Chapter 16
Changes in Dynamics of Seismic Processes Around Enguri High Dam Reservoir Induced by Periodic Variation of Water Level

T. Matcharashvili, T. Chelidze, V. Abashidze, N. Zhukova, and E. Meparidze

Abstract The importance of elucidating the effects of small periodic influences on the behavior of complex systems is well acknowledged. In the present research, a possible impact of regular water level variations in large reservoir as an example of small external influence (comparing to tectonic forces) on the dynamics of local seismic activity was investigated.

In general, large reservoirs located in the seismically active zones are often considered as a factor which quantitatively and qualitatively influences the earthquakes generation. It was many times reported that during impoundment or immediately after it (namely from several months to several years), both the number and the magnitude of earthquakes around reservoir significantly increased. These changes in earthquake generation are named the reservoir induced seismicity (RIS). After several years of regular seasonal load/upload of the reservoir, the seismicity essentially decreases down to the level when lesser earthquakes occur with lower magnitudes. To explain this decrease, the authors of the present paper recently proposed a model of phase synchronization of local seismic activity by the periodic variation of the water level – the reservoir-induced synchronization of seismicity (RISS).

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

The evidence is presented showing that an increase of the order in dynamics of daily occurrence, as well as temporal and energy distribution of earthquakes took

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place around Enguri high dam water reservoir (Western Georgia) during the periodic variation of the water level in the lake.

It is shown that when the water level variation in a reservoir is close to periodic, monthly frequency of earthquake occurrence reveals two maximums: in spring and autumn. There is a clear asymmetry in the seismic response, possibly due to load/unload response ratio (LURR) effect; the maximal release of seismic energy is during loading, i.e., in the spring.

16.1 Introduction

It is known that the dynamics of natural systems may often be affected by a small external influence [Pikovsky et al., 2003; Postnov et al., 2003]. Phase synchronization is recognized as one of possible mechanisms when poorly correlated small interactions could lead to essential dynamical changes in systems behavior. Phase synchronization has been observed in many biological systems, numerical models and laboratory experiments [Matcharashvili et al., 2008; Nascimento et al., 2004; Pikovsky et al., 2003; Postnov et al., 2003]. At the same time, there are rare examples when the phase synchronization effects in complex environmental processes have been quantitatively evaluated using modern data analysis approaches.

In the present research we have investigated the character of dynamical changes in the local seismic activity around a large reservoir under quasi periodic forcing caused by water level variation during reservoir exploitation.

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 [Simpson, 1986; Simpson et al., 1988; Smirnov, 1995; Talvani, 1997]. Since the mid of the past century, the RIS has been observed at many reservoirs located in seismically active areas. At the same time, many aspects of changes in seismic process induced by water reservoir remain subjects of intense scientific discussions and investigations [Assumpção, 2002; Smirnov, 2005].

Namely, we still lack knowledge on geological, hydrological, or physical features of relation between the observed increase of seismic activity and the impact of water in the lake. Presently this relation is explained by changes in the ambient stress condition due to the load (unload) of the water or, respectively, an increase of interstitial pore pressure in the rock matrix beneath the reservoir due to downward percolation of fluid. It is also supposed that the water reservoir-related changes in the seismicity of surrounding area (the so-called reservoir-induced seismicity – RIS), decrease after several years down to the level when even lesser earthquakes may occur with lower magnitudes comparing to the basic level of local seismic activity [Assumpção, 2002; Nascimento, 2004]. The problem of underlying dynamics of this decrease of seismic energy release following the initial RIS activity is not finally resolved.

In our previous researches based on the field and laboratory data, the evidence has been presented that the decrease of seismic energy release associated with RIS may be caused by the quasi periodic variation of the water level in a large reservoir [Matcharashvili, 2008; Peinke et al., 2006]. Based on the results of field (water level variation, seismic catalogues) and model laboratory (stick-slip acoustic emission) data analysis, it was shown that small (compared to tectonic strain) periodic influence on a complex seismic process may invoke phenomena which we call reservoir induced phase synchronization of seismicity (RISS).

