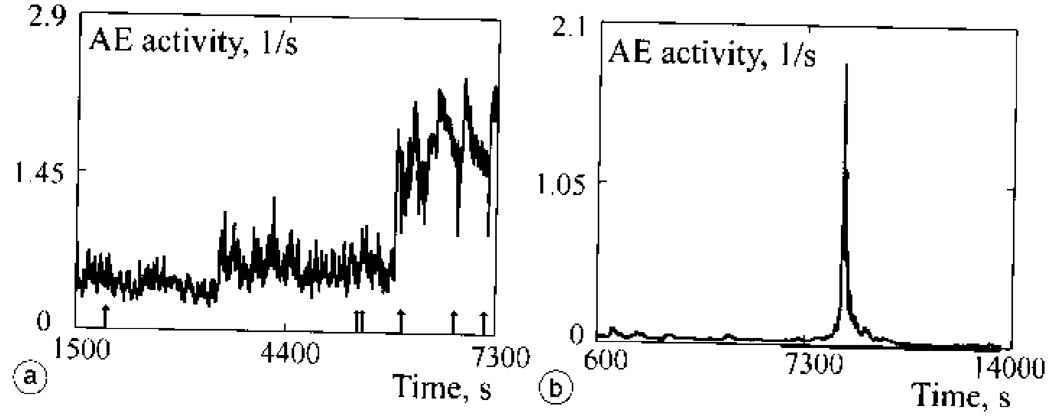

Fig. 4a,b. a) AE activity of granitic sample *versus* time. The arrows represent the moments of spark gap converter action (the amplitude of charge is not less than 3 kV). b) AE activity of granodiorite sample *versus* time. Electric actions took place during the time interval 7125-13 620 s; the parameters of periodic pulses produced by the G5-54 generator were 2.5 kHz, 20 mks, 50 V.

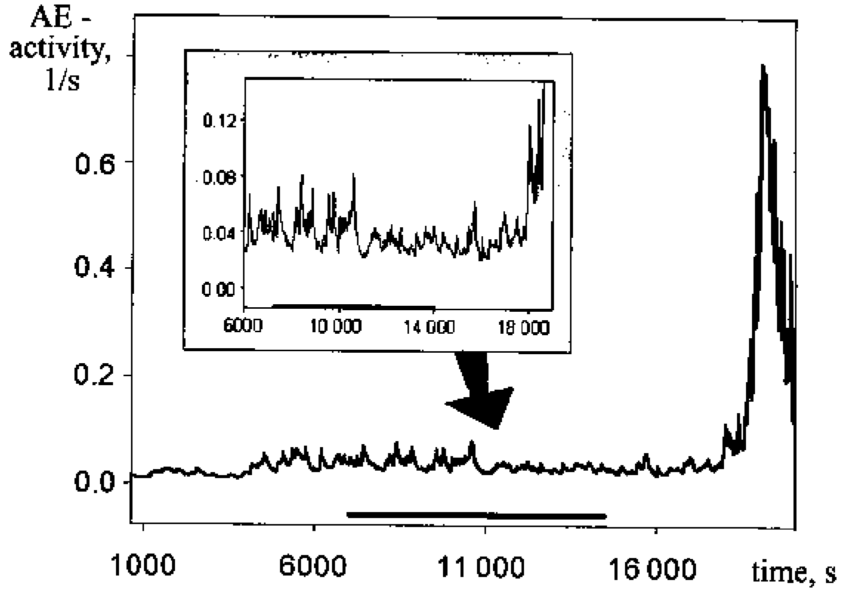

Fig. 5. AE activity of granodiorite sample *versus* time. Electric actions took place during the time interval 7150-14000 s; the parameters of periodic pulses produced by the G5-54 generator were 2 kHz, 5 mks, 60 V. The figure also shows the expanded range of diagram which demonstrated that the AE activity growth follows the temporal drop after power impact.

larity for different scale lengths (from laboratory sizes of some cm up to natural seismological scale). There are a number of works (for instance: Petri, 1994; Zapperi, 1997) confirming the similarity of near-critical dynamics from large scale earthquakes down to the microscopic scale of the specimens rheological structures. Among them the works implying AE measurements (Diodati, 1991; Canneli, 1993, etc.) have revealed that the statistical parameters of AE events flow (AE activity, amplitude and duration of AE) reflect the self-organized criticality of the fracture processes. This means the self-similarity of emission effects at various scales of length. Resuming the first part of our studies one can remark that the well-known multi-scale similarity is valid for electromagnetic emission (EME) during rocks fracture as well.

