ELECTROMAGNETIC INITIATION OF SLIP: LABORATORY MODEL

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Abstract

In the paper, the results of laboratory experiments on the electromagnetic (EM) initiation of mechanical instability (slip) are presented. Series of strong EM pulses were applied to the mechanical system driven close to the critical state, namely, to the (dry) rock samples placed on an inclined supporting sample at the slope angle less than, but close to the critical slip angle. The elementary theoretical model founded on the analysis of ponderomotive forces in dielectrics and explaining basic experimental data is suggested.

Key words: slip initiation, electromagnetic pulse, ponderomotive force.

1. INTRODUCTION

In 1983-1988 the Institute of High Temperatures of the Russian Academy of Sciences (IVTAN) performed series of MagnetoHydroDynamic (MHD) soundings as well as “cold” discharges at the Bishkek test area, Central Asia. In the experiments, initially aimed at finding resistivity precursors of strong earthquakes in the upper layers of Earth crust, an unexpected effect of microseismicity activation by strong electromagnetic (EM) pulses has been discovered (Tarasov et al., 1999). Analysis of sequences of interevent intervals (waiting times) of the regional seismological catalogue using
methods of nonlinear dynamics shows that during the period of discharges (1983–1988) the waiting time dynamics becomes much more regular compared to the periods before and long after cessation of experiments (Chelidze et al., 2003). These results may serve as an indication of the possible control of dynamics of a complex seismic process by strong EM impacts at least in the temporal domain.

The field of MHD-dipole is quite small at distances of the order of 100 km, where the effect has been observed. For the resistivity of rocks of the order of 100-1000 Ωm (the resistivity of rocks at the 5-10 km depth in the test area, according to Tarasov et al., 1999), at the distance of the order of 100 km from the dipole source (the distance to the area where the activation of microseismicity has been noted) the intensity of dipole field for the source used in Bishkek experiments is of the order of $10^{-5}$ V/m. The value locally can be several orders of magnitude higher due to the voltage amplification effects such as secondary fields at the tips of water-saturated cracks and random lattice percolation process of conductive inclusions (Benguigi, 1988; Chelidze et al., 2002).

Of course, only the system which is close enough to the critical state can manifest anomalous sensitivity to small external impacts. According to the recent investigations, the Earth’s crust in seismically active regions can be in the critical state or in the state of self-organized criticality (Bak et al., 1988; Scholtz, 1990). Thus, in order to reproduce this effect in laboratory it seems necessary to apply EM impact to the mechanical system that is close to the critical state.

The laboratory data on acoustic emission during compression of artificial samples (Sobolev et al., 2000) and on slip initiation (Chelidze et al., 2002) confirm the possibility of initiation of fractures or mechanical instability by strong electromagnetic pulses when the system is close to criticality.

In this paper, new data on the EM control of slip are analyzed. We show that the EM impact can either activate or hamper the slip, depending on the direction of the field; the elementary theoretical model is suggested.

2. EXPERIMENTAL SETUP

The experimental setup has been designed in such manner that the mechanical system could be easily driven to the critical state where the triggering of mechanical instability by some weak impact such as electrical pulse became more probable. The system consists of two pieces of rock; the upper piece can slip on the fixed supporting sample if a special frame tilts the latter one up to the critical angle $\alpha_c$ (Fig. 1).

The electrical part consists of EM pulse generator and acoustic signals amplifier. The signal from the standard generator of amplitude 0.5–5 V is applied to the input of the amplifier and goes out from the output with the amplitude up to 1300 V. Up to 10 DC-pulses of that amplitude were applied to the sample. The duration of pulses was from 5 to 10 s; the interval between pulses was also from 5 to 10 s; the high voltage
source (discharger) was also used. Another amplifier was designed for registration of acoustic signals from the sensors which respond to the slip events. The amplifier’s output voltage was sufficient for registration of acoustic signals by the sound card of PC. The scanning of the process was performed on the frequency 96 kHz, i.e., the sampling rate was 1/96000 s.