In the present work we continued investigation of the character of dynamical changes in local seismic activity accompanying the above-mentioned synchronization with the periodic variation of water level. As far as the proposed RISS is regarded as a weakest form of synchrony – the phase synchronization [Nascimento et al., 2004], the investigation of dynamics of seismic process under a small periodic external influence acquires special importance in the light of the above-mentioned lack of appropriate researches for real natural and technical systems.

16.2 Data and Methods Used

The data sets used in the present research have been collected in 1973–1995 at one of the largest in Europe (272 m in height) Enguri high dam reservoir located in Western Georgia, Caucasus (42.030 N, 42.775 E) (Fig. 16.1). Strictly speaking, the data of daily water level variation in reservoir lake and daily number of

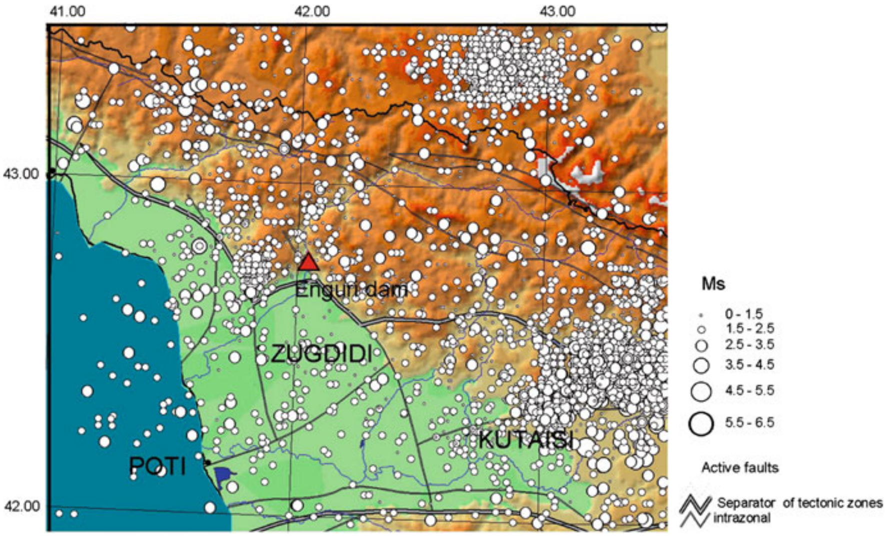

Fig. 16.1 Location of the Enguri high dam and patterns of local seismicity

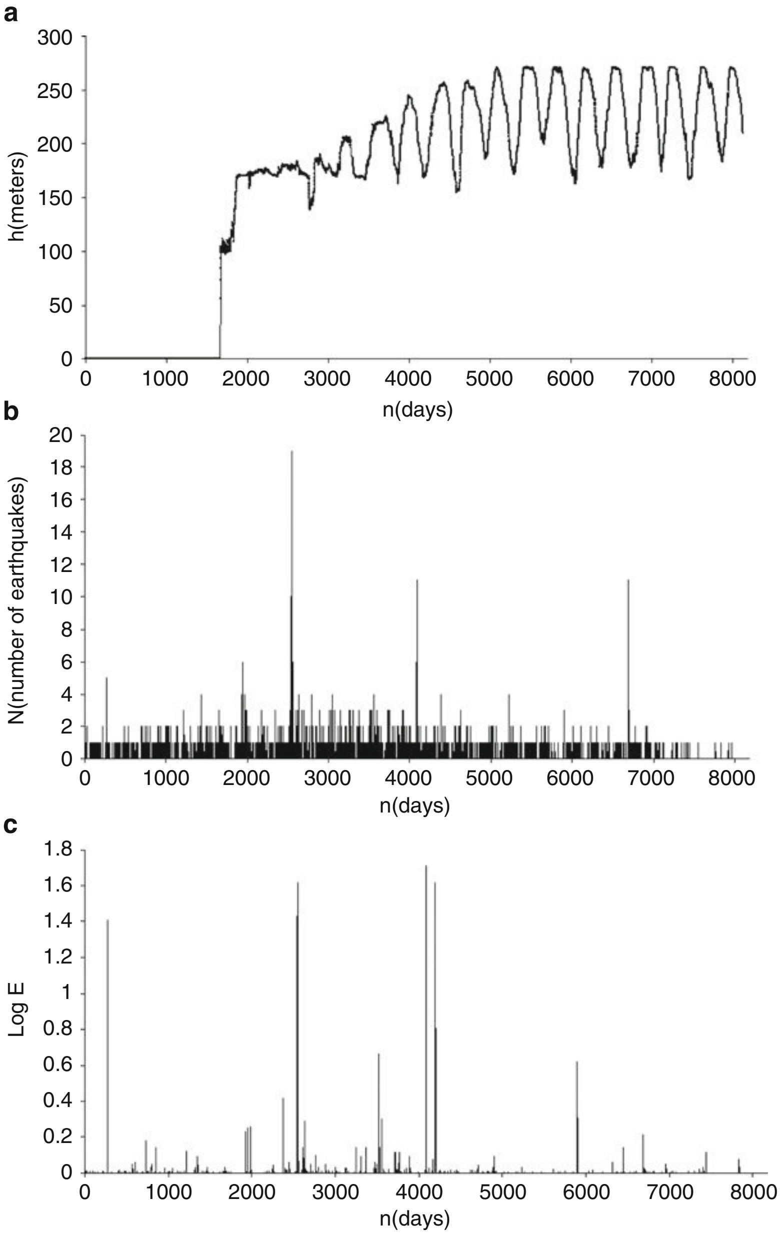

Fig. 16.2 (a) Record of the daily water level in the lake of Enguri dam from 1975 to 1993, (b) daily number of earthquakes, (c) Log of normalized daily released seismic energy

earthquakes that occurred in the above-mentioned period have been collected (Fig. 16.2 a and b). The size of the area around Enguri high dam, which can be considered as prone to reservoir influence, has been estimated 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 $E(t) = \sum_{i=1}^{N(t)} E_i(t)^{1/2}$ [Bowman et al., 1998] was calculated. Here E_i is the energy of i-th event. Location of the Enguri high dam reservoir was assumed as a "virtual epicenter of impending strong earthquake" (for details see [Peinke et al., 2006], where it is shown that the radius of the 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 consist of seismic events above representative magnitude threshold $M \geq 1.6$ within this 90 km area for 1973–1995. 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.

The sets of water level variation and seismic data used in the present study are available at the M. Nodia Institute of Geophysics (Tbilisi, Georgia).

Laboratory data of acoustic emission of stick-slip process have been collected on the specially developed laboratory setup represented by a system of two roughly finished basalt plates [Chelidze and Lurmanashvili, 2003; Chelidze et al., 2005]. To model small external influences on complex stick-slip (model of earthquake generation) the external faces of plates in our laboratory set up were subjected to periodic electric (48 Hz) perturbations (with amplitudes varying from 0 to 1000 V). The impact of this relatively small movement, normal to plate, was superimposed on the constant dragging force (normalized power of an external sinusoidal forcing is shown in Fig. 16.3 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. 16.3b). Specifically, the power of emitted during stick-slip 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 the characteristics that were formerly described in [Peinke et al., 2006], the mean effective phase diffusion coefficient $D = \frac{d}{dt}\left[\left\langle \Delta\varphi^2 \right\rangle - \left\langle \Delta\varphi \right\rangle^2\right]$ 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 (RQA) was used [Marwan et al., 2002; Marwan, 2003; Zbilut and Webber, 1992]. RQA is especially useful to overcome the difficulties often

