Acoustics of stick-slip deformation under external forcing: the model of seismic process synchronization

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Abstract: - Essential dynamical changes, such as synchronization, different types of resonances, triggering etc. caused by relatively small comparing to external influences, are encountered in various fields, from mechanics to biological and even social processes. Thus it is only natural that similar phenomena are observed in many geophysical fields, as the Earth is embedded in the oscillating field of different origin with extremely wide range of frequencies, from seconds to months and years. For example there are a lot of observations that seismic activity is coupled of such weak oscillating fields as Earth tides, solar activity, atmospheric pressure, electromagnetic pulses (storms), seasonal variations, and reservoir exploitation.

The intensity of stress, invoked by these superimposed periodical oscillations is as a rule much smaller than that of the main driving force – tectonic stress. Nevertheless, finally, this weak interaction may invoke mentioned phenomena, (e.g. triggering/synchronization), or, at least, change (increase) level of ordering of the system behavior in the time domain (so called phase synchronization). We reproduced these effects in laboratory conditions and it turns out that mechanical or electromagnetic (EM) forcing is a flexible tool for study of triggering and phase synchronization (PS) phenomena in laboratory slider experiments.

In the paper, the results of laboratory and field experiments on the mechanical or electromagnetic (EM) initiation and synchronization of mechanical instability (slip) of a slider-spring system are presented. Slip events were recorded as acoustic emission bursts.

Key words: stick-slip, forcing, synchronization, acoustics, seismicity, delay,

1 Introduction

Synchronization and triggering are encountered in various fields, from mechanics to biological and social processes. Thus it is only natural that synchronization phenomena are observed in many geophysical fields, as the Earth is embedded in the oscillating field of different origin with extremely wide range of frequencies, from seconds to months and years. For example there are a lot of (disputable) observations that seismic activity is coupled with the action of such weak oscillating fields as Earth tides, solar activity, atmospheric pressure, electromagnetic pulses (storms), seasonal variations, and reservoir exploitation. The intensity of stress, invoked by these superimposed periodical oscillations is as a rule much smaller (of the order of 0.1-1 bar) than that of the main driving force – tectonic stress. Nevertheless, as it follows from the recent findings in the field of complex dynamics (2) this weak interaction may affect general dynamics of investigated system and invoke, at least, the phenomenon of phase synchronization (the weakest form of synchrony without ssential dynamical changes), or even the distinct increase of the level of ordering of the system. It is evident that these phenomena cannot be understood in the framework of traditional linear approach and that such high sensitivity to weak impact imply essentially nonlinear interactions.

2 Problem formulation

At present there are important gaps in the current knowledge on triggering/synchronization of seismic processes:

- quantitative assessments of the strength of phase synchronization are not performed.
- the possibility of phase synchronization on the multiple frequencies of forcing is not investigated.
- it is not clear, whether the strength of phase synchronization is time-dependent (in particular, does it change before strong earthquake?)
- the possibility of controlling the amplitude of seismic/acoustic events by variation in forcing intensity is not investigated.

- physical mechanisms of synchronization at mechanical, electromagnetic etc. forcing are not clear.
- mathematical model of stick-slip synchronization at forcing is not well developed.

New tools for quantification of the strength of synchronization have been developed last years (10). These modern techniques of synchronization analysis allow closing these gaps and are quite new for seismology. Their application to seismic and laboratory acoustic time series may reveal new regularities and lead to introduction of new characteristics of seismic process. Understanding of nature of seismic synchronization earthquakes may give the new tool for control of seismic process and prediction of impending strong event. Indeed, according to the recent findings periodic contributions appear in the microseisms spectra before strong earthquakes; the revealed periods vary from minutes to years (11). Clear PS effect was discovered in laboratory experiments with spring-slider system by application of weak periodic force (3, 4, 5, 6). These results may give answer to the questions: can relatively weak external impact control seismic process and what parameters should the impact have.