Electrodes were applied in the following ways: (a) to the bottom of the supporting sample in a coplanar manner or to the sides of the supporting sample (the first mode); (b) to the upper surface of the sliding sample and the bottom of the supporting one (the second mode). In the first case, the EM field is oriented roughly parallel to the slip surface and in the last case current lines are normal to it. In most cases the supporting and the slipping blocks were prepared from basalt; these samples were saw-cut and roughly finished. The slipping block has 10 cm length, 10 cm width and was 2 cm thick. Other samples, such as granite, labradorite, and glass, which were better finished, were also tested. The height of surface protuberances was in the range of 0.1–0.2 mm for basalt samples and 0.05–0.1 mm for other ones.

3. EXPERIMENTAL PROCEDURE AND CASE STORIES
The main objective of experiments was to find out whether EM-pulse could indeed displace the rock sample, resting on the supporting sample at the slope of support that is less than but close to the critical slip angle.
After finding the critical angle, the slope of support was decreased by 0.1–2°. In this state, the upper sample was stable for many hours (2 days), which means that other sources of instability such as building vibration by trucks, elevator, wind, etc were not strong enough to initiate the slip. The critical angle for the rough surface varies from one test to another because it is impossible to reproduce exactly the arrangement of asperities between the support and the slipping blocks in different experiments. The scatter in values of critical angle for the same sample is of the order of ±2.5° (Fig. 2), so we can define only the average value of $\alpha$, which changes from one test to another. That is why before the EM impact the sample was kept at the angle less than the (average) critical one for 10 minutes and only after this exposure it was subjected to the EM-impact. That allows assessing correctly the statistics of EM-activation, as the probability of slip in the time intervals without EM-impact can be compared with that in the time intervals, covering the whole EM-activation period. The activation period lasts several minutes and it includes also the gaps between pulses. A sequence of pulses applied in a single experiment and gaps between them will be related as a run. Practically the probability of slip without EM-impact at $\alpha < \alpha_*$ was zero: no slip was observed during any of 10 min preliminary repose periods (a total of 500 min).

The first mode

We found that the application of EM-pulses in the first mode, i.e., to the coplanar electrodes at the bottom of support, initiates a slip in approximately 40 cases from 600
runs (i.e., the slip initiation probability is around 0.07) either during pulse (i.e., in the active phase), or after it (i.e., in the passive phase). The last observation means that the polarization of the sample can be important for the slip initiation. As the delay of slip after switching off the pulse was sometimes considerable (seconds), our guess is that in this case polarization is related mainly to the accumulation of the bulk charge near electrode surfaces. This phenomenon (electrode polarization) is well known; it accompanies application of high voltage to ionic conductors and its relaxation is slow.

The typical recording of acoustic emission generated by the slip event is shown in Fig. 3 for different time scales.

Fig. 3. Recording of acoustic emission generated by the electromagnetically initiated slip of the basalt sample (upper traces). Lower traces shows EM pulse switching on (thick lines) and switching off (thin lines) periods. The slip was initiated just after active period; y-axis shows the amplitude of the signal in db; x is the time axis. Lower panel is the initial part of the same recording for stretched time axis.

Besides the pulse generator, a second source of high voltage, namely the electrical discharger TESLA OPOCMO TVI 200 has been used for initiation of slip. In this case, the voltage applied was of the order of 10 kV. Again, series of pulses were applied to the sample in the first mode and in this case the probability of slip initiation was much higher – around 0.2.
The second mode

In the second mode, the electrodes were applied to the upper facet of the slipping block and to the bottom side of support, i.e., in this case the applied electrical field was oriented in the direction of the normal to the slip surface.

More than 300 pulses were applied in 13 experimental runs (24 pulses in a run) at the same inclinations of support as in the first mode, but not a single slip event has been registered. Even at the slope angle $\alpha = 28.6^\circ$, that is much larger than the critical value $\alpha_c = 25\pm 2.5^\circ$, the sample stays stable under EM impact. This means that when the EM is applied in the second mode, it increases the friction force (EM field hampers slip).

Finding of mechanical equivalent of EM impact

For assessment of mechanical equivalent of electrical impact, both direct and theoretical methods were used.

