Comparative analysis of acoustic and electromagnetic emissions of rocks

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Abstract. Comparative analysis of acoustic and electromagnetic emissions recorded during the intact rock samples deformation and dynamic rupture of simulated crustal fault is presented. Specialized machines for uniaxial compression and shear tests of rock samples with identical data acquisition systems for both test cases were employed. Increase of acoustic emission was observed accompanied by significant rise of intensity and amplitude of electromagnetic signals at high stress of the rock samples under the uniaxial compression or dynamic failure in the spring-block model. Such correlation is consistent with the previous conclusions that an increase of electromagnetic emission may be considered as a rock failure precursor. Any specific characteristics of the detected electromagnetic signals to be used for prediction of impending rock failure or the earthquake fault rupture were not found. The similarity of electromagnetic signals and their spectra obtained at the press equipment and the spring-block model suggests that in both cases, the signals observed are generated by the crack formations and shear. The electromagnetic emission appeared only in dry samples. The samples saturated by water with the salinity of over 0.1% demonstrated no electromagnetic emission.

1. Introduction

Initial interest in the electromagnetic emissions (EE) from the Earth's crust was motivated by search for the earthquake precursors [1, 2, 3] where the possible physical models and sources of the EM fields were analyzed. For investigation of the EM emission (hereafter EE) nature, numerous attempts were made for laboratory simulation of the EE generation in rock samples under uniaxial and confining pressures, as well as under the three-point loading. In addition, a few experiments were performed at the spring-block models (sliders) simulated the crust fault. Extensive bibliography on EE studies is presented in [4, 5, 6].

As a rule, the researchers performed simultaneous recording of the EE and the acoustic emission (AE): that approach provides a possibility to relate the EE parameters to the cracking process and the subsequent formation of the sample failure. It was found that, in contrast to the AE, the EE signals appear at sufficiently high loads close to the sample failure. The physical nature of such EE emission was considered in [5, 7, 8, 9, 10 and others].

During the experiments at the sliders, the significant EE signals were recorded at the different process stages [11]. The EE signals in the "stick-slip" process might be related to the contact friction and destruction of the granular particles of the gouge layer in the contact zone. A three-stage model of the "stick-slip" process was suggested in [12], dominant signal frequency for each stage being different or EE disappears entirely. Several authors consider these characteristic changes of frequency as a precursor of dynamic failure [12, 13]. Authors [13] note that the kHz-range EE continues during
the dynamic failure as well, and the friction process at the slow slip stage can result not only in the granular material destruction in the contact zone, but also in the partial melting of the material with formation of ultrathin (a few microns) frictional melting films.

In the laboratory experiments cited above, to record the EE signals, the measurements of both pressure-stimulated currents (PSC) and EM fields were engaged. The PSC measurement was performed by use either the contact method [6, 14, 15] or the distant electrodes [16]. Note that in case of the contact measurements, processes at the interface surface can give rise to false signals by many times greater than the actual EE signals [17].

When measuring the EM fields, the distant electrodes connected to the recording system should be used. For suppression of the external EM fields, the method of compensation electrodes or shielding of the measuring equipment, or a combination of both techniques were employed.

Spectral analysis of the recorded signals is a common approach to the laboratory results. It is supposed that the amplitude-frequency characteristics of the signals can provide information on the stress-strain state of the material under study as well as on development of the defect formation, material fracturing and impending failure.

In addition to previous research, we studied the features of the EE behavior in the different rock samples under the various mechanical stress levels. We compared the results obtained at the press equipment with the characteristics of the EE signals emitted from the granulated gouge material in the spring-block system modeling the crust fault. For provision of correctness of the data comparison, we employed the identical data acquisition systems for both test cases.

2. Test equipment

We investigated the AE and the EE signals at the uniaxial compression [18] and the shear machines [19, 20] developed at the Joint Institute for High Temperatures, RAS. For our studies, both machines were modified to register the EM signals. For the tests at both machines, we employed the same measuring techniques and identical data acquisition systems providing a possibility of accurate comparison of the obtained test results.

The equipment for uniaxial compression of the rock sample is lever press [18]; AE and EE signals were measured under the condition of continuous slow rise of the sample load. Thus, the employed equipment provides much less acoustic noise as compared to a hydraulic-driven press machine. The maximum compression force is 300 kN: that corresponds to a maximum sample stress of 40–60 MPa depending on the actual sizes of the test sample.

For tests with uniaxial compression, we used the limestone and the sandstone samples. The sample dimensions were 200×120×60 mm, the density being 2.0–2.4 g/cm³, the porosity – 9–11%, and the failure stress – 20–30 MPa. We studied both dry and wet samples. The last ones were saturated with saline water with the NaCl weight content of 0.1, 1.0, and 10%. The electrical resistivity of the dry samples is over 10⁵ Ωm, and of the wet samples – 1–100 Ωm.