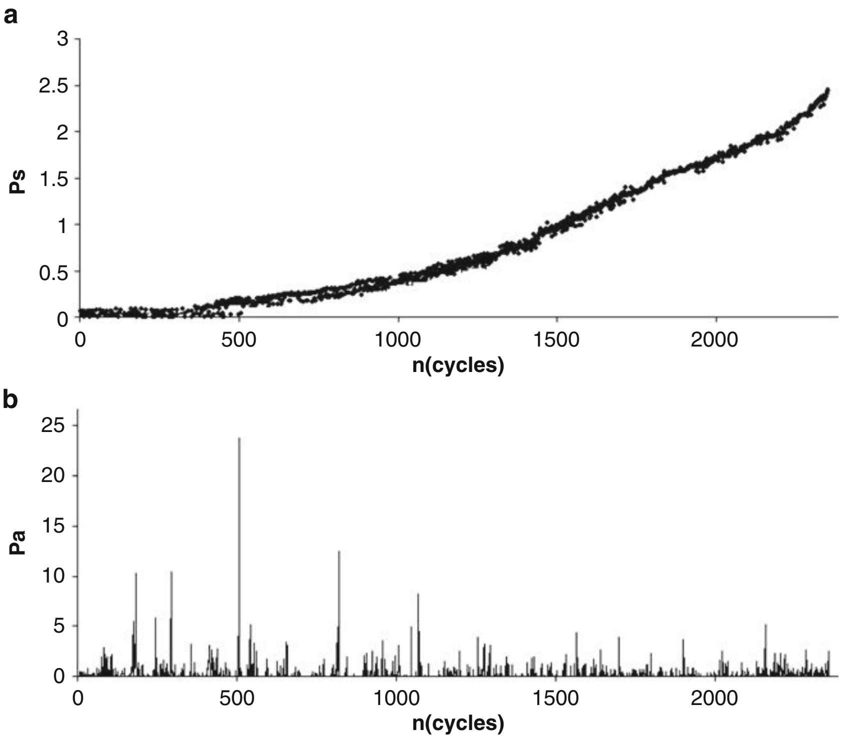

Fig. 16.3 Results of experiments on stick-slip, which is considered as a good laboratory model for seismicity, affected by weak external perturbations: (a) Normalized power of the external sinusoidal forcing, P_s, superimposed on the constant drag force; (b) normalized power of acoustic emission of stick-slip events, P_a

encountered while dealing with nonstationary and rather short real data sets. The recurrence plots (RP) are defined as:

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

where ε_i is a cut-off distance. $\Theta(x)$ is the Heaviside function. A correct choice of cut-off distance ε is one of the main problems of RQA. It is desirable to have ε as small as possible, but the presence of noise always necessitates larger values. There are several suggestions how to set ε correctly [Iwanski and Bradley, 1998; Marwan et al., 2002; Marwan, 2003; Zbilut and Webber, 1992]. We selected the cut-off distance as 10% (for waiting times and daily number of earthquakes) and 20% (for magnitude sequence) of overall mean distance [Belaire-Franch et al., 2002; Marwan, 2003]. 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 [Eckmann et al., 1987]. In the present work, the recurrence rate $RR(t)$ and determinism $DET(t)$ — the measures based on an analysis of diagonally oriented lines in the recurrence plot have been calculated [Marwan et al., 2002; Marwan, 2003]. Generally, the recurrence rate $RR(t)$ is the ratio of all recurrent states (recurrence points) to all possible states and is therefore a 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 the investigated dynamics.

16.3 Results and Discussions

The fact that water level variations in Enguri reservoir lead to distinctive changes in earthquake generation of local area is evident from Fig. 16.4. Almost uniform distribution of earthquakes occurrence before water level periodic variation was replaced by distribution with distinctive maximums in spring and autumn.

As it was mentioned in the previous section, several methods of quantitative indication of phase synchronization in field and laboratory data have been used. For example, the results of calculation of phase diffusion coefficient, D [Peinke et al., 2006], between water level periodic variation and seismic activity around reservoir are presented in Fig. 16.4. It follows from this figure that during the whole history of lake construction and exploitation, beginning from the territory flooding (n = 1668 in Fig. 16.2 a) and ending by regular regime (n $\approx$ 5000), D is indeed minimal for the time interval of periodic water level variation.