Fig. 4a. The acoustic signal emitted during EM-initiated slip (basalt samples, record with steep increment); (b) the corresponding wavelet transform. The scale of shading from minimum to maximum is shown at the bottom.
In the first case the mechanical force initiating slip at the same angle \( \alpha < \alpha_c \) that has been set in experiments with EM-impact was measured by spring and torsion dynamometers (accuracy of \( \pm 0.01 \) N and \( \pm 0.005 \) N, respectively). Both methods gave comparable results. The force equivalent to the slip-initiating EM-impact is of the order of 0.2 N. Another way to get mechanical equivalent is to calculate it from the general equation of balance of forces for a sample placed on the inclined plane

\[
F = mg(\mu \cos \alpha - \sin \alpha),
\]

where \( m \) is the mass of the sliding sample, \( g \) is the Earth acceleration, \( \mu \) is the friction coefficient, and \( \alpha \) is the slope angle.

If \( \mu \) is known (for basalt samples \( \mu = 0.47 \)), the slip-initiating force can be calculated for any angle. For example, if \( \alpha_c \) equals 25°, at \( \alpha = 24^\circ 50' \) the initiating force is 0.42 N. This value is of the same order as in direct experiments, 0.2 N. Thus, in the situation close to the critical one, even 0.2 N force can initiate slip of the sample weighting 700 g.

Fig. 5a. The acoustic signal emitted during mechanically initiated slip (basalt samples, record with the smooth onset); (b) the corresponding wavelet transform. The scale of shading from MIN to MAX is shown at the bottom.
Our guess is that the EM impact is equivalent to the above value, i.e., it promotes slip in the first mode and hampers it in the second mode by the additional force of the order of 0.2–0.4 N.

4. ANALYSIS OF RECORDED ACOUSTIC WAVEFORMS

The results of experiments, namely, the acoustic signals emitted during the initiated slip, were recorded as *.wav files with 96 kHz sampling frequency at 8 bit resolution. These files include both the slip episodes and the intervals of record before slip (background). Here we consider only records without pinning of signal, i.e., records that are not distorted by device. Wavelab and MatLab packages were used for analysis of recordings of acoustic emission at electromagnetic and mechanical initiation of slip.

Two main types of recording were observed: with a steep increment of AE signals and the ones with a much smoother onset (Figs. 4a, 5a); each of them can be observed at both methods of slip initiation.

The 3D patterns of original signals were obtained using program WaveLab (Figs. 6a, 7a); they show that some periodic components span the whole time axis. As they are present even before the slip initiation, we guess that they are connected with weak vibrations due to computer and generator fans and other alias sources.

For filtering the background noise and further analysis of recordings, *.wav files were imported to the MatLab and their wavelet transform was performed. Mayer wavelet with a compact support in the frequency domain was applied (Figs. 4b, 5b). In the wavelet transforms of original signals the noisy background components are quite evident also, and are additionally localised in the frequency domain. Calculated wavelet coefficients were used for filtering of original signal. Namely, the wavelet components related to the frequency range of noise, quite different from these of slip movement, were excluded (Fig. 8). The de-noised signal reproduces the slip-generated wave package quite satisfactorily.

The resulting de-noised data were again analysed using Wavelab, and filtered 3D images of frequency distribution in the time domain during slip were obtained (Figs. 6b and 7b).

An analysis of above images shows that the emitted signals are concentrated in 500–20000 Hz frequency range and that the manner of slip initiation (EM or mechanical) does not change significantly the wavelet and spectral patterns.

5. THE ELEMENTARY THEORY OF EM COUPLING WITH THE FRICTION FORCE

In order to understand physics of EM-slip it is necessary to consider fundamentals of surface phenomena. Intermolecular and intersurface forces, responsible for adhesion and friction, can be loosely divided into three categories: (a) purely electrostatic forces
Fig. 6. 3D pattern of emitted signal with a steep increment, corresponding to Fig. 4: (a) original; (b) filtered using wavelet transform.