The shear machine represents spring-block system simulating the crust fault and providing slow deformation of the granular gouge material between two blocks [19]. We employed the sandstone movable block, the concrete fixed block, and the quartz sand gouge in the inter-block contact area. The normal load on the movable block was provided by loading masses of 20 to 100 kg. The shear load of the movable block is provided by the electromechanical drive with the minimal loading speed of 1.25 mm/min. When the shear force acting on the movable block exceeds the frictional force, the sharp slip of the movable block occurs up to the reaching the new balance between the shear and frictional forces and the "stick-slip" process repeats again simulating the seismic cycle in the crust fault.

The movable block dimensions were 200×120×60 mm, the sandstone density and porosity were 2.3 g/cm³ and 10%, respectively. The fixed block dimensions (L×W×H) were 1000×500×60 mm, the density and porosity being 2.4 g/cm³ and 9%, respectively. The thickness of the quartz sand layer was 2 mm, the sizes of the sand grains being 0.3 to 0.5 mm. We used the dry sand and the saline water-saturated sand with the NaCl weight content of 0.1%.
When recording the AE and the EE signals at both machines, the same technique and the identical data acquisition system were used for the accurate comparison of the signals at the different types of the sample loading. Fig. 1 shows the functional diagrams of measurements for both machines.

**Figure 1.** Functional diagrams of the measuring equipment: a) uniaxial compression of the rock sample: (1) rock sample; (2, 3) acoustic sensors; (4, 5) electrodes; (6) force cell; (8) screen; (9–12) signal amplifiers; (13) ADC; (14) computer; (15) plunger; (16) insulator; (17) stop; b) spring-block model: (1) movable block; (2, 3) acoustic sensors; (4) electrode (second electrode (5) is installed on the back side of the sample); (7) force cells; (8) screen; (12–15) signal amplifiers; (16) ADC; (17) computer; (18) spring; (19) load; (20) insulator; (21) fixed block; (22) granulated material.

We employed the PAE20-200 acoustic sensors with the frequency band of 1–200 kHz located on the two orthogonal faces of the rock sample. A large number of preliminary experiments showed that the spectrum of AE signals at the frequencies above 200 kHz up to 1 MHz does not exceed that of the self-noise of the measuring channel.

To measure the EE signals, we used the 150×100 mm flat copper electrodes. The electrodes were located at the distance of 10 mm from two parallel sample faces and fastened in such a way as to damp the acoustic field at the frequencies above 100 Hz. At the shear machine the electrodes travel together with the movable block. The frequency band of the EE measuring was 0.1–200 kHz. It can be assumed that when such registration technique is used the contribution to the measured signal is determined by both the EE-emission from the sample itself, and the displacement currents due to the capacitive coupling the sample with the electrodes.

In the experiments with the uniaxial compression, we employed the force measuring channel with the FS1 (5001DST) transducer to measure the loading force from 0 to 300 kN. At the shear machine, the shear force measuring channel was employed with the FS2 (UMM-K50) transducer to measure the shear force 0 to 500 N.

The ADC USB3000 was used to convert the analog signals to the digital data and to transmit the data to computer. Sampling rate in each channel is 500 kHz. The used sampling rate per channel was certainly sufficient for reliable registration up to 200 kHz. This statement was verified by collation of the test signals at the sampling rate of 500 kHz and 2 MHz. The PowerGraph© software manages the procedures of the ADC parameters setting and the data input into the computer.

The rock sample and the movable block with the sensors were surrounded by the electric shields. However, the shield itself might be a noise source due to its wall vibrations. To attenuate such interference, the shield walls were equipped with the reinforcement ribs.

Along with the external electrical interferences, the sample and the movable block are affected by the external acoustic interferences propagating through the structural components of the facilities. To detect the external interferences we employed the control equipment with the schematic diagram similar to that in Fig. 1. The scheme has two channels to measure the electrical interferences and two channels to measure the acoustic noise. The electric field sensors (electrodes) are installed at the distances of about 1 m from the shield. One acoustic sensor is installed on the bed frame of the facility, and another – on the shield. Preliminary tests demonstrated that the resonant frequencies in the spectra are not related to any resonating parts of the loading equipment.

