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ORIGINAL ARTICLE

Increase of order in seismic processes around large reservoir induced by water level periodic variation

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Abstract The importance of small periodic influences on the complex systems behavior is well acknowledged. In the present research, the possible impact of water level variation in large reservoir on the dynamics of local seismic activity was investigated. Large reservoirs located in the seismically active zones are often considered as a factor, quantitatively and qualitatively influencing earthquakes generation. During impoundment or after it, both the number and magnitude of earthquakes around reservoir significantly increases. After several years, these changes in earthquake generation, named as reservoir-induced seismicity (RIS) essentially decrease down to the level, when lesser earthquakes occur with lower magnitudes. To explain this decrease, the authors of the present paper recently proposed the model of phase synchronization of local seismic activity by the periodic variation of the water level – reservoir-induced synchronization of seismicity (RISS).

Generally, RISS presumes a kind of control of local seismic activity by synchronizing small external periodic influence and hence increase of order in dynamics of regional seismic activity. To reveal these changes in dynamics of phase-synchronized seismic activity around large reservoir field, seismic and water level variation data were analyzed in the present work. Laboratory stick–slip acoustic emission data as a model of natural seismicity were also analyzed.

The evidence is presented that increase of order in dynamics of daily earthquake occurrence, earthquakes temporal, and energy distribution took place around Enguri high dam water reservoir (Western Georgia) during the periodic variation of the water level in the lake.

Keywords Acoustic emission · Dynamics · Earthquakes · Reservoir · Water level variations

1 Introduction

Dynamics of different processes in natural systems often are affected by complex interaction with each other. In this respect, it is most important that they often respond to the small external influence in sense of phase synchronization even when processes are poorly correlated [18]. Phase synchronization of complex systems to external driving has been observed in many biological systems, numerical models, and laboratory experiments [14, 18, 19]. At the same time, the phase synchronization effects in complex environmental processes rarely are considered from the quantitative dynamical analysis point of view. In the present research, the character of dynamical changes in the regional seismic activity under phase

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synchronizing forcing by water level variation in a large reservoir was investigated.

Generally, the scientific and practical importance of investigation of possible mechanisms related to the dynamics of influence of high dam water reservoirs on local earthquakes generation is well acknowledged [1, 15, 22, 23, 25, 26]. Since the mid of the past century, the RIS has been observed at many reservoirs and their geological, hydrological, and physical features remain subjects of intense investigation.

At present, many aspects of dynamics of RIS become understandable [1, 26]. Namely, the increase of seismic activity is related to the complex impact of the water lake on the earth crust under the reservoir and is explained by the changes in ambient stress conditions due to the load (unload) of the water or, respectively, to the increase of interstitial pore pressure in the rock matrix beneath the reservoir due to downward percolation of fluid. It is also known that the water reservoir related changes in the seismicity of surrounding area – RIS, decreases after several years down to the level when even lesser earthquakes may occur with lower magnitudes compared to the basic level of the local seismic activity [1, 15]. At the same time, the underlying dynamics of the mentioned decrease of seismic energy release, following the initial RIS activity is still an open problem.

In our previous research based on field and laboratory data, the evidence was presented that the decrease of seismic energy release associated with RIS may be caused by the periodic variation of the water level in the large reservoir [17]. Based on the results of water level variation, as well as seismic and stick–slip acoustic emission data analysis, it was shown that small (compared to tectonic strain) periodic influence on a complex seismic process may invoke local reservoir-induced phase synchronization of seismicity. As far as we deal with the weakest form of synchrony – phase synchronization [16] and taking into account the earlier-mentioned lack of appropriate research, in the present work we aimed to investigate the character of dynamical changes in regional seismic activity caused by the influence of water level periodic variation in the large reservoir.

2 Used data and methods

Data sets of daily water level variation have been collected at one of the largest in Europe, 272 m height, Enguri high dam reservoir located in the Western Georgia, Caucasus (42.030 N, 42.775 E) in 1973–1995 (Fig. 1(a)).