2.1 Experiments: triggering and synchronization

The main objective of triggering experiments was to find out whether EM-pulse could indeed displace the rock sample, resting on the supporting sample at the slope of support, less than but close to the critical slip angle. The details of experiments are presented in (3). 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 α_c. Electrical field was applied either parallel (first mode) or normal (second mode) to the slip surface. Supporting and slipping blocks were prepared from roughly finished basalt (the height of surface protuberances was in the range 0.1-0.2 mm). The basalt samples were preferred because they do not contain significant quantity of piezoelectric minerals.

Experimental set up in synchronization experiments represents a system of two horizontally oriented plates of the same roughly finished basalt.

A constant pulling force F_p of the order of 10 N was applied to the upper (sliding) plate; in addition, the same plate was subjected to periodic mechanical or electric perturbations with variable frequency (from 20 to 120 Hz) and amplitude (from 0 to 1000 V), which were much weaker compared to the pulling force; the electric field was normal to the sliding plane. Slip events in both triggering and synchronization experiments were registered as acoustic bursts by the sound card of PC.

Details of the setup and technique are given in (6).

3 Results

3.1 Triggering

We found that the application of EM-pulses (1300 V) in the first mode, i.e. to the coplanar electrodes at the bottom of support, initiates 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), either after it (i.e. in the passive phase). The last observation means that the polarization of the samples can be important for the slip initiation. The probability of slip triggering rises to 0.2 when the applied voltage was increased to 10 kV. Not a single slip event has been registered in the second mode (300 tests), when the applied electrical field was oriented in the direction of the normal to the slip surface, even at the repose angle larger than the critical one. That means that in the second mode EM field hampers slip.

3.2 Synchronization

Synchronization of oscillating autonomous system of natural frequency ω_0 by forcing frequency ω results in modification of systems' frequency ω_0 to so called observed frequency Ω.

In our experiments the following parameters were varied: i) the stiffness of the spring, K_s; ii) the frequency, f of superimposed periodical perturbation; iii) the amplitude of the excitation (applied voltage V_a); iv) the velocity of drag, v_d; v) the normal (nominal) stress σ_n.

The system during conventional stick-slip without forcing either do not manifest any visible periodicity (initial part of record in Fig.1a and Fig.1b – with expanded time scale) or manifests quasi-periodicity depending on the parameters K_s and v_d. The slip process, affected by the periodic ($f \approx 60$Hz) additional electromagnetic (EM) forcing of varying intensity is shown in the Fig.1a and in Fig.1b and Fig.1.c – at the expanded time scale. The significant synchronization at this frequency occurs at $V_a \geq 500$V (central section of Fig.1a). Under EM excitation the AE events (microslips) occur twice per period (Fig.1c).

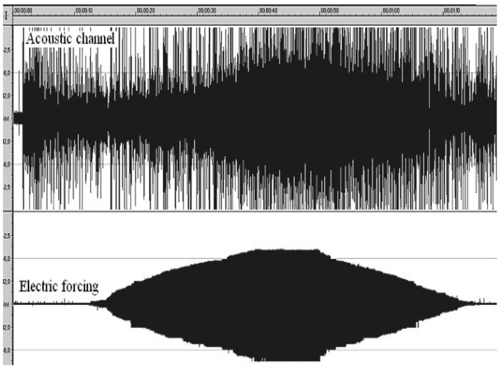


Fig. 1a.

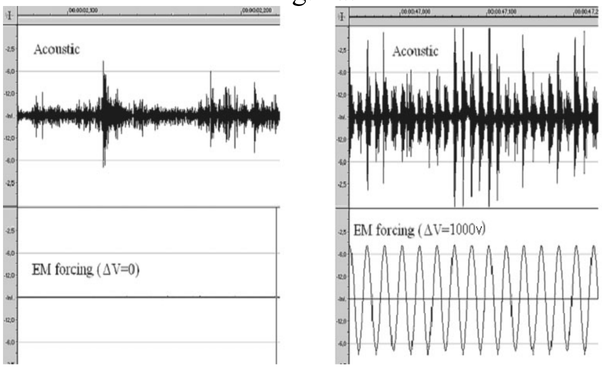


Fig.1 b Fig.1.c

Fig. 1a. b,c. The upper traces record AE signals generated by slips; the lower channel records EM forcing; a – the full record, b – non synchronized and c- synchronized (expanded) sections. In Figs. 1a, 4,10,11,12a,13a and 14 a the vertical axis shows the intensity of signal in dB and horizontal axis shows the time.