3. Experimental results
3.1. Uniaxial compression test

We studied eight limestone and four sandstone samples under uniaxial compression. Note that the results for all samples were mainly similar. We suggest that the obtained AE and EE signals may be divided into two types. The AE signals of the first type were detected at the compression stress of up to 14–17 MPa only; that corresponds to the elastic part of strain-stress curve. Fig. 2a shows the waveforms and the spectra of the ADC input AE and EE signals for a particular sandstone sample. Both signals are the multi-harmonic damping oscillations. At least 90–95% of the signal energy is concentrated within the frequency band of 10 to 100 kHz. At the compression stress of 14–17 MPa, we detected only the first type EE signals. Similar to the AE signals, the second type EE signals are not observable against the self-noise background of the measuring channels. Fig. 2a shows the waveform and the spectrum of the first type EE signal at the ADC input. The signal has the form of the short impulse appearing 2–40 μs ahead the AE signal. The impulse front is determined with the high accuracy and, therefore, it can serve as a marker of the crack occurrence time. The impulse duration probably reflects the crack formation duration.

The second type AE and EE signals were not detected at low loads against a background of the self-interference of the measuring channels. They appear at the loads above 0.4–0.6 of the destruction value. As the load increases, the second type AE signals became more frequent and more intense. At the load of 0.8–0.9 of the destruction value, the portion of such signals is 10–15% of the total AE signal quantity.

Fig. 2a shows that the first type EE signal has the form of the short impulse appearing 2–40 μs ahead the AE signal. The impulse front is determined with the high accuracy and, therefore, it can serve as a marker of the crack occurrence time. The impulse duration probably reflects the crack formation duration.

Fig. 2b shows the waveforms and the spectrum of the EE signal of second type as well. As a rule, the signals start with a short initial impulse. The impulse commencement may be determined with the high accuracy as well, so in this case as well it can serve as a marker of the time of shear crack occurrence. The initial impulse is followed by the damping oscillations of a complicated shape. The
The oscillation duration of EE signals is comparable to that of the AE signals. The EE signals occur only simultaneously with the AE signals. However, only a small fraction of 5–10% of AE signals is accompanied by the EE signals exceeding the self-noise of the measuring channel. Thus, as a rule, the EE signals are detected in the case of large AE signals.

Fig. 3b shows the recorded waveform and the spectrum of AE signal of the second type at the ADC input for the same sample. The AE signal duration is of the order of magnitude longer than the same for the signals of the first type. At least 90–95% of the signal energy is concentrated within the frequency range of 1 to 50 kHz. As the load increases, the second type EE signals appear to be more often and more intensive. At the load of 0.8–0.9 of the sample failure stress, the fraction of these signals is again of 10–15% of the total EE signal number.

When the samples are saturated with water of 0.1% NaCl weight content, the EE signals occur more rarely and the energy ratio decreases by a factor of about two. When the NaCl weight content in water is 1% or 10%, we did not observe the EE signals at all. The absence of the signals in highly mineralized water might be explained by the local recombination of the opposite charges.

3.2. Shear machine

As for the shear machine, the AE and the EE signals were measured at various normal loads of a contact area within the range of 0.2 to 1.0 kN. When there was no sand gouge between the movable and the fixed blocks, at any normal stress within the range of 0.1 to 0.4 MPa, the AE signals of high amplitude were observed. In this case, the EE signals did not exceed the self-noise of the measuring channel. When the sand gouge was applied, the large AE signals were observed also within the above mentioned load range.

The AE signals look like the damping multi-harmonic oscillations. The top panel of Fig. 3a shows the signal waveform during the dynamical slip of the movable sandstone block at the normal stress of 0.27 MPa. The bottom panel of Fig. 3a shows the non-processed signal fragment without averaging and decimation. Individual signals may overlap each other in the time domain. Both the form of the signals and their spectra are similar to the first type AE signals recorded in the uniaxial compression tests (Fig. 2a). This fact is a reason for a hypothesis, unproven yet, that the AE signals of the second type might be associated with the shear deformation.

With the load increase, the AE signals overlap each other more often. Fig. 3b shows the recording of such AE signals obtained during the particular dynamic slip at the normal stress of 0.39 MPa. The signal data were averaged and decimated by 32 times. The middle panel of Fig.3b shows a fragment of the signals in extended time scale without averaging and decimation. The signals have a bay-like form and the bay amplitude is proportional to the slip velocity. The EE signal spectrum has large amplitudes at the frequencies below 5 kHz.

The EE signals occur when the normal stress is over 0.15 MPa. Within the load range of 0.15 to 0.25 MPa, the EE signals are single pulses with duration much shorter than for the AE signals. Fig. 3a shows a short EE pulse appearing 15 μs ahead the AE signal. However, the electrical pulses do not occur in every dynamic slip case, but only in one of three or four cases. The EE signal commencement can be a marker of the dynamical slip start and its duration corresponds the slip duration.

With further increase of the normal load above 0.25 MPa, the number of the EE pulses increases and they occur in each dynamic slip. The pulse duration increases insignificantly, and their amplitude rises by a factor of two to three. In addition, the low-frequency oscillations with a complex shape appear in the signal. The EE signals have the bay-shape and their amplitude is approximately proportional to the slip velocity. Fig. 3b shows the recording of such EE signals during the "stick-slip" process. Signals are averaged and decimated by 32 times. The bottom panel of Fig. 3b shows enlarged fragment of the signals without data averaging and decimation. There are 3 to 4 electrical pulses within the interval of 4 ms.
a) EE and AE signals at the normal stress of 0.27 MPa; b) EE and AE signals at the normal stress of 0.39 MPa. Upper panel: EE, AE signals, and shear force recordings during dynamic slip of the movable block. EE graph is shifted down by 0.6 V for clarity. Middle panel: Enlarged view of the EE and the AE signal fragments (recorded data without averaging and decimation). Bottom panel: Spectra of the EE and the AE signals. In the left bottom panel, also shown is the spectrum of a single electric pulse (EE pulse) having a form of spike. (See two such spikes on the EE record in the left upper panel).

If the water-saturated sand gouge is applied with the NaCl weight content of 0.1%, then the EE signals are decreased by a factor of 2 to 4. When the NaCl weight content in water is 1%, the EE signals are not detectable against a background of the self-noise of the measuring channel similar to the uniaxial compression tests.

4. Discussion
The EE signals recorded both in the uniaxial compression and the shear tests indicate that with the compression and the normal loads increase in these tests, respectively, the specific number the signals of the first type and their amplitude increase noticeably. Following [16, 21, 22], we assume that first type signals are associated with the crack formation and propagation, whereas the resonant frequencies are somehow related to the crack dimensions and stiffness. With the further load increase in both cases, the second type signals appear, and their amplitude exceeds the self-noise of the measuring channel. In the shear tests, the EE signals even begin to overlap each other, so it becomes impossible to analyze each of them individually. The fact that such signals appear at sufficiently large loads gives a reason to suggest that they are associated with the shifts along the dislocation boundaries, the boundaries between grains, etc. In general, this EE behavior is consistent with the data [5, 6, 13, and others]. An
increase of the second type signal occurrence and their amplitude in the uniaxial compression tests, when the rock sample approaches the critical stress-strain state, might be considered as a possible rock failure precursor.

Similarity of characteristics of the first type EE signals obtained in the uniaxial compression and the shear tests gives a reason to hypothesize that in both cases we deal with the signals caused by the cracking processes. Similarity of characteristics of EE signals of the second type obtained at both tests under high loads gives a reason to assume that in both cases, we deal with the signals caused by the shift processes or shear cracking. The electrical pulses are most likely generated at destruction of the sand grains and the subsequent friction of the formed fragments. This assumption is supported by the fact that the sand gouge subjected to multiple dynamic slips changes its appearance and looks like a cataclastic structure with more fine grains. The EE pulse onset might serve as a marker of the fracture occurring, and the pulse duration might reflect the fracturing time.

Nevertheless, we failed to reveal a change in any peculiarities of the recorded signals pointed in immediate approaching the sample failure or dynamic slip. In particular, we did not observe any systematic shift of characteristic frequency of the signal spectra towards lower frequencies, as was the case, for example, in [12]. The characteristic frequency of the EE signals varies quite randomly, but remains within the band of 1 to 20 kHz. Moreover, the EE signals are absent if the NaCl mineralization of saturating water is above 1%.

Indeed, we need to note that under the actual geological conditions, taking into account the electrical conductivity of the rocks over the earthquake source, an attenuation of the EE signals of kHz-MHz range will be very strong. It means that the EE signals of kHz-MHz range recorded before earthquake and considered as its precursors should not be attributed to the processes in the earthquake source.

5. Conclusions
1. An increase of intensity of the EE signals of the second type under the uniaxial compression might serve as a precursor of the rock sample failure. Nevertheless, it is necessary to determine the statistically significant threshold of the signal intensity (number density, and/or amplitude) above what the signals might be considered as the precursors. The EE signals in the shear tests appear only after the dynamic slip onset and, therefore, cannot serve as precursors of impending dynamic slip (laboratory "earthquake") along the simulated fault.

2. Similarity of the EE signals and their spectra obtained in the uniaxial compression and the shear tests suggests that in both cases, we deal with the signals caused by the cracking processes prevail under low and moderate loads, and the subsequent various shear processes.

3. At significant salinity of the water saturating the rock sample (above 1%), the EE signals do not appear. It may be explained by the opposite charges recombination in the conducting medium.

4. The EE pulse commencement is much more distinct than for the AE pulses. It is 2–40 μs ahead of the AE signal onset that is quite reasonable. It may be effectively used to locate AE signal sources more accurate.

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