In the laboratory model of seismicity (acoustic emission accompanying stick-slip process), it was also shown that phase diffusion coefficient D strictly decreases

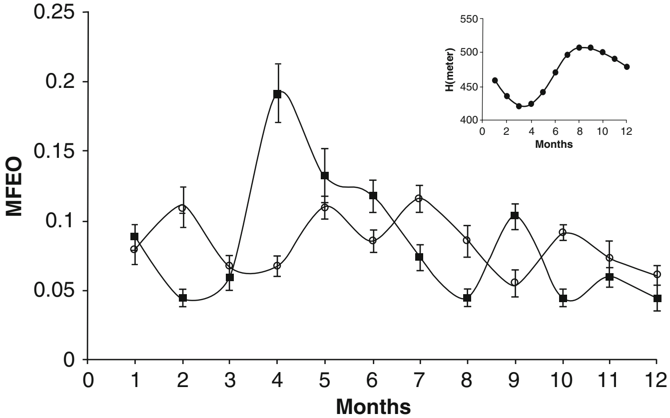

Fig. 16.4 Monthly frequency of earthquake occurrence before (open circles, thin line) and during water level periodic variation (dark squares, bold line)

when acoustic emission time series are phase synchronized (Fig. 16.6). The same conclusion follows from Fig. 16.7, showing essential increase of phase synchronization measure calculated for onsets and maximums of AE.

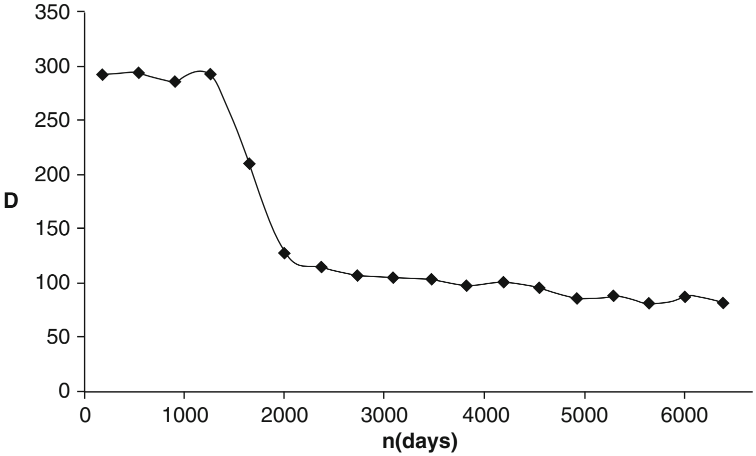

Fig. 16.5 Variation of phase diffusion coefficient of phase differences between daily released seismic energy and water level daily variations, calculated for consecutive sliding windows containing 365 events, shifted by 365 events (periodic forcing begins from n ≈ 5000)

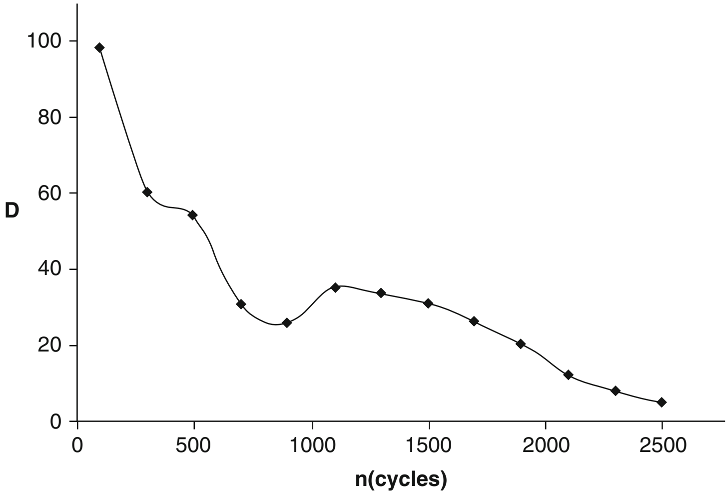

Fig. 16.6 Variation of phase diffusion coefficient of phase differences between power of external sinusoidal forcing, P_s, and power of acoustic emission of stick-slip events, P_a, calculated for consecutive sliding windows containing 200 events, shifted by 200 events (periodic forcing of large enough amplitude begins from $n \approx 2000$)