Fig. 7. 3D pattern of emitted signal with the smooth onset: (a) original; (b) filtered using wavelet transform.
Wavelet coefficients (levels) are related to pseudo central frequencies in the following way:

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Fig. 8. Filtering of the signals, using wavelet transform. Original coefficients and thresholded coefficients plots for: (a) the signal with the steep increment (Fig. 4); (b) the signal with the smooth onset (Fig. 5). The original and de-noised signals practically coincide.
arising from the Coulomb interaction between charges; (b) polarization forces arising from the dipole moments, induced by internal (bound charges, dipoles) or external electric field; (c) quantum-mechanical forces, responsible for covalent bonding and so-called steric interactions. All these forces can act simultaneously, resulting in some total adhesion (friction) force. For friction we have

\[ F_f = \mu F_n, \]

where \( \mu \) is the friction coefficient and \( F_n \) is the normal component of force acting on the body (gravity, compression).

From the above classification, it can be deduced that in principle the external electrical field can affect the intersurface adhesion (friction) forces, changing \( \mu \) and thus initiating slip of the body placed on the inclined plane. We can rewrite (2) in the following way:

\[ F_f = \mu (F_n + F_p), \]

where \( \mu \) is the friction coefficient and \( F_p \) is the increment/decrement of normal component of force due to the application of EM field.

Of course, coupling of EM-impact with friction of the sample containing piezoelectric materials is a trivial phenomenon. However, the EM-activation is clearly observed on samples that are practically free of piezoelectric minerals (basalts). That is why we exclude piezoelectric effect as a principal mechanism of EM-slip.

The elementary theoretical model of EM coupling with friction can be formulated in the following way. It is well known that an application of EM field to the dielectric invokes some forces acting upon molecules of the body; the resultant of them is called the ponderomotive force \( F_p \) that affects the whole sample. The force is proportional to the gradient of the field intensity squared and it carries away the sample in the direction of the largest intensity. The tension tensor \( T_n \) operating on the element of dielectric’s surface in EM field of intensity \( E \) under the assumption that the sample of dielectric constant \( \varepsilon \) is surrounded by the immobile dielectric medium in ESU system is (Tamm, 1956)

\[ T_{np} = \frac{\varepsilon + (\partial \varepsilon / \partial \delta) \delta}{8\pi} E^2 n, \]

when the field \( E \) is parallel to the external normal \( n \) to the considered surface element, and

\[ T_{nn} = -\frac{\varepsilon - (\partial \varepsilon / \partial \delta) \delta}{8\pi} E^2 n, \]

when the field \( E \) is normal to \( n \).

We can imagine that the elastic strings are stretched along the field lines (Tamm, 1956): in our case they pull together the surfaces of sliding and supporting samples.
according to relation (4) in the second mode and build the side thrust on each other according to relation (5) in the first mode.

The above equations can be simplified if the dielectric increment due to the striction force is negligible: \( \frac{\partial \varepsilon}{\partial \delta} \rightarrow 0 \). Introducing the area of dielectric’s surface \( S \) and taking into account the above assumption, the ponderomotive force is

\[
\mathbf{F}_p = \pm \frac{\varepsilon}{8\pi} E^2 \mathbf{n} = \pm \frac{\varepsilon S}{8\pi} \left( \frac{\Delta V}{d} \right)^2 \mathbf{n},
\]

(6)

where \( \Delta V \) is the applied voltage and \( d \) is the distance between electrodes; the sign depends on the mutual orientation of dielectric’s surface and electrical field.