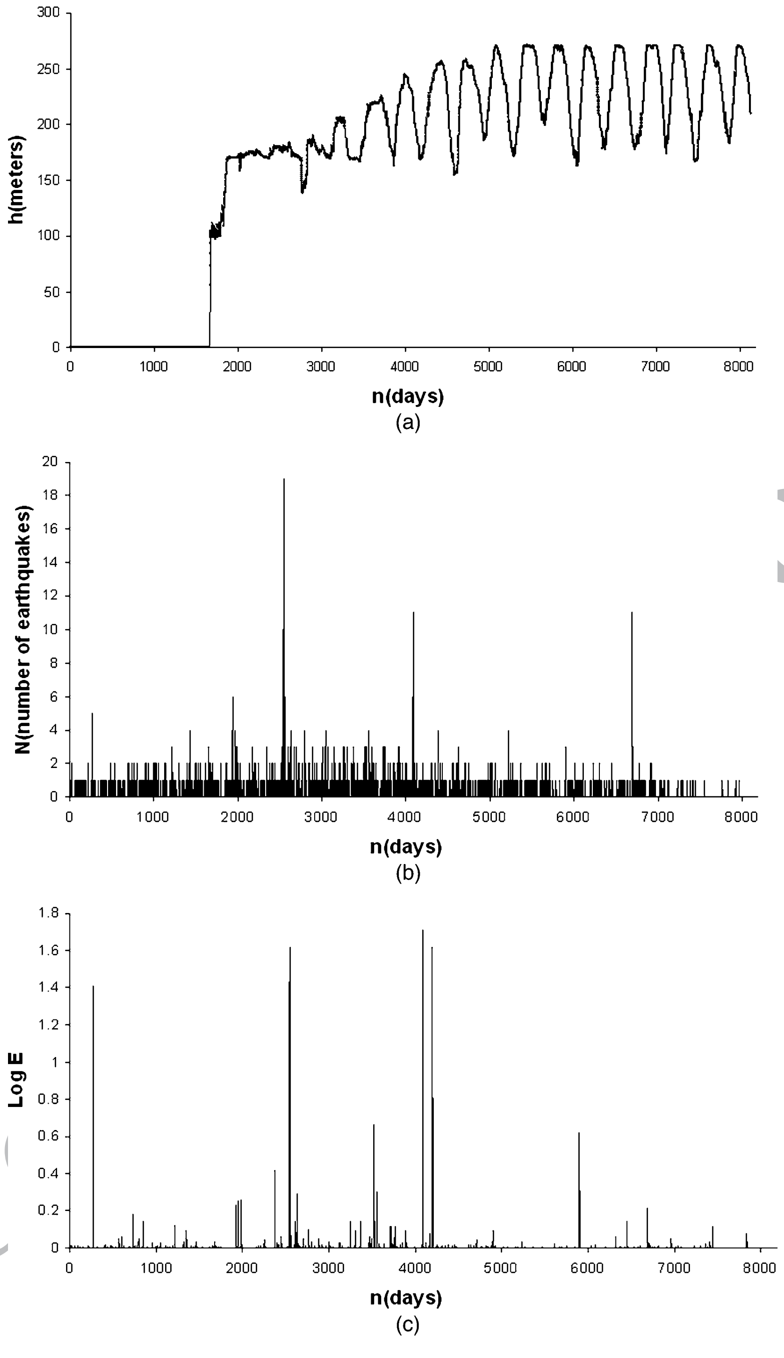
The size of the area around Enguri high dam, which can be considered sensitive to the reservoir influence, was evaluated based on the concept of energy release acceleration in the seismically critical regions. Namely, the minima of curvature parameter C (defined as $C =$ power-law fit RMS error/linear fit RMS error) deduced from the Benioff strain $E(t) = \sum_{i=1}^{N(t)} E_i(t)^{1/2}$ [3] was calculated. Here, E_i is the energy of the ith event. Location of the Enguri high dam reservoir was assumed as a "virtual epicenter of impending strong earthquake" (for details see [17], where it is shown that the radius of an area around Enguri high dam, sensitive to the reservoir influence is about 90 km). Data sets of daily occurred number of earthquakes and released daily seismic energy by seismic events above representative magnitude threshold $M \geq 1.6$ within this 90 km area for 1973–1995 are shown in Fig. 1(b) and (c). Besides these daily data, time series of sequences of magnitudes and time intervals between consecutive earthquakes (waiting times), unevenly sampled for the same time period and area, also were analyzed.

Used data sets of water level variation and seismic activity around Enguri high dam were obtained from data bases of the M. Nodia Institute of Geophysics (Georgia).