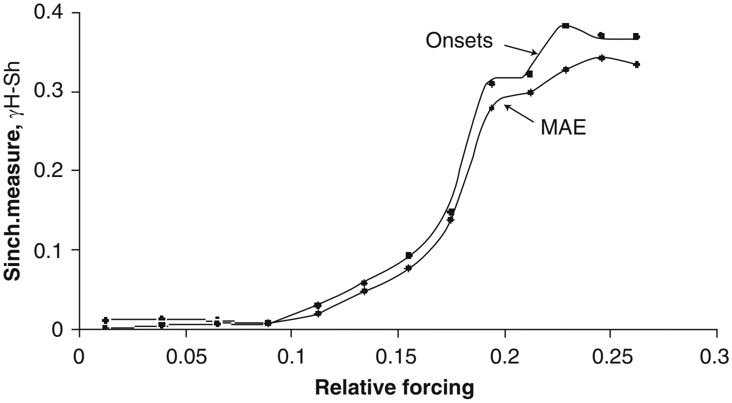

Fig. 16.7 Synchronization measure vs. relative force of external influence. Results for time series of onsets and maximums of stick slip AE (MAE) are shown

The decrease of seismic energy release shown in Fig. 16.2c which follows the period of RIS, may be explained by phase synchronization of seismic activity with quasi-periodic water level variation (it was mentioned above that we name this effect RISS). RISS observed at Enguri reservoir can be considered as an example of purposeful man-made influence on complex dynamics of seismic process.

To have more grounds for such a statement it should be mentioned that according to the present understanding the dynamics of earthquake-related processes in the earth crust is recognized as non random, having both low and/or high dimensional nonlinear structures [Iwanski and Bradley, 1998; Matcharashvili et al., 2000; Rundle et al., 2000; Smirnov, 2005]. One of the characteristic features of such processes in close-to-the-critical state is their high sensitivity 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 towards understanding such a control mechanism passes through investigation of dynamics of seismic processes, when a small external influence leads to phase synchronization.

It is known that nonlinear dynamical systems often respond to such external influences in a complicated way. One of 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. [Calvo et al., 2004]. 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 [Pazo et al., 2003; Rosenblum et al., 1996]. Generally, depending on the strength of coupling, interacting systems may have different dynamical features [Pazo et al., 2003]. It is most important that contrary to other forms of synchrony which lead to increase of order in the behavior of synchronized system, the phase synchronization does not require strong coupling between the processes involved. This in turn means that the presence of order and the character of changes in dynamics of phase synchronized system are not obvious.

This is why we aimed to investigate the character of dynamical changes in seismic process when phase synchronization with periodic variation of water level occurs. RQA, often used to detect changes in the dynamics of complex systems [Iwanski and Bradley, 1998], is the most convenient data analysis tool for this purpose. As follows from our RQA results, when the external influence on the earth crust caused by a water reservoir becomes periodic, the extent of regularity of earthquake daily distribution (evaluated as %REC and %DET) essentially increases (see Fig. 16.8 a, bold line). This result was tested by comparing with the surrogate data. Averaged results derived from RQA of 20 shuffled (asterisks) and phase randomized (triangles) surrogates (Fig. 16.8 a), assure that the above-mentioned increase of regularity in earthquakes distribution should not be an artefact. It is important to mention that an influence of increasing amount of water and its subsequent periodic variation essentially affects also the character of earthquakes magnitude and temporal distribution (see Fig. 16.8 b). The 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 the original values (not shown here). It is interesting to mention that the dynamics of temporal and energetic distributions of earthquakes changes even under irregular variation of water level, though not so much as under periodic variation.