As regards the main part of the investigation the obtained indicative results are represented in figs. 3a,b, 4a,b and 5. In most cases, the activity of AE increases after the start of electric action. This growth occurs with some delay after the instant of action beginning. Then AE-activity decreases to background or (in some cases) still below the average level. Remarkable results were obtained on a halite sample. Figure 3a shows that the enhanced activity of AE due to electric action remains during the session with square-wave generator. Figure 3b demonstrates the triggering effect of electric pulses produced by the G5-54 generator on acoustic emission of a concrete specimen with 1 cm granite inclusions whose weight is about 5% of total weight of a solid. The case of long delay of AE activation by electric impacts is represented in fig. 4b showing the temporal plot of AE activity of the granodiorite specimen. The response to the effect of pulses supplied by square wave generator G5-54 was revealed 1000 s after the generator power was turned on. It is seen in fig. 4b that the activity multiplies by 20 times in comparison with background level but thereafter it drops rapidly to the initial level. Figure 4a gives the timing dependence of AE activity of granitic specimen with short term EI; the spark gap converter being the source of such solitary few kV voltage pulses. One can see that the mean value of AE activity doubles some time after the first discharge, the twofold level remaining steady during the long period. The change in the trend of AE activity plot occurs after the second discharge and the lag like the one observed after the first discharge is present. The activity of AE is increased again, the increment being considerably more than before. Finally the average level of AE activity does not change during the time up to specimen fracture. In this state each repeated discharge causes an abrupt drop of AE being followed by AE growth in stepwise manner up to steady level before discharge. Sometimes the action of external electromagnetic field results in a temporal reduction of AE activity. This is apparent from plots on fig. 5 that demonstrate the dependence of AE activity of the granodiorite specimen *versus* time. Thereafter minor AE falloff is followed by a very rapid outburst of activity. This speaks in favour of a united origin of responses in the cases of fig. 5 and, for instance, of fig. 4b discussed above.

3. Discussion

It has been found by experimental studies that the effect of the electromagnetic field on strained structures has different modes depending on the source of the EM field, the specimen material, the value of the main load, and the time of specimen exposure under this load. The superposition of these factors affects the kind of response to electric impact, particularly the variations of response specific parameters.

As a rule, the responses of AE from loaded terrestrial materials represent a growth of AE activity. Sometimes (rarely) such growth follows by the temporal drop of AE activity after power impact (fig. 5); the integral effect being an increment of AE events. The parameters describing AE response to power impact are as follows: triggering time (the lag of response), the increment of activity, the length of response (the duration of enhanced level of activity for the steady response case or the typical width of AE activity spike for short-term responses), the presence or absence of aftereffect, the aftereffect duration. Meanwhile, the statistical parameters of a flow of AE events can be taken as the parameters of straining process. In our experiments, the main parameters of AE flow which describe the extent of disorder (caused by both natural heterogeneity and forming zones of microcracks concentration; Kuksenko, 1977, 1986) are the dispersion of AE activity, the duration and average amplitude of AE signals. It should be noted that during the test of rock specimens by uniaxial compression, the heterogeneity of specimens was increased due to generation of new zones of enhanced defects population. The occurrence of this indicates the transition from the first (diffusive) stage of the fracture process to the second stage (the phase of defects concentration and coalescence; Kuksenko, 1977). Such a transition may be an explicit example of self-organized criticality observable by the number of measuring tools including AE (Swanson, 1984; Gershenzon *et al.*, 1989; Morgounov, 1999).

A very slow decrease of AE activity of the halite specimen after the session with G5-54 generator pulses (fig. 3a) represents the aftereffect of electric action. This is quite similar to the manifestations of vibration effect on AEs (Bogomolov *et al.*, 2001). Because the halite is a highly resistant material, the results suggest that both polarization and conductive effects play an essential role during additional electric action.

Taking into account the rate of response rise and subsequent drop one can assume that the response arises inside the domain with locally strained structure, and this entails the avalanche defects formation there. Generally two types of response to electromagnetic power action may be specified. The first corresponds to observations of short-term increase in AE activity. In this case, the activation front is quite sharp. Usually such responses were recorded when the sample is overburdened by compressive load of moderate value. During repeated electric impacts at the same stress, the responses of this type decrease: we have recorded minor or marginal manifestations or did not observe any such repeated response at all.

Taking into consideration the well-known Kaizer effect one can try to explain AE response suppression during repeated electric impact. Usually the Kaizer effect is formulated in terms of stress drop and increment: the growth of AE after stress drop requires stress increment by the value exceeding the drop (Tang *et al.*, 1997). They assumed microcracking to be controlled by the stress increment. Actually the rate of crack growth depends on a number of parameters (Atkinson, 1984), the specific surface energy being very important. This parameter of crack surface state is sensitive to electric effects as well as to the fluid or vapour adsorption. Change in the value of surface energy is to accelerate or reduce subcritical cracks evolution (the length is much less than Griffith's). Such changes are followed by changes in observable AE activity which look quite similar to the Kaizer effect. The origin of this formal similarity is as follows. The increment of load as well as all external impacts results in some energy influx which is sufficient for evolution and/or propagation of a certain limited number of structural defects. A spike of AE activity due to external action (electric impact, in particular) may be treated as a manifestation of rapid growth of available microcracks triggered by EI. Thus, the repeated EI over given current stressed-strained state of a specimen obtained no result (no triggering) because of the absence of defects which have been prepared for propagation but wait to be triggered. A new population of microcracks arises after load increment to change the specimen state. Then the responses of AE to triggering electric impacts should occur again.

The second type of responses may be specified by a steady increment of AE activity. The enhanced level of AE remains *quasi*-stationary for a long time after electric impact. Then (in the case of no repeated impacts) it returns smoothly to the initial value. Sometimes the activity decreases to the level below the initial background. So the aftereffect takes place for responses of the second type. In the case when repeated electromagnetic impacts occur on the steady phase of response to primary EI, the transition to the new state with still higher activity of AE appears to be possible. As a rule, the second type responses were revealed at high enough values of the main compressive load (close to breaking loads). All this suggest that such AE responses indicate that the considerable part of tested specimen volume is at near critical conditions (close to critical point). Typically, the temporal dependence of parameters related to energy release follows power distribution near critical point. We considered the law of AE activity growth during bifurcation induced by EI (*i.e.* during the transition to enhanced activity level, see fig. 4a). The power relation of AE activity appears to be valid for more than 70% of amount of second type responses under consideration. In the case of seismic data, the relation described near critical dynamics (Bowman and King, 2001; Malinetski and Kurdumov, 2001) has been reduced to polynomial dependence of Benioff strain *versus* time. The authors are planning the subsequent processing of AE data to derive the above dependence. It is surprising that the activation of AE and inelastic straining described as second type response to EI leads to a new steady state rather than fracturing when the compressive load was of order of 0.9 of the maximum value for a given specimen. In this case, the fracture took place a long time after the AE bifurcation, the load being fixed.

The comparison of responses of first and second types by their lifetimes and leading edge times suggests that the first type indicates faulting inside localized domains. The second type of recorded responses seems to represent an AE-manifestation that the sample structure bifurcates to the new state. The diffusive (more uniform) distribution of defects controlling the rate of plasticity and/or other inelastic processes makes AE more regular.

The results obtained during our investigations demonstrated that the chosen approach is reasonable, further work is very promising.

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