Acoustic emission data were collected on the stick – slip laboratory setup represented by a system of two roughly finished basalt plates [5, 6]. The external faces of plates were subjected to periodic electric (48 Hz) perturbations (with amplitudes, varying from 0 to 1000 V) superimposed on the constant dragging force (normalized power of an external sinusoidal forcing is shown in Fig. 2(a)). The waveforms of both acoustic emission and the sinusoidal EM field were digitized at 44 kHz. From the digitized waveforms of acoustic emission data sets, the time series (catalogs) of power of emitted acoustic energy were compiled (Fig. 2(b)). Exactly, the power of emitted acoustic energy was calculated as the area between the acoustic signal curve and the x-axis during the period of the superimposed external 48 Hz sinusoidal forcing divided by the time duration of these 2π periods. Additionally, sequences of time intervals between consecutive maximal amplitudes of acoustic signals (waiting times) were analyzed.

Besides formerly described in [17] characteristics, the mean effective phase diffusion coefficient

Fig. 1 (a) Record of the daily water level in the lake of Enguri dam from 1975 to 1993, (b) daily number of earthquakes, and (c) log of normalized daily released seismic energy



$D = \frac{d}{dt}[\langle \Delta\varphi^2 \rangle - \langle \Delta\varphi \rangle^2]$ was calculated as an additional statistical measure of the quality of synchronization between water level variation and seismicity, as well as between external periodic forcing and power of acoustic emission.

In order to investigate dynamical changes in analysed processes, Recurrence Quantitative Analysis or (RQA) was used [27]. RQA is especially useful to overcome the difficulties often encountered dealing with nonstationary and rather short real data sets. The recurrence plots (RP) are defined as:

$$R_{i,j} = \Theta(\varepsilon_i - \|\bar{x}_i - \mathbf{x}_j\|).$$

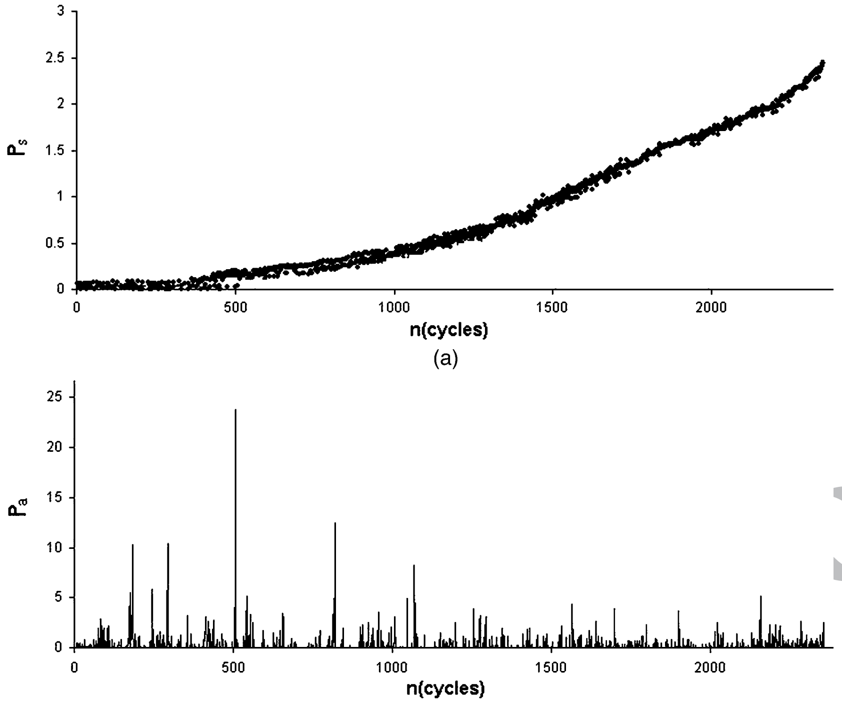


Fig. 2 Results of experiments on stick–slip, which is considered as a good laboratory model for seismicity, affected by weak external perturbations: (a) Normalized power of the external sinusoidal forcing, P_s, superimposed on the constant drag force; (b) normalized power of acoustic emission of stick–slip events, P_a

Here, ε_i is a cutoff distance and $\Theta(x)$ is the Heaviside function. Correct choice of cutoff distance ε is one of the main problems of RQA. It is desirable that ε be as small as possible, but the presence of noise always necessitates larger values. There are several suggestions how to set correctly ε [7, 12, 27]. We selected the cutoff distance as 10% (for waiting times and daily number of earthquakes) and 20% (for magnitude sequence) of overall mean distance [2, 12]. As a quantitative tool of complex dynamics analysis, RQA defines several measures mostly based on diagonally oriented lines in the recurrence plots: recurrence rate, determinism, maximal length of diagonal structures, entropy, trend, etc. [7]. In the present work, recurrence rate – RR(t) and determinism – DET(t) measures based on the analysis of diagonally oriented lines in the recurrence plot have been calculated [11]. Generally, recurrence rate RR(t) is the ratio of all recurrent states (recurrence points) to all possible states and is therefore the probability of the recurrence of a certain state. The ratio of recurrence points forming diagonal structures to all recurrence points is called the determinism DET(t). The larger values of RR(t)and DET(t) indicate the increase in regularity of investigated dynamics.

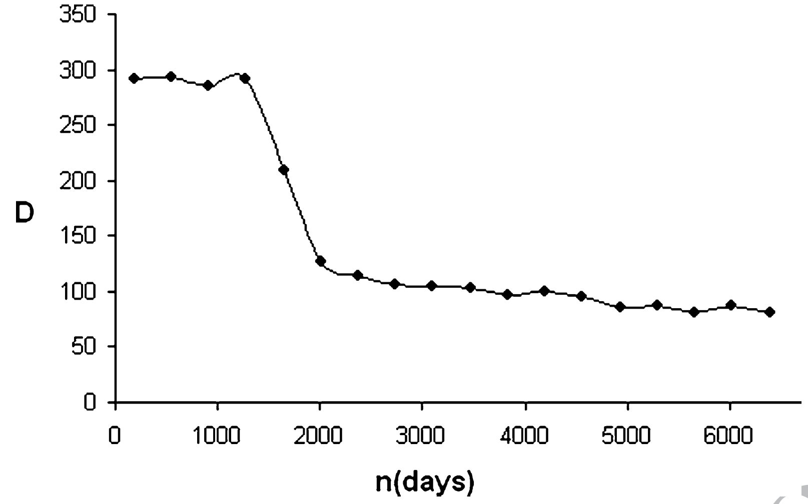
3 Results and discussions

As an additional quantitative indication of phase synchronization between water level periodic variation and seismic activity around large reservoir, observed in our previous research [17], in the present research we have calculated the phase diffusion coefficient, D. As follows from Fig. 3, during the whole history of lake construction and exploitation, beginning from the territory flooding ($n = 1668$ in Fig. 1(a)) and ending by regular regime ($n \approx 5000$), D indeed is minimal for the time interval of periodic water level variation (Fig. 4). A1

In the laboratory model of seismicity, acoustic emission during stick–slip experiments, it also was shown that phase diffusion coefficient D strictly decreases when acoustic emission time series are phase synchronized (see, e.g., Fig. 8 in [17]).

We explain the decrease of seismic energy release shown in Fig. 1(c) which follows the period of RIS, by phase synchronization of seismic activity with water level variation (RISS). This seems to be a very important example of purposeful man-made influence on complex dynamics of seismic process. In this respect, it should be mentioned that according to recent publications data the dynamics of earthquake-related processes

Fig. 3 Variation of phase diffusion coefficient of phase differences between daily released seismic energy and water level daily variations, calculated for consecutive sliding windows containing 365 events, shifted by 365 events (periodic forcing begins from $n \approx 5000$)



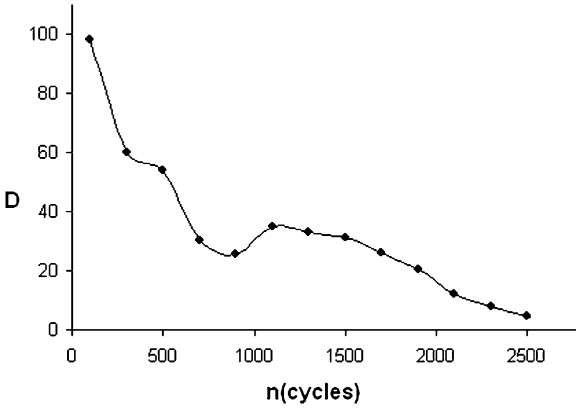


Fig. 4 Variation of phase diffusion coefficient of phase differences between power of external sinusoidal forcing, P_s and power of acoustic emission of stick–slip events, P_a calculated for consecutive sliding windows containing 200 events, shifted by 200 events (periodic forcing of large enough amplitude begins from $n \approx 2000$)

in the earth crust are recognized as nonrandom, having both low and/or high-dimensional nonlinear structures [8, 13, 21, 24]. One of the characteristic properties of processes in nonrandom systems, which are close to the critical state, is their high sensitivity to initial conditions as well as to relatively weak external influences. This general property of complex systems acquires special significance for practically unpredictable seismic processes. Indeed, insofar as we are not able to govern initial conditions of lithospheric processes, even principal possibility of controlling dynamics of seismic process has immense scientific and practical importance (e.g., to modify the release of accumulated seismic energy via series of small or moderate earthquakes instead of one strong devastating event using the specific external impact). The way toward understanding such control mechanism passes through investigation of dynamics of seismic processes, when small external influence leads to phase synchronization.

It is known that nonlinear dynamical systems often respond in a complicated way to such external influences. One of the possible responses is synchronization since Huygens synchronization is understood as a phenomenon when coupled nonlinear systems become mutually adjusted. Presently, several types of synchronization are known, e.g., identical, generalized, phase synchronization, etc. [4]. The phase synchronization between water level periodic variation and seismic activity, observed in our previous and present researches, is recognized as the weakest form of synchrony when interacting nonlinear oscillators remain largely uncorrelated [16, 20]. Generally, depending on the strength of coupling, interacting systems may have different dynamical features [16]. It is most important that contrary to other forms of synchrony which lead to increase of order in behavior of synchronized system, phase synchronization does not require strong coupling between involved processes. This, in turn, means that the presence of order and character of changes in dynamics of phase-synchronized system is not obvious.

This is why we aimed to investigate the character of dynamical changes in seismic process when phase synchronization with water level periodic variation occurs. RQA, often used to detect changes in

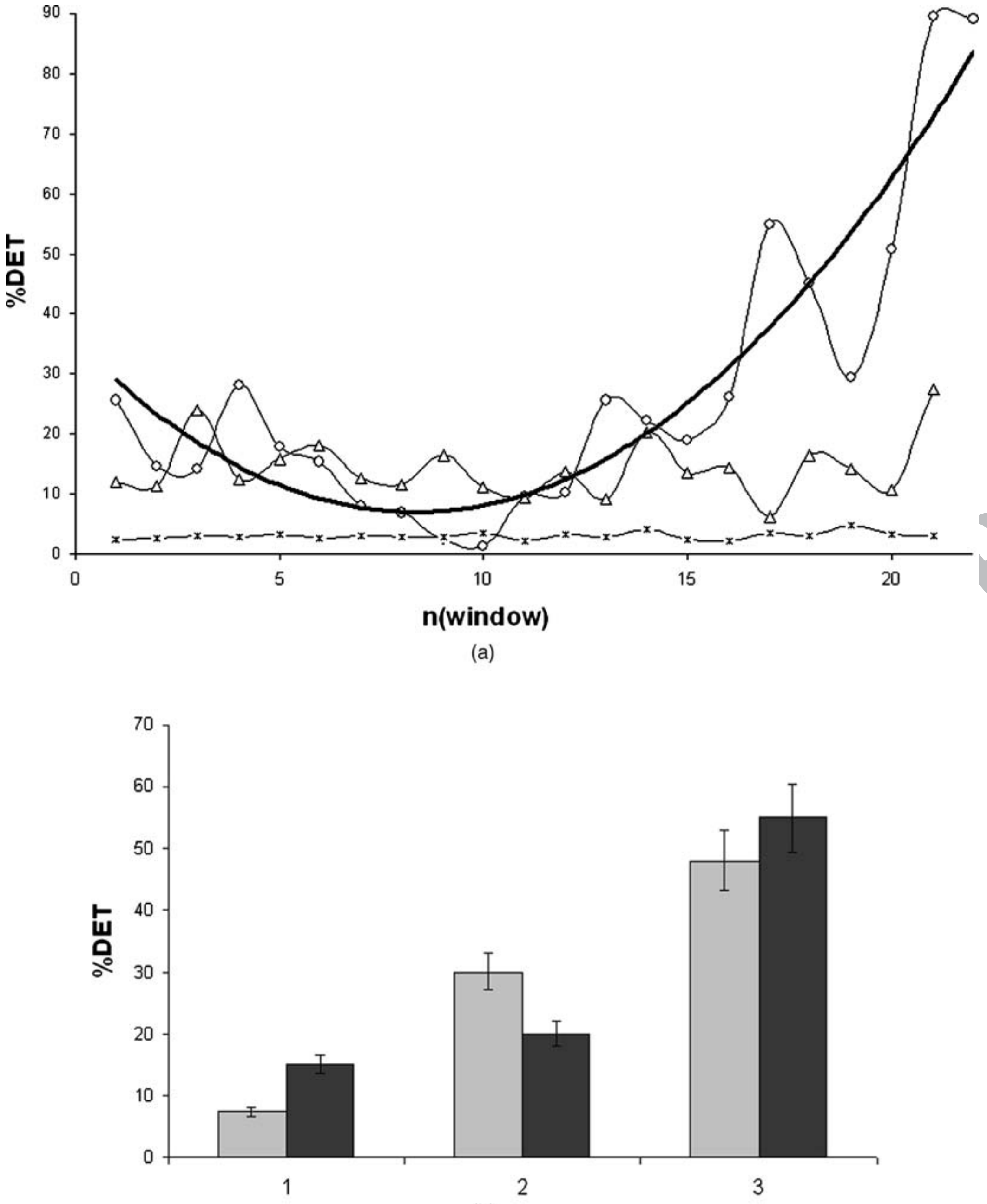
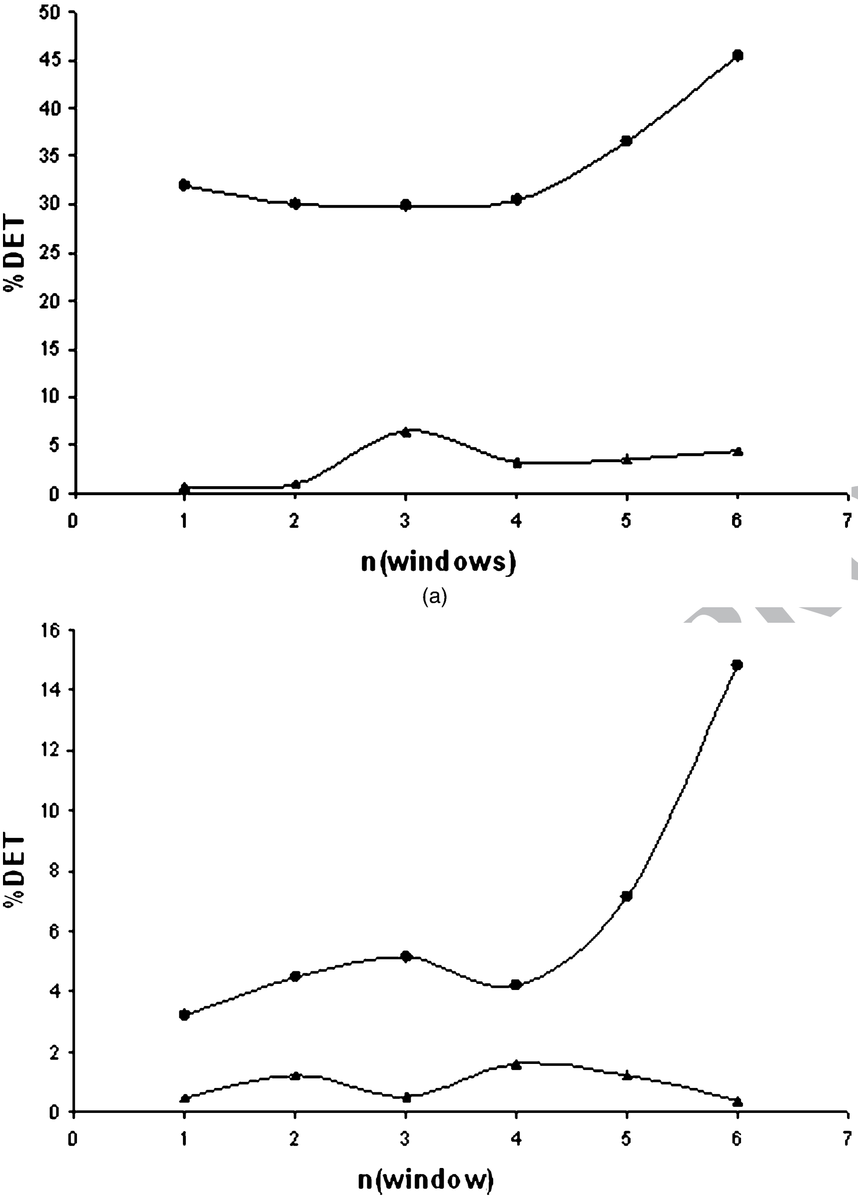


Fig. 5 (a) RQA %DET of daily number of earthquakes calculated for consecutive non overlapping 1-year sliding windows (*circles*). Averaged results of RQA %DET for 20 shuffled (*asterisks*) and phase-randomized (*triangles*) surrogates of daily number of earthquakes in consecutive 1-year sliding windows; (b) RQA %DET of magnitude (*black columns*) and waiting time (*grey columns*) sequences: (1) before impoundment, (2) during flooding and reservoir filling, and (3) periodic change of water level in reservoir

the dynamics of complex systems [9], is the most convenient data analysis tool for this purpose. As follows from our RQA results, when external influence on earth crust caused by water reservoir becomes periodic, the extent of regularity of earthquake daily distribution (evaluated as %REC and %DET) essentially increases (see Fig. 5(a), bold line). This result was tested by comparing with the surrogate data. Averaged

Fig. 6 RQA %DET calculated for consecutive nonoverlapping 400 data sliding windows of: (a) power of acoustic emission; (b) time intervals between consecutive maximal amplitudes of acoustic signals (*waiting times*). Averaged values for 20 shuffled time series are shown by triangles



(a)

(b)

results derived from RQA of 20 shuffled (asterisks) and phase-randomized (triangles) surrogates (Fig. 5(a)), assure that the mentioned increase of regularity in earthquakes distribution should not be an artifact. It is important to mention that influence of increasing amount of water and their subsequent periodic variation essentially affects also the character of earthquake's magnitude and temporal distribution (see Fig. 5(b)). Extent of order in earthquakes temporal (black columns) and magnitude (grey columns) distribution calculated as value of %DET, substantially increases when the reservoir forcing becomes periodic. Results of %DET calculation of corresponding surrogates are always less than 50% to original values (not shown here). It is interesting to mention, that dynamics of earthquakes temporal and energetic distributions change even under water level irregular variation though not so much as under periodic variation.

The conclusions considered earlier on increase of order in seismic process under water level periodic variation using %DET measurements are confirmed by calculation of other RQA measures (% REC, Entropy, Laminarity).

As far as real-field seismic data sets are short and incomplete, we carried out similar analysis on the acoustic emission data sets, obtained on laboratory spring-slider system under periodic electromagnetic (EM) forcing, which simulates the periodical loading by reservoir. Stick–slip experiments are considered as a model of a natural seismic process [10, 21]. Time series of the emitted acoustic power during consecutive cycles (2π periods) of the external 48 Hz periodic forcing of stick–slip process were analyzed as well as time intervals between consecutive maximal amplitudes of acoustic signals (waiting times). As is shown in Fig. 6 (circles), the extent of order increases both in energetic distribution as well as in temporal distribution of acoustic emission when synchronization is achieved (last window in Fig. 6). The averaged results of 20 surrogates shown by triangles confirm the conclusion that observed changes are indeed related to ordering in dynamics of acoustic emission under weak external forcing.

4 Conclusions

Dynamics of seismic process during RISS has been investigated. Data sets of daily water level variation and released seismic energy as well as waiting time and magnitude sequences were analyzed. As a model of natural seismicity, the laboratory stick–slip acoustic emission data were also analyzed. Methods of phase diffusion coefficient calculation and RQA were used.

Based on the results of investigation carried out both on field and experimental time series, we conclude that the order in dynamics of earthquake's daily occurrence, as well as in earthquake's temporal and energetic distributions increases when water level variation becomes periodic. Laboratory stick–slip acoustic emission data confirms results of field data analysis.

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