The above conclusions regarding the increase of the order in seismic process under the influence of periodic variation of water level 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 [Johansen et al., 1999; Rundle et al., 2000]. 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 it is shown in Fig. 16.9 (circles), the extent of order increases both in energetic distribution as well as in temporal distribution of acoustic emission when synchronization is achieved (last windows in Fig. 16.8). The averaged

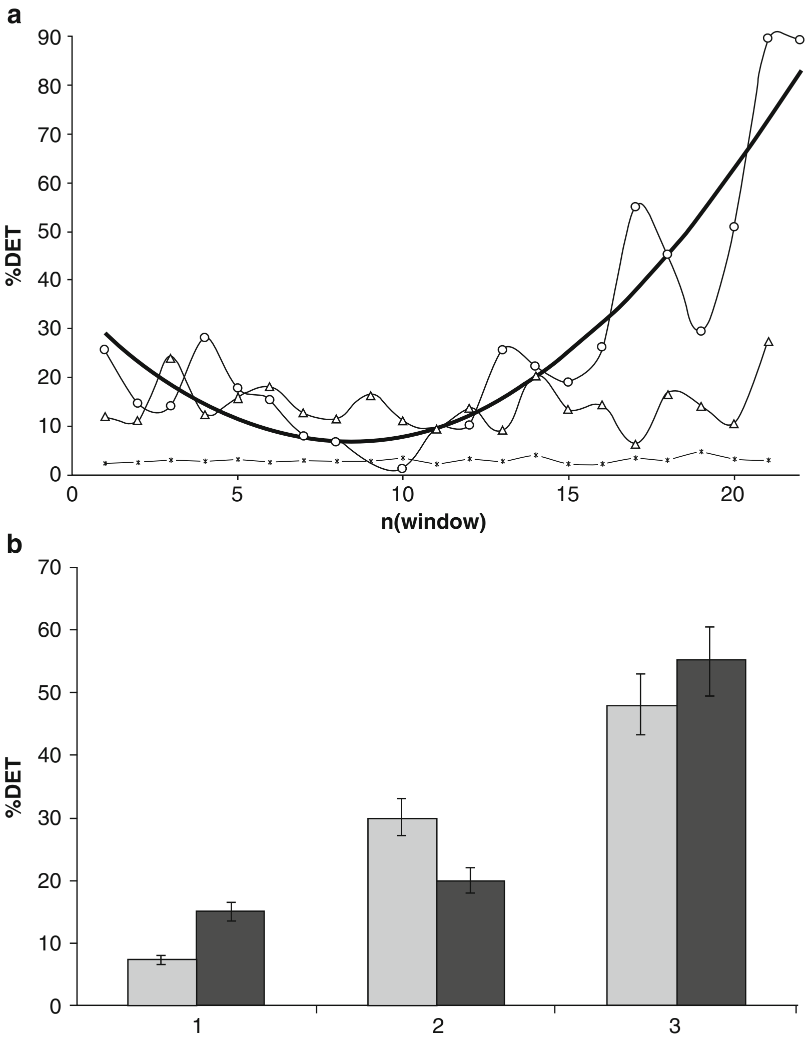

Fig. 16.8 (a) RQA %DET of daily number of earthquakes calculated for consecutive non overlapping one-year sliding windows (circles). Averaged results of RQA %DET for 20 shuffled (asterisks) and phase randomized (triangles) surrogates of daily number of earthquakes in consecutive one-year sliding windows; (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

results of 20 surrogates shown by triangles confirm the conclusion that the observed changes are indeed related to ordering in dynamics of acoustic emission under weak external forcing.