Synchronization was observed only at some definite sets of parameters (K_s, f, V_a). The "phase diagram" for variables f, and V_a or so-called Arnold's tongue (10) is presented in the Fig. 2.

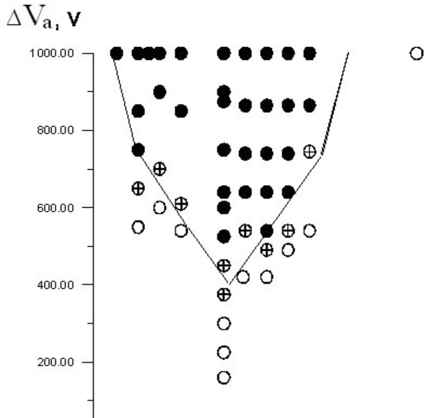


Fig.2. Stick-slip synchronization area Arnold's tongue) for various intensities (V_a) and frequencies (f) of the external EM forcing. Filled circles – perfect, circles with crosses – intermittent and empty circles – absence of synchronization.

Relatively weak mechanical periodic perturbations also imposes on the slip a clear periodicity. Synchronization affects not only waiting times, but also frequency-energy distribution. Decrease of contribution of extreme events at synchronization is confirmed by calculation of the coefficient of variation CV (CV=standard deviation/mean). As it is shown in Fig.3, the extent of the deviation from the mean value of released AE power calculated for consecutive sliding windows, decreases at synchronization. That means that synchronization limits the energy release associated with individual events (quantization effect). Sudden decrease or total cessation of synchronizing forcing is followed by acoustic burst of much larger energy than during periodic forcing (Fig.4).

Fig. 3. Coefficient of variation of power of acoustic emission time series at increased external forcing for 500 data length sliding window with 50 data shift. Here only half of record of Fig.1 is used from the start of the`test to the maximum synchronization state.

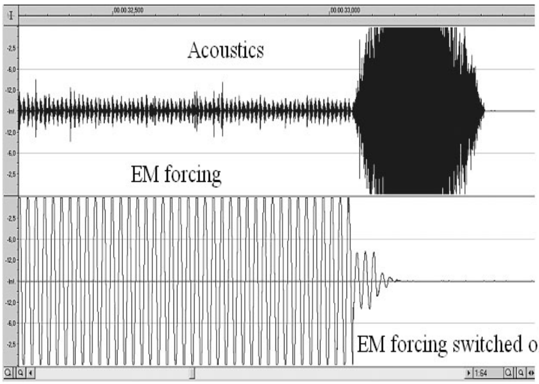


Fig.4. Increased acoustic energy release after cessation of periodic forcing, which means that synchronization limits the energy release

associated with the individual events (quantization effect).

4 Synchronisation: quantitative analysis

In order to assess synchronization in the qualitative manner we used the easiest approach for estimating phases of acoustic signal: digitized waveforms were transformed to sharp spikes to have well pronounced markers. Then time series (catalogues) of time intervals (waiting times) between consecutive maximums ($\Delta t = t_i - t_{i-1}$) or between onsets of acoustic wave trains for π periods of external sinusoid were compiled.

After all, because our dataset was transformed to a spike train, containing distinct markers, we used phase difference determination technique described in Pikovsky (10). Additionally, in order to achieve more reliable phase construction and precise synchronization testing, the instantaneous phase of real acoustic signal was defined employing analytic signal concept, based on the Hilbert transform (10). Both approaches yield similar results. For the same reason of getting quantitative measures of synchronization, the mean effective phase diffusion coefficient $D = \frac{d}{dt}\left[\left\langle \Delta\varphi^2 \right\rangle - \left\langle \Delta\varphi \right\rangle^2\right]$, probability density distribution and he Shannon entropy based synchronization measure *(γH-Sh)* and the degree of determinism (%D) by RQA for waiting time series have been also calculated (8). All mentioned methods were applied to the experimental data (Fig.1) obtained under variable intensity of forcing; the results are shown in Figs. 5-8.

In Fig.5 we present the temporal evolution of phase difference $\Delta\phi$ obtained from Hilbert transform of waiting times sequences. Well-defined horizontal part of synchrogram represents the time, during which the acoustic emission becomes phase synchronized to the external sinusoidal influence in the wide range of their amplitudes (from approximately 500 V to 1000V).

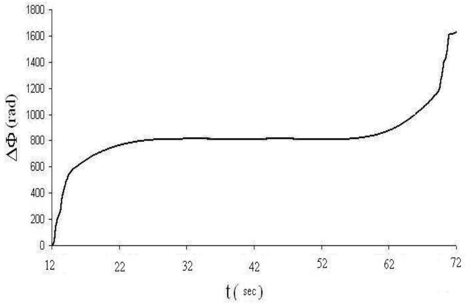


Fig.5. Phase differences between the whole sequence of maximums of acoustic emissions' bursts and external sinusoidal signal (Fig.1). Note plateau with small ΔΦ in the synchronized section.

The full width at half maximum (FWHM) of probability density distribution of phase differences between AE pulses and sinusoidal forcing is much narrower for the synchronized part of Fig.1. The phase diffusion coefficient is also minimal in this section of record (see Fig. 6) as well as Shannon entropy based synchronization measure *(γH-Sh)* (Fig. 7).

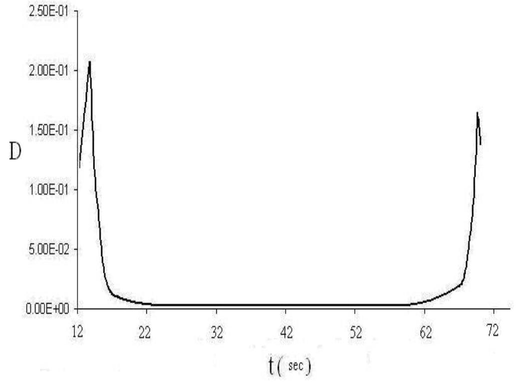


Fig.6. Variation of phase diffusion coefficient D of phase differences, calculated for consecutive sliding windows, containing 500 events for the whole sequence of Fig.1.

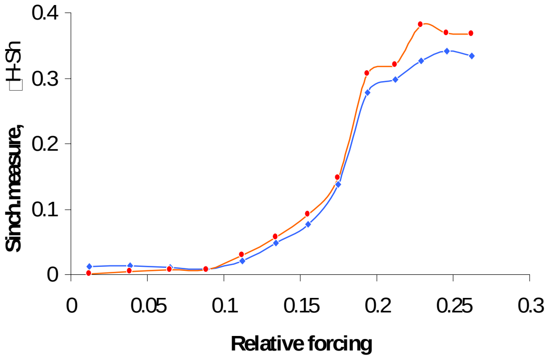


Fig.7. Shannon entropy based characteristic phase synchronization measure (γH-Sh) versus relative intensity of forcing for the first half of Fig.1a; red curves – for onsets of AE pulses, blue ones – for AE maxima.

In the same central section of Fig.1a the percent of determinism %DET, calculated by RQA approach (8) is maximal (Fig.8).

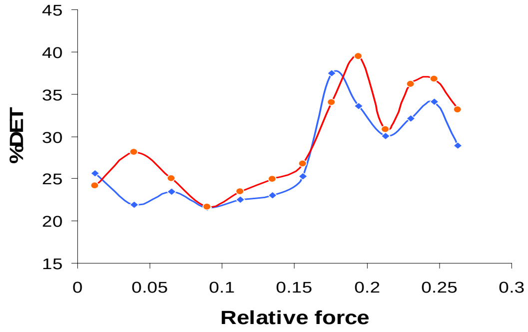
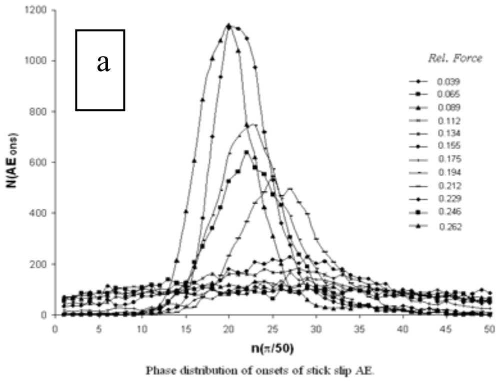
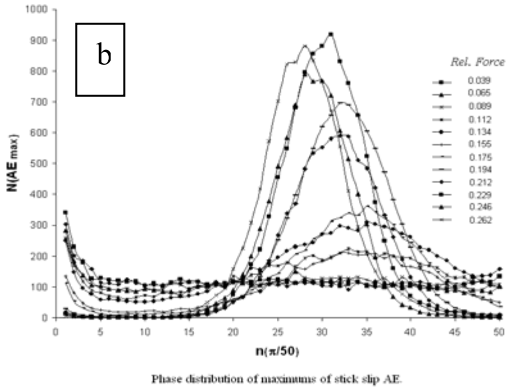