Substituting into relation (6) the values: \( \Delta V = 1200 \), \( V = 4 \) ESU, \( \varepsilon = 5 \); \( S = 100 \text{ cm}^2 \) and \( d = 5 \text{ cm} \), which correspond to the capacitor created by two electrodes applied in the second mode, we obtain

\[
|\mathbf{F}_p| = 5 \times 10^{-6} \text{ N}.
\]

That is much less than the experimental values of electromagnetic pull, which is of the order of \( 0.2 \) N. Here we have to note that the value of \((\Delta V/d)\), substituted in eq. (6), is an average value for the whole system and on the contact between two blocks the gradient can be quite different. The matter is that: (a) the samples were not ideally finished and there were some air-filled gaps between them in the contact area; (b) the resistivity of basalt samples at room humidity is in the range of \( 10^4 \text{–} 10^6 \Omega \text{m} \) (Volarovich et al., 1962) and the resistivity of air is much larger, of the order of \( 10^{16} \Omega \text{m} \). This means that the major part of the voltage drop occurs in the gap and the local gradient of EM field in the gap between samples can be much larger than that for the whole system between the electrodes. In order to assess the forces acting in the narrow gap between slipping and supporting samples, it is necessary to consider the gradient in the gap between the samples. The inner surfaces of slipping and supporting samples carry bound charges due to the polarization of material, and thus create the local gradient of electrical field in the gap. The opening of the gap itself is varying; we can introduce some effective value of opening \( d_{\text{eff}} \). Then, applying again eq. (6) to the “inner” capacitor we obtain for the ponderomotive force \( \mathbf{F}_{\text{pi}} \) acting on the gap surfaces the formula:

\[
\mathbf{F}_{\text{pi}} = \pm \frac{\varepsilon_{\text{eff}} S}{8\pi} \left( \frac{\Delta V_{\text{eff}}}{d_{\text{eff}}} \right)^2 \mathbf{n},
\]

(7)

where \( \Delta V_{\text{eff}} / d_{\text{eff}} \) is the effective voltage gradient in the gap and \( \varepsilon_{\text{eff}} \) is the effective dielectric constant of the gap which is between values of \( \varepsilon \) for the air and the sample: \( 1 < \varepsilon < 5 \).

Assuming \( \varepsilon_{\text{eff}} = 2.5 \), \( S = 100 \text{ cm}^2 \), we have to put in eq. (7) the gradient \( (\Delta V_{\text{eff}} / d_{\text{eff}}) = 0.07 \text{ V/cm} \) in order to obtain the experimental values of slip-initiating ponderomotive force, namely, \( \mathbf{F}_p \approx 0.2 \text{ N} \).
Thus, expression (3) can be rewritten, taking into account (7):

$$F_i = \mu (F_a + F_p).$$  \hspace{1cm} (8)

It is evident that the expression (8) is similar to the expression for the friction force, taking into account the pore pressure term (Sibson, 1994).

The above value of $F_p$ can be considered as an order of magnitude of ponderomotive force that promotes the slip in the first mode and hampers it in the second mode, according to the expression (7) for the accepted set of parameters.

Both our experiments and theoretical considerations are related to the “dry” environment, namely to the air humidity of $60 \pm 20\%$ at the temperature of $20 \pm 5^\circ\text{C}$.

In the “humid” environment, when the rock’s pore space is fully or partially saturated with water, additional factors should be taken into account: (a) the pore pressure increment (decrement) in the gaps caused by the electrokinetic flow of fluid at the application of EM field; (b) the change of surface fracture energy of cracks due to electroosmotic fluid inflow into the cracks of an undersaturated rocks due to the EM impact. Both these factors can facilitate fracture process in water-bearing rocks.

6. CONCLUSIONS

Series of strong EM pulses were applied to the mechanical system driven close to the critical state, namely to the (dry) rock sample placed on the inclined supporting sample at the slope angle less than, but close to the critical slip angle. The electrical field was applied so that current lines were either parallel (the first mode) or normal (the second mode) to the slip surface. It has been found that in the first mode the EM impact initiates slip with probability $P \approx 0.07$ at the voltage $\Delta V = 1.3 \text{ kV}$ and with probability $P \approx 0.2$ at $\Delta V \approx 10 \text{ kV}$. On the other hand, in the second mode the application of EM pulse hampers the slip considerably: the upper sample was stable even at the angle, that was larger than the critical one. The elementary theoretical model founded on the analysis of ponderomotive forces in dielectrics and explaining basic experimental data is suggested. The basic expression for a friction force under EM impact, containing electrical component of friction force and similar to that of a shear stress with the pore pressure term, has been obtained.

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References


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