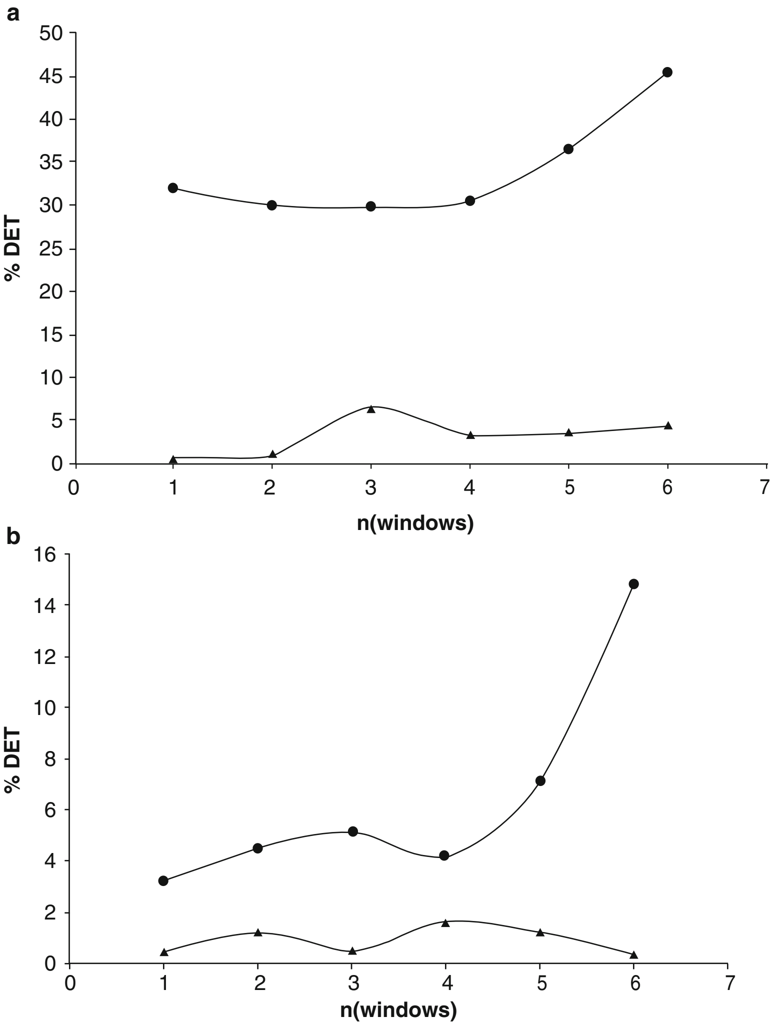

Fig. 16.9 RQA %DET calculated for consecutive non overlapping 400 data sliding windows of: (a) power of acoustic emission; (b) time intervals between consecutive maximal amplitudes of acoustic signals (waiting times). Averaged values for 20 shuffled time series are shown by triangles

16.4 Conclusions

The 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 analysed. As a model of natural seismicity, the laboratory stick-slip acoustic emission data were also analysed. 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 earthquakes' daily occurrence, as well as in earthquakes' temporal and energetic distributions increases when water level variations become periodic. Laboratory stick-slip acoustic emission data confirms the results of field data analysis.

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References

Assumpção, M., Marza, V.I., Barros, L.V., Chimpliganond, C.N., Soares, J.E.P., Carvalho, J.M., Caixeta, D., Amorim, A., Cabral, E., 'Reservoir induced seismicity in Brazil', *Pure Applied Geophysics*, 159, 2002, 597–617.

Belaire-Franch, J., Contreras, J. D., Tordera-Lledo, L., 'Assessing nonlinear structures in real exchange rates using recurrence plot strategies', *Physica* D, 171, 2002, 249–264.

Bowman, D.D., Ouillon, G., Sammis, C. G., Sornette, A., Sornette, D., 'An observational test of the critical earthquake concept', *Journal of Geophysical Research*, 103, 1998, 24359-24372.

Calvo, O., Chialvo, D., Eguíluz, V., Mirasso, C., Toral. R., Anticipated synchronization: A metaphorical linear view, *Chaos*, 14, 2004, 7–13.

Chelidze, T., Lursmanashvili, O., 'Electromagnetic and mechanical control of slip: laboratory experiments with slider system', *Nonlinear Processes in Geophysics*, 20, 2003, 1–8.

Chelidze, T., Matcharashvili, T., Gogiashvili, J., Lursmanashvili, O., Devidze, M., 'Phase Synchronization of Slip in Laboratory Slider', *Nonlinear Processes in Geophysic*s, 12, 2005, 1–8.

Eckmann, J.P., Kamphorst S., Ruelle, D., Recurrence plots of dynamical systems. *Europhysics Letters*, 4 (9), 1987, 973–977.

Goltz C, *Fractal and chaotic properties of earthquakes*, Springer, Berlin, 1998.

Iwanski, J., Bradley, E., 'Recurrence plots of experimental data: To embed or not to embed?', *Chaos*, 8, 4, