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ACOUSTIC EMISSION MEASUREMENTS TO SIMULATE EFFECT MICROSEISMICITY TRIGGERING BY PHYSICAL FIELDS

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The results of laboratory modeling of effect of power electromagnetic impacts (EI) over stress-strained structures in specimens of terrestrial materials have been represented in given work. We recorded Acoustic Emission (AE) of loaded specimens of terrestrial materials in order to understand the principles of earthquake triggering by externally applied physical fields. We carried out long duration rheological tests, while making high frequency measurements of strain and AE. Our experiments revealed the response of AE activity to power applied externally (application of electromagnetic field and vibrations). A number of specimens of different heterogeneous materials (semi-brittle rocks, concretes with inclusions) were tested. Possible ways of results explanation as well as interrelation with full-scale observations of electromagnetic triggering have been discussed.

Introduction and experimental set-up. This paper is devoted to the simulation of phenomenon of weak seismicity triggering by actions of impulsive physical fields (so-called power impacts, EI). Initially the effects allowing to control deformation processes in seismogenerating zones manifested itself as induced seismicity, which results from underground nuclear explosions [1], or from fluid industrial waste injection to borehole located in seismic area [2], or from variation of water level in large water storage, or from mining operations, as reviewed in [3], etc. Thereafter it was revealed that dynamical actions are able to redistribute the seismicity in following manner. They are to decrease the number of major events due to growth of energy released by week earthquakes. Presently, some approaches to realize this very promising scenario are in progress. The research of Japanese scientists who studied interrelation between microseismicity distribution and water injection near Nojima Fault may be considered as one of them [4]. The second approach based on well known effect of vibration triggering involves using of powerful vibrators [5,6]. The third (newest) way is electromagnetic actions by electric current flashing. Because of electrokinetic effects and capillary water in terrestrial crust the last idea is to proceed from assumptions relevant to the first way. Pioneer results on the effect of power electromagnetic pulses produced by magnetohydrodynamic (MHD) generators to test tee seismic activity in regions of Bishkek and Garm testing fields were obtained in Russia and Kyrgyzstan (UIPE, OIVTRAN) [7]. It is very important that such external impacts always triggered the seismic events of minor magnitude (M<5). Given work represents the results of laboratory modeling of effect of power electromagnetic impacts over stress-strained structures in specimens of terrestrial materials. It is well known that acoustic emission (AE) is a good indicator of inelastic straining processes and microfracture. The activity of AE appears to be very sensitive to all changes in strain rate of tested specimen. So, during modeling experiments we focused measurement system to record the AE of specimens of terrestrial materials loaded by uni- or biaxial compression and additionally undergoing by electromagnetic impacts excited externally. To reveal increments or decrements of AE activity correlating to electromagnetic impacts or other physical field power on (so-called AE responses to power actions) was a specific task of each experimental session. Besides, the investigation of AE structure based on the waveform analysis appears to be significant to verify the physical origin of emission pulse: noise and apparatus misoperation should be filtered out. The experience has demonstrated that the combined analysis of statistic and structural data on AE allows to obtain more reliable results and to facilitate results interpretation [8]. According to our first, trial experiments [9], 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. We continue structural studies of while recording AE signals since this may give essential information about rate of defects formation and accumulation in a loaded solid.

The work on modeling above electromagnetic influence involves the creep test of specimens of rocks and of artificial heterogeneous materials overburden by uniaxial or biaxial compression. The experiments were performed on spring rheological installation UDI with maximum compressive load of 100 tons (designed by A.N. Stavrogin, VNIMI, S-Petersburg). The Fig.1a shows the experimental set up.

Some specimens of semi-brittle or pseudo-plastic materials were examined with the help of minor, 20 tons spring rheological machine (fig. 1 b). The spring compliance of minor press is 10 times more than that of UDI. This allows, in contrast to UDI, that the change in main load is quite negligible in spite of certain shortening of a creeping specimen under compressive load and correspondent elongation of loading spring. We tested a number of intact samples manufactured from granodiorite, quartzite, granite and halite. Some concrete specimens which were prepared by Stavrogin routine [10] and have the sizes exceeding that of rocks were tested as well.