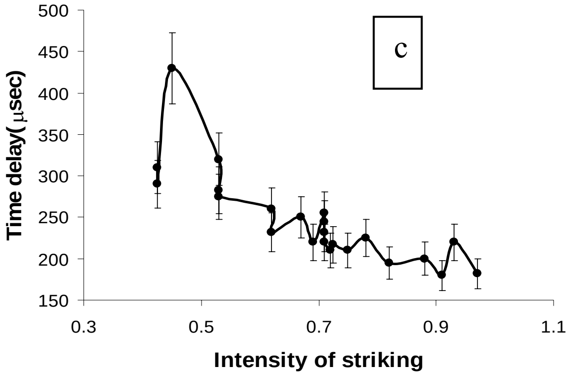
Fig.8. RQA %DET measures of stick-slip-generated AE time series for the first half of Fig.1a.

5 Phase time delay

The acoustic response lags behind the periodic forcing phase; the lag is inversely proportional to the forcing intensity (Fig. 9 a,b). It is interesting to note that the similar effect of time delay was observed in experiments, when slip was triggered by mechanical striking of various intensity (Fig. 9c, (12). The delay is quite similar for both AE burst onsets and AE wave train maxima (Fig. 9 a and d).







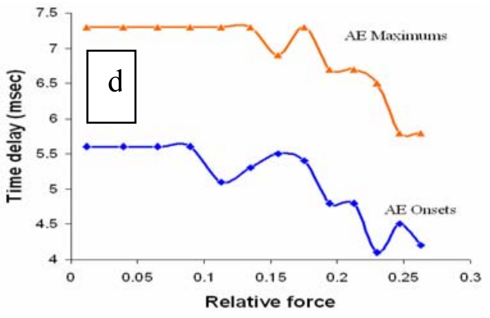


Fig.9. AE phase delay relative to forcing phase: distributions of AE number versus delays for a-onsets and b – maximums of acoustic signal at periodic EM forcing; c –time delays for slips triggered by mechanical strike, d - phase time delays at synchronization by periodic EM forcing.

6 High-order synchronization

High-order synchronization (HOS) means that the forcing and observed frequencies in the system are related to each other by some winding ratio $(n{:}m)$ that is $n\,\omega = m\,\Omega$.The phenomenon of HOS can be observed at changing frequency (Fig.10) or mode of forcing (Fig.11,12).

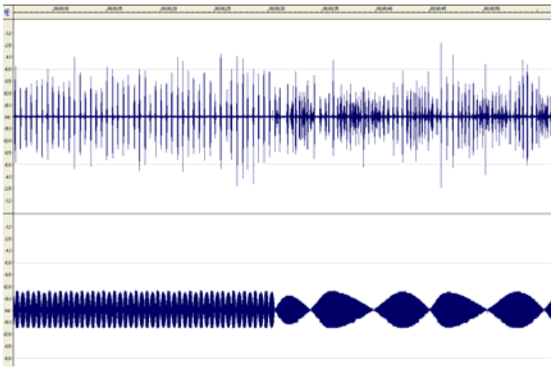


Fig. 10. Transition (bifurcation) in stick-slip from 1:1 synchronization to high order synchronization at increasing the period of EM forcing from 0.5 s to 4.5 s

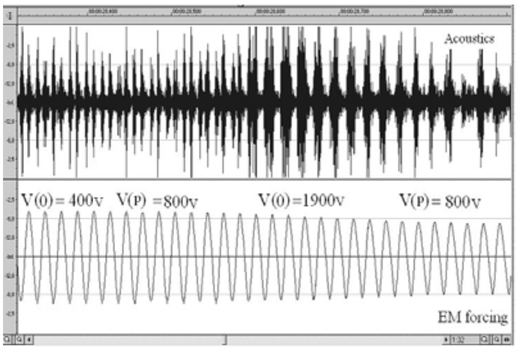


Fig.11. Transition (bifurcation) in stick-slip from 1:2 to 1:1 synchronization at simultaneous action of direct V(0) and periodic V(p) voltages; transition occur at $V(0) > V(p)$

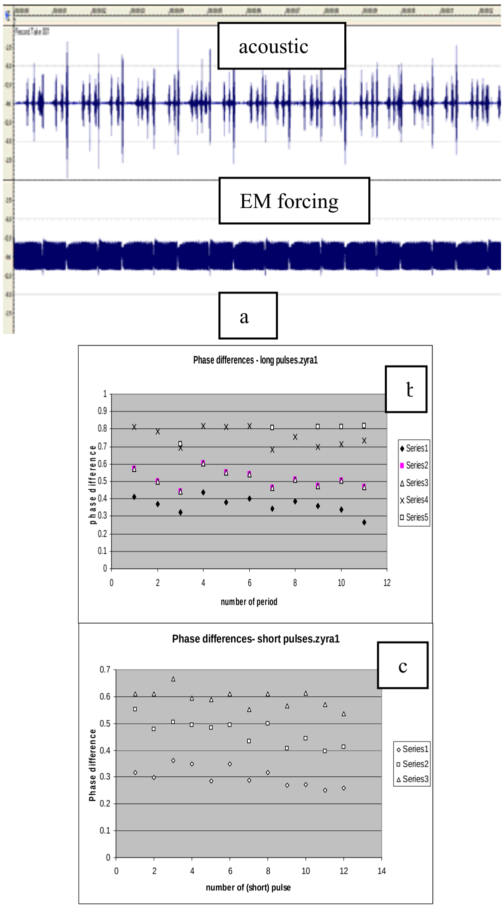


Fig.12. High order synchronization at EM forcing by short and long pulses, n<m ; a – full record; b – phase differences for long pusles; c - phase differences for short pusles

Fig.12 b and c show that the phases of multiple AE bursts (slips) triggered by the EM pulse depend on the duration of pulse and manifest well ordered, almost constant phase difference distribution relative to the EM pulse onsets. The strong PS was observed also in the case $n>m$ both for EM (Fig. 13) and mechanical forcing (Fig. 14); in the latter case the AE bursts were synchronized hundreds of forcing periods apart.

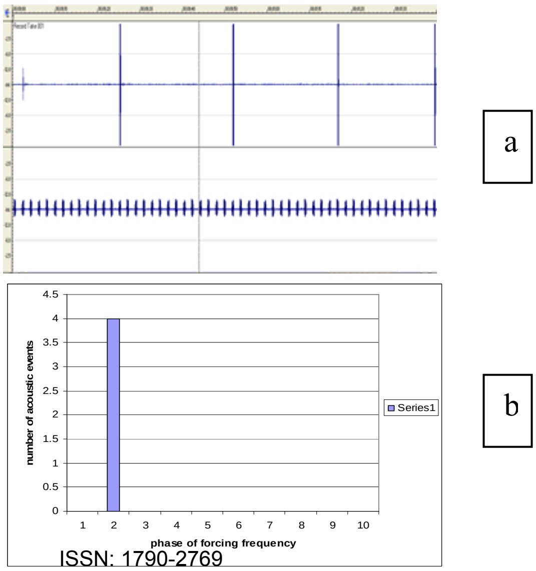


Fig.13. a- high order EM synchronization: n>m; in this case 14 n=m, b – number of AE bursts in the certain phase of EM forcing

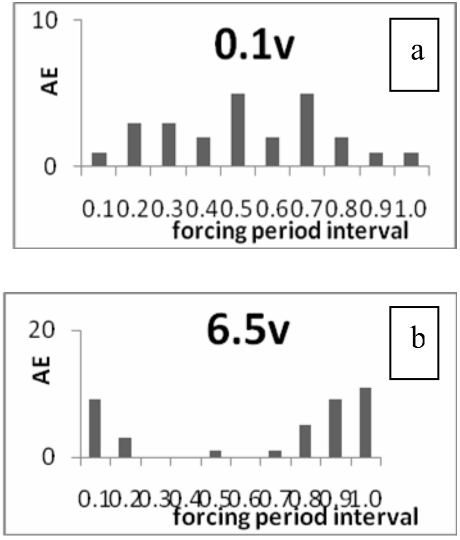


Fig.14. Distribution of acoustic emission onsets relative to the forcing period phases (in decimals) for different intensities of normal mechanical forcing, exerted by mechanical vibrator; a – at 0.1 V and b at 6.5 V applied to vibrator.

7 Field data - Synchronization by reservoir loading

As an example of possible synchronization of seismic process under small external influence we present results of our analysis of seismic activity around Enguri dam lake (Western Georgia). There are three distinct periods of area loading: (i) before impoundment, (ii) lake filling and (iii) periodic change of water level (Fig.15a). We suggest that this small periodic reservoir influence on the complex seismic process invokes synchronization of regional seismic activity as well as the decrease of probability of large earthquakes occurrence around reservoir due to quantization effect of periodic forcing, which prevents accumulation of large strain in reservoir surroundings. We calculated phase differences $\Delta\phi$ between the phases of the cumulative values of the daily released seismic energy and the phases of the daily water level variation (Fig. 15b). Three straight lines indicate different behaviour of the dynamics in the mentioned three periods. In particular, a tendency to phase synchronisation is found for the last period, where the phase differences remain nearly constant. The PS state can be ascribed to ordering (quantization) of seismic activity under periodic reservoir-induced forcing.

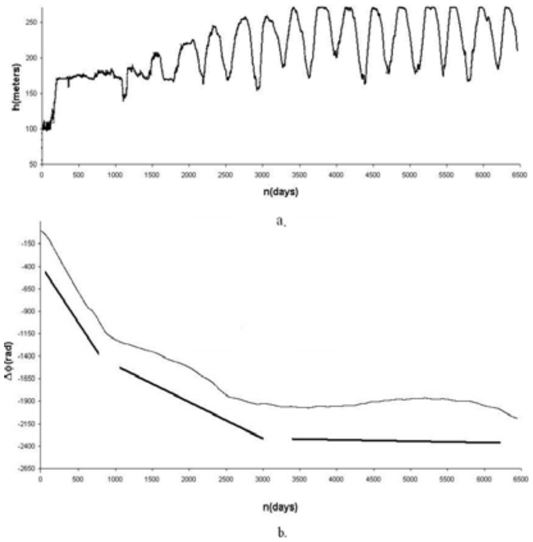


Fig. 15. a) Record of the daily water level in the lake of Enguri dam from 1975 to 1993, b) phase differences between the phases of the cumulative values of the daily released seismic energy and the phases of the daily water level variation. Three straight lines indicate different behaviour of the dynamics: a tendency to phase synchronisation is found for the last period, where the phase differences remain nearly constant.

8 Conclusions

Experiments on the standard spring-slider system (fixed and sliding basalt samples), subjected to a constant pull and superimposed to it weak mechanical or EM periodic force in dry environment show that, at definite conditions, the system manifests the effect of phase synchronization of microslip events with the weak periodic excitation. The quality of synchronization depends on the intensity and frequency of the applied field; the corresponding Arnold's tongue region is constructed. Application of special techniques (measuring phase differences, phase diffusion coefficient, Shannon entropy, Recurrence Quantification Analysis) allows quantification of the strength of synchronization of microslips with EM impact

We hope that the methods applied in the present work to the laboratory data can be used in future for detection and quantitative assessment of seismic process synchronization by a weak external impact.

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