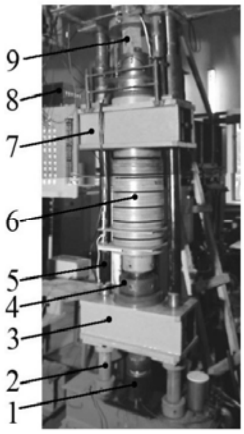

Fig.1a. General view of rheological installation UDI
1- hydraulic jack
2,5- supporting rods,
3-lower cross-arm
4- clamping-nut,
6-springs
7-higher cross-arm,
8- block of amplifiers
9- specimen
Dimensions of concrete specimen are 100x120x250 mm3

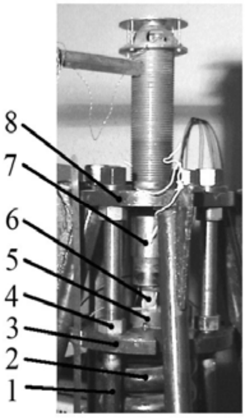

Fig.1b. Small rheol. installation.
8-Higher plate
7-Higher cross-arm
6-Specimen
5-Lower cross-arm
4-Check-nuts
3-Baseplate
2-Spring
1-Columns

Specimen located on the lower pivot with built-in AE sensors, which constructively integrated with cable amplifiers. System of five lower sensors provided for AE sources location. From the top specimen is limiting by higher pivot while it's alignment is performing with using the spherical joint integrated with lower pivot. In most cases for low AE signals recording the single noise-immune sensors are used. These sensors applied to the side surface of specimen. Signal from the one of the side sensors (SE2000, DECI Co, US) after amplification and filtration performed the operating of trigger of recording equipment – ADC

(CAMAC standard). AE signals were recorded on wide frequency region 80 kHz – 5 MHz. This allows signals waveform control. The measuring system operates in a waiting mode: recording starts every time when the signal magnitude exceeds threshold.

Additional electric power impacts produced by external sources took place during a straining session with constant level of compressive load. It took place with some lag in time, i.e. just after load increment but before measuring session to avoid the bias of unsteady processes caused by non-uniformity of load ramping up and edge effects (surface microchipping etc.) Permanent registration of AE started when the manifestations of transition processes (low frequency fluctuations) became of order of natural noise.

During experiments the following sources of additional power action were used: square-wave generator G5-54 giving square-wave signals, which amplitude was close to 50 V and duration was of order of 5–50 μs; the frequency was being 1–3 kHz; 10 kV generator of sparks (without waveform control); capacitor discharges supplying electric pulses with parameters: the time of voltage ramping was about 1 μs and the peak voltage was of order of 1 kV. A generator of triangle pulses GI-1 (300V being the voltage amplitude) and sinusoidal generators G3-112, G3-33 were used to simulate power impacts as well. The waveform of powerful electric pulses applied for Earth soundings at Bishkek geodynamic test site if taken into account for above selection of generators: simulating natural-scale EI the most measuring sessions involved action of square-wave pulses supplied by G5-54 generator. Other sources were used to reveal the significance of such factors as voltage amplitude, rate of pulse rise, and pulses repetition rate for AE activation considered. Our investigation of acoustic responses to EI was planed to involve a comparison with the effect of vibration stimulation of AE activity described previously [9, 11–14]. To reproduce vibration effects for the same samples that were affected by additional EIs during experiments on UDI machine we arrange vibration sessions by fastening small size vibrator (buzzer) to the lateral surface of the tested specimen. Sinusoidal AC signals of generator G3-112 or G3-33 were supplied to the input of vibropack (small size buzzer or speaker unit) to excite vibrations of given frequency. During vibration session we controlled the constancy of amplitude and frequency of electric signals supplying vibropack.

Experimental results. We used temporal plots of AE activity in order to estimate the dynamics of cracks growth, in particular under effect of EI. We performed the moving window averaging of AE events accumulation rate to calculate the AE activity. Experimental data has been checked for false events presence. Criteria of such verification were spectral parameters of AE.

Obtained indicative results of our investigation the have been represented on Fig. 2–6. 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; the integral effect being increment of AE events. The growth occurs with some delay after the instant of action beginning. Then AE-activity reduces to background or (in some cases) still below the average level. Fig. 2a demonstrates the triggering effect of electric pulses produced by G5-54 generator on acoustic emission of quarzite specimen. One can see from fig.2 that the response to EM pulse can be distinguished easily even in case of low level of AE activity. AE activity curve showed by Fig. 2a one can explain in terms of stick-slip eathquake nucleation model. We have a part of curve with a great energy release after triggering action of external source of electromagnetic pulses and after some time we have a part with quick drop of AE activity (analogue to stress drop) to level lower in comparison with level before power action. It should be noted, that the quarzite specimen has interior cracks with consolidated edges (peculiar locking structure). One can assume that the localization of strain at some of the old crack results in the shift of crack faces like behavior of contacting blocks in well-known stick-slip model of earthquake.

The case of long delay of AE activation by electric impacts has been represented by the Fig. 2b showing the temporal plot of AE activity of granodiorite specimen. The response to the impact of pulses supplied by square wave generator G5-54 has been revealed after 1000 seconds from the generator power on. It is seen on the Fig. 2b that

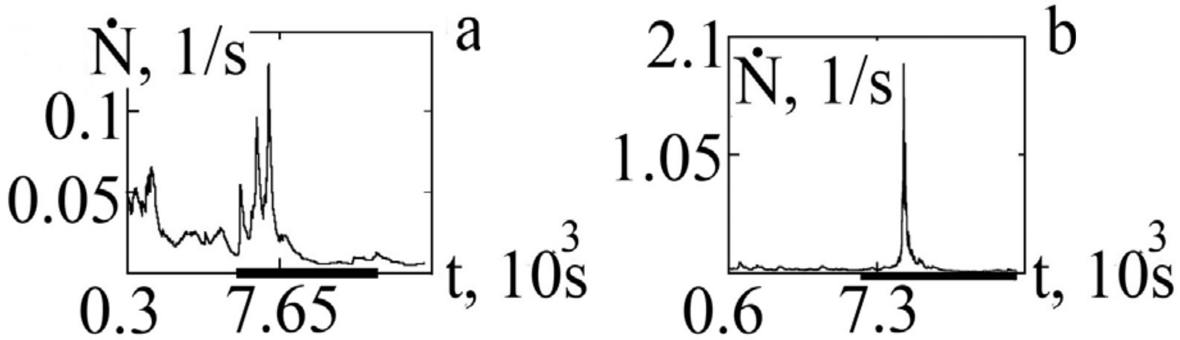

Fig. 2. a) AE activity of quartzite specimen vs. time. Electric actions took place during interval 5700–12400 s; the parameters of periodic pulses produced by G5-54 generator were being 2 kHz, 5 mks, 60 V;
b) AE activity of granodiorite specimen vs. time. Electric actions took place during interval 7125–13620 s; the parameters of periodic pulses produced by G5-54 generator were being 2.5 kHz, 20 mks, 50 V.

the activity multiplies by 20 times in comparison with background level but thereafter it drops rapidly to the initial level.

In addition to conglomerate rocks (granitic and granodioritic specimens) AE responses of gabbro specimens have been considered as well (fig. 3a). As one can see on the fig. 3a the AE response is similar to AE responses of granitic Westerly specimens tested under the vibration actions. This case the delay is near 1000 s. Aftereffect (the part of the plot corresponding to repeated AE increase and very slow decrease of activity) takes place also in this experiment. It’s duration somewhat exceeds the delay before activation.

To confirm the accuracy of our measurements we reproduced the result of our previous works [11, 14] concerning triggering effect of weak low frequency vibrations. Fig. 3b gives the temporal plot of AE activity of granite specimen during vibration session. The plot demonstrates distinctive response to the vibrations action. Sessions with vibrations has been arranged with using the speaker as the source vibration and G3-33 generator as electric supply. The fig. 3b shows that the length of response delay is of order of 1000 s. Activity of AE growths by 4 times in comparison with its initial background. Drop of AE activity takes place after vibration source turning off, but in the first 500 seconds after the stop of vibrations one can see at fig. 3b the short time increment of AE activity. Thereafter the activity drops slowly up to level lower than that before vibrations.

Let’s compare the plots on fig. 3a and 3b. Both plots describe the delay of activation and the aftereffect of actions of physical fields. So, the comparison shows the similar feature of the responses to the vibrations (fig. 3b) and of that caused by electromagnetic impacts (fig. 3a). There are some spontaneous activations accompanying the triggering responses on the fig.3a. Such activations were observed on the different materials. During the experimental sessions without additional EI mathematical expectation of spikes estimated by control specimens testing was of order of 4000–6000 seconds. It’s particular value depends on the load level and time from the last load increment. Taking into account the frequency of spontaneous spikes occurrence and number of EI sessions one can derive that only small part of AE activity fluctuations may be related to spontaneous activations, which coincide with the time of actions applied externally. So, the plot on fig. 3 demonstrates the example of AE activity response to EI during experimental session at which no big spikes of amplitude exceeding the dispersion take place before electromagnetic impact.

In a number of cases it is not difficult to distinguish AE response from the spontaneous spike. One can see this on the examples given by the fig. 2a and fig. 3a. The plots show the difference between AE activity parameters (such as amplitude and/or duration) of spontaneous and forced spikes. In particular case shown on fig. 3a the duration of spontaneous fluctuation occurred after EI (at 7500 s) is minor compared to that of forced AE activation, the waveform being dissimilar.

In addition to dry rocks specimens we also studied experimentally the reaction of dense but water-saturated granodiorite specimens to short high voltage discharges applied externally (Fig. 4). The reaction to a series of 10 pulses with amplitude of about 600 V was observed with the delay of near 1000 seconds and displayed the sharp increase in AE activity (by a factor of tens). After 3000 s the AE activity decreases almost to the initial level. When acoustic activity of a rock sample is very low (for instance, few tens counts were recorded rather than flow of AE events) the effect of electric stimulation of AE may be revealed in terms of temporal distribution of events (see Fig. 4b). One can see that AE signals were recorded mostly during periods when high voltage discharges took place every 10 seconds.

It should be noted that the rheological test on spring machine (when the constant value of stress is supported by compressed springs) is the most unfavorable to observe the effect of electromagnetic triggering. This is related unavoidably to relaxation of metastable state (which is very sensitive to triggering impacts) without energy influx like that at a press with given constant rate of compression growth. Energy influx is superimposed on relaxation processes under the condition of constant strain rate, so the state of the tested specimen tends to be metastable and hence sensitive to external power impacts, EI. Meanwhile pure relaxation is to take place under constant loading condition as long as the value of load is below fracturing (when cracks growth becomes strengthen than relaxation). Such relaxation involves rock mechanics aspect (reduction of local stress concentration within tested specimen) and electric relaxation (change in electric polarization). As reported in [13], creep tests of rocks specimens have demonstrated that the effect of AE activation due to electromagnetic pulses is not so apparent as in the case of constant strain rate test [15]. Experiments [13] revealed such peculiar feature of AE activity reaction to

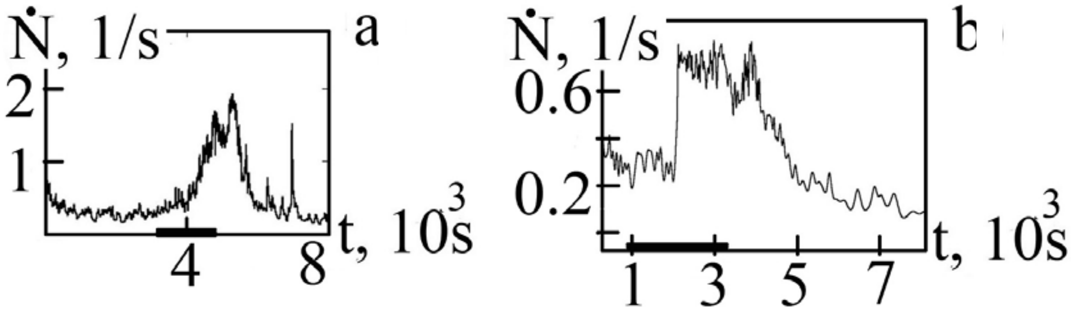

Fig. 3. a) AE activity of gabbro specimen *vs*. time. The band indicates the period of electric action by the G5-54 generator (2 kHz, 30 mks, 60 V). b) AE activity of granitic specimen vs. time. The band indicates the vibration session (1 kHz).

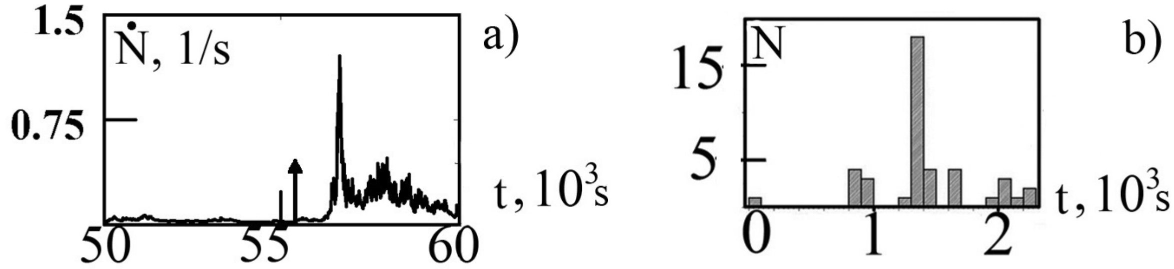

Fig. 4. Examples of growth of AE after high-voltage stimulation: a) water saturated granodiorite specimen, arrow is a moment of set of 10 discharges, with near 1 kV voltage spike each; b) dry granodiorite specimen, capacitor discharges were in: 850–950 s, 1250–1350 s, 1650–1700 s.

electromagnetic impacts as its degradation when repeated power action occurs. Fig. 5a shows this phenomenon: the response of AE activity to the second time voltage supply (repeated generator power on) is minor in contrast to that correspondent to first time power on. No visible response to third time electric bias took place. Only after long exposure of tested specimen its AE activity becomes again sensitive to electromagnetic impacts. Meanwhile, under condition of constant rate straining the reaction of AE to consecutive voltage power on was well reproducible [15]. Special experiments were conducted to confirm that influx of mechanical energy is the cause of different modes of acoustic activation effect stimulated by similar electromagnetic pulses but under different straining conditions. Motivated in part by the concept that even small stress or strain increments can contribute metastable state we arranged vibration sessions on our loading machine, by fastening a small size vibrator (buzzer) to the lateral surface of the specimen being tested. Sinusoidal AC signals of the G3-112 generator were supplied to the input of a vibropack for exciting vibrations of a given frequency. During the vibration session, we controlled the constancy of amplitude and frequency of the electric signals supplied to the vibropack. By this way we tried to simulate dynamic component of load (always being present under constant rate straining). Although such simulation is too rough, combination effect of dynamic loads (weak vibrations) and electromagnetic pulses is worth analyzing. Fig. 5b demonstrates the distinct reaction of acoustic emission of concrete sample to combined action of electric pulses and vibrations. At first power impact test (2000–8000 s) we initially turned on the source of electric pulses and then the vibropack. Vice versa order of power on corresponds to the second test period (12000–20000 s). In both cases the response of AE activity to combined vibroelectric action exceeds the superposition of typical acoustic responses (for given material and given conditions) to separate action of electric pulses and vibrations. The increment of AE activity in the second case is less that that in the first. This may be correspondent with general responses degradation tendency mentioned above.

Biaxial loading by constant stress, in contrast to uniaxial compression, allows recording distinct reaction (namely the response to electric stimulation) of a specimen even under creep test. Experiments were held on the same 100 tons spring press with the help of spring attach for lateral compression, the maximum lateral load being 30 tons. Results are shown on Fig. 6; the plots of AE activity indicate that action by periodic pulses of moderate voltage (a) as well as high voltage capacitor discharges (b) can stimulate AE growth. In both cases the activation occurs in same delay after start of electric action; the length of delay being near 1000 s in the case (a) but in the case (b) it being less than 100 s. Fig. 6 demonstrates that electric stimulation was powered on when the mean level of AE activity drops after recent stepwise increment of main load at the beginning of measuring session. Quasi-monotonic plot decrease is interrupted due to a response to electric pulses action.

It was found previously [16] that the increment of uniaxial compressive load results in electric polarization of overburden specimen. The effect took place in spite of that the specimen material had no piezoelectric properties. The polarization appears to relax slowly at constant load condition [16]. A polarization of heterogeneous material (rocks) implies the presence of electric induction, and hence domains, dipoles and, sometimes, even charge carriers inside specimen. Undoubtedly, for water saturated samples double electric layers contribute the changes in polarization. It is important for further explanation of nature of AE activation by electric pulses that electric fields applied externally can counteract with elements of forming metastable electrical structure. Particularly, momentum stress may be created by a vector product of external electric field and polarization vector. It is well-known that microcracking is more sensitive to momentum stress than to simple increment of a stress component, the latter being negligible on the background of main load. The example of Fig. 6 (electric action during continued creepage) is well correspondent with such hypothesis.

Generalizing the results presented by Fig. 4–6, one can conclude that the effects of AE triggering, which manifests itself even at unfavorable detection conditions is to be universal for wide class of terrestrial materials under subcritical loads.

Discussion. The comparative analysis of AE activity responses of specimens of various rocks demonstrates the presence of generalized features of EI influence. Let’s try to discuss possible physical mechanisms to provide the effect of EI. It has been found while experimental studies that the effect of electromagnetic field on strained structures has different modes depending on the source of electromagnetic field, the specimen material, the value of main load, and the time of specimen exposure under this load. The superposition of these factors predestines the kind of response to electric impact, particularly the variations of responses specific parameters.

Generally two types of response to electromagnetic power action may be specified. The first type corresponds to observations of short-term increment of AE activity (Fig. 2). In this case the activation front is quite sharp. Usually such responses were recorded when the sample is overburden by compressive load of moderate value. Taking into account the rate of response growth and subsequent drop one can assume that the response arises inside domain with subcritical stressed-strained conditions, and this entails the avalanche defects formation there. In the most cases such type responses of rocks specimens reduce during the repeated electric impacts at the same stress: we have recorded minor or marginal their manifestations or don’t observe any such repeated response at all.

The second type of responses may be specified by steady increment of AE activity (fig. 3). The enhanced level of AE remains quasystationary during 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 initial background. So the after-

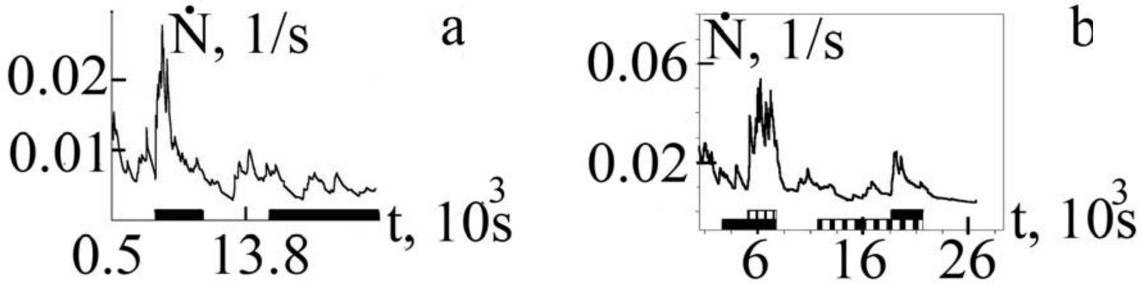

Fig. 5. AE activity of intact concrete sample with pyrofyllite inclusion vs time:
a) stimulation by square wave unipolar periodic electric pulses, band denotes the time of action;
b) combined electrovibroaction: solid band shows the period of action by unipolar electric pulses (50 V amplitude), dotted band denotes vibration action period.

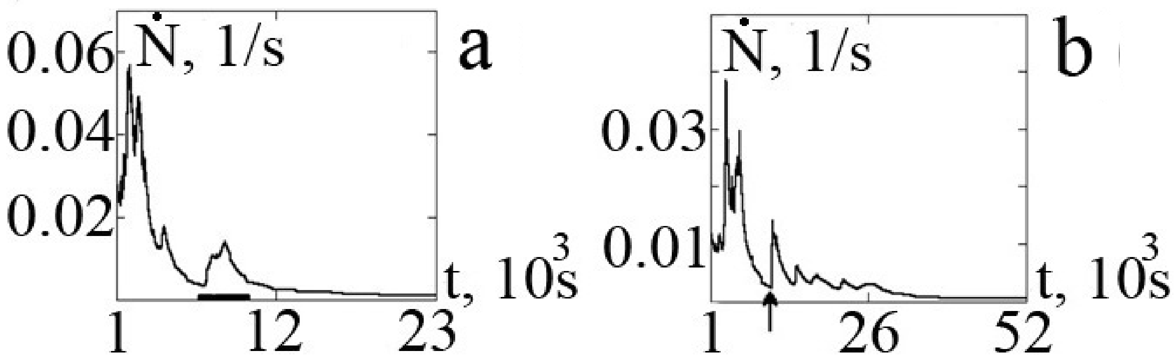

Fig. 6 Examples of growth of AE of intact concrete samples loaded by biaxial compression and electric pulses. The lateral stress is about 20% of main stress: a) action of the same periodic pulses as in the case of Fig 6a, b) action by solitary high voltage pulse of capacitor source.

effect takes place for responses of 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 main compressive load (close to fracturing loads).

Discussing the place of electromagnetic effects in straining and rupture of terrestrial materials in relevance to earthquake nucleation one can treat the electromagnetic triggering of inelastic strain rate as a one side of unified relationships between mechanical (straining, fracture) and electromagnetic phenomena in loaded solids. The distinctive property of stressed-strained state of terrestrial materials is its self- similarity for different scale length (from large scale of earthquakes down to the microscopic scale of the specimens rheological structures) and the similarity of dynamics of such state near critical point. Some works implying AE measurements [17, 18] 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, the multi-scale similarity being valid for electromagnetic and acoustic emissions during rocks specimens fracture.

The greatest electromagnetic phenomena undoubtedly related to straining process in earth crust is the shining during or some hours before strong earthquake which sometimes was observable even visually. Long ago this fact was well known for Central Asia seismic region. Recently this phenomenon has attracted new attention due to explaining model proposed in [19] and some other publications. It is curious and important that the fundamental of proposed explanation of strange lights preceded shock is close and even overlaps partially with the basic principles of Kinetics of defects in solids (point carriers, dislocations, microcracks) which are relevant to triggering effect of power impacts. The consideration below may speak in a favor of this. The idea of [19] is that the immense pressures generated prior to an earthquake cause igneous rocks, which normally act as insulators, to briefly behave like “p-type” semiconductors, meaning that they contain mobile positive charges that can conduct electrical charge. Crystals in volcanic rocks contain paired oxygen atoms, called peroxy groups, which can snap under stress. Freund speculates that once a peroxy group is snapped, a negative oxygen ion will remain trapped in the lattice of the rock, while a positive charge – or hole – will be free to flow outwards.

Given model of charge transfer in earth crust notes the possible mechanism of interaction of free carriers of electric charge with electromagnetic field applied externally to the loaded geologic media or to tested specimen. The density of released positive charges is to oscillate due to pulses of electromagnetic field**.** A funny coincidence is that above mechanism is quite similar to well-known effect excitation of ionic sound in plasmas! Oscillation of charge carriers will be delivered to the main frame of loaded body (the crystal lattice in the simplest case).

Since the triggering effect of vibrations, even very weak, is well-known above interaction of electromagnetic field with charges generated according to [19] is a candidate for explanation of electromagnetic triggering. Actually at the conditions of our modeling experiment this may excite vibrations of amplitude of 10^{-8}–10^{-7} of main stress value, meanwhile the vibrations of lower frequency but of amplitude close to 10^{-6} can increase the AE activity (see for example fig. 9 or that from [9]) It should be noted that other mechanical actions caused by electromagnetic pulse such as attraction of electrodes, ponderomotive force acting on steel pivots contacting with specimen etc. are negligible compared to enough estimate. The similarity of rocks relaxation effects after increment of load and after voltage supply were considered in [16]. Results of this work demonstrated the electric polarization takes place that in both cases, the polarization being finally related to inelastic straining as the materials tested have no piezoelectric properties.

Besides above the cloud of positive charges is to influence the dislocation processes. Our previous work [14] appealed to a model of moving dislocations realizing plastic strains of solid or at least of some domains inside loaded material. When the dislocations move across a domain containing charged defects (positive holes in our case) they become charged and contribute electric charge transfer (this may be essential in low conductivity semiconductors). Charging or discharging dislocations may occur depending on the density of point defects. The movability of dislocations at given stress and temperature is controlled by point charge carriers surrounding and screening charged dislocations (so called effect of Cottrell cloud). Dislocation slippage realizing the plasticity at microlevel are to control the relaxation rate of overstress localized at some sites. The probability of microcracking is the maximal at such sites of stress concentration, described as sources of emission signals. The more rate of stress relaxation the less intensity of AE caused by microcracking and vice versa. So, one can distinguish at least two mechanisms of that how electromagnetic pulses could influence over inelastic component of rocks straining which is followed by observable change in AE. The subsequent research is likely to give some quantitative estimates of effectiveness of AE triggering by electromagnetic impacts in addition to above qualitative consideration.

Now the first results obtained during our investigations demonstrated that the chosen approach to modeling relationships between mechanical and electromagnetic effects or phenomena in geologic media is reasonable, further work in this direction is very promising.

Reference

1. *Tarasov N.T., Tarasova N.V.* Influence of nuclear explosions on seismic regime // Doklady RAN. – 1995. – V. 343. – No 4. – P. 543–546.
2. *Healy J.H., Rubey W.W., Griggs D.T., Rateigh C.B.* The Denver earthquakes // Science. – 1968. – V. 161. – No 3848. – P. 1301–1310.
3. *Nikolaev N.I.* The influence of engineering activity on seismic regime [in Russian]. – Moscow: Nauka, 1977. – 198 p.
4. *Tadokoro K., Nishigami K., Ando M., Hirata N. A. et. al.* Seismicity changes related to a water injection experiment in the Nojima Fault Zone // Island Arc. – 2001. – V. 10. – No 3/4. – P. 235–243.
5. *Nikolaev A.V.* Problems of nonlinear seismics [in Russian]. – Moscow: Nauka, 1987. – 288 p.
6. *Alexeev A.S., Glinsky B.M., Drjahlov S.I. and oth.* Effect of electroseismic induction during vibroseismic sounding // Doklady RAN. – 1996. – V. 396. – N 5. – P. 664–667.
7. *Tarasov N.T., Tarasova N.V., Avagimov A.A., Zeigarnik V.A.* The effect of electromagnetic impacts on seismicity over the Bishkek geodynamic test ground // Russian Geology and Geophysics. – 2001. – V. 42. – N 10. – P. 1641–1649.
8. *Manzhikov B.Ts., Bogomolov L.M., Ilyichev P.V., Sychev V.N.* Structure of acoustic and electromagnetic emission signals on axial compression of rock specimens // Russian Geology and Geophysics. – 2001. – V. 42. – N 10. – P. 1690–1696.
9. *Bogomolov L.M., Manzhikov B.Ts., Trapeznikov Yu.A. et. al.* Vibroelasticity, acoustic-plastic effect, and acoustic emission of loaded rocks // Russian Geology and Geophysics. – 2001. – V. 42. – N 10. – P. 1593–1604.
10. *Stavrogin A.N., Protosenya A.G.* Plasticity of rocks. – Moscow: Nedra, 1979.
11. *Aladyev A.V., Zakupin A.S., Bogomolov L.M., and oth.* Regularities of acoustic emission of terrestrial materials specimens during creep test

under physical fields power impacts // Seismological problems in millennium. – Novosibirsk: SO RAN, 2003. – P. 168–172.

12. *Sobolev G.A., Ponomarev A.V., Kolytsov A.V.* // Izv. RAN. Ser. Fizika Zemli. – 1995. – N 12. – P. 72.
13. *Bogomolov L.M., Ilyichev P.V., Zakupin A.S., et. al*. Acoustic emission response of rocks to electric power action as seismic- electric effect manifestation // Annals of Geophysics. – 2004. – V. 47. – N 1. – P. 65–72.
14. *Trapeznikov Yu.A., Bogomolov L.M., Manzhikov B.Ts*. On the origin of stepwise response of loaded samples to effect of microvibrations // Earthquake prediction and deep geodynamics. – Almaty, 1997. – P. 167–172.
15. *Ponomarev A., Sobolev G., Koltsov A.* Acoustic emission under electric excitation // Book of Abstracts, ESC XXVIII General Assembly. – Genova, 2002. – P. 238.
16. *Kuksenko V.S., Mahmudov H.F., Ponomarev A.V.* Relaxation of electric fields, induced by mechanical loads in natural dielectrics // Physics of Solid State. – 1997. – V. 39. – N 7. – P. 1202–1205.
17. *Diodati P., Marchesoni F., and Piazza S.* Acoustic emission from volcanic rocks- An example of self-organized criticality // Phys. Rev. Lett. – 1991. – N 67. – P. 2239–2243.
18. *Canneli M., Cantelli R., and Cordero F.* Self-organized criticality of the fracture processes associated with hydrogen precitation in Niobium by acoustic emission // Phys. Rev. Lett. – 1993. – No 70. – P. 3923–3926.
19. *Freund F.* Time-resolved study of charge generation and propagation in igneous rocks // J. Geophys. Res. – 2000. – V. 105. – B5. – P. 11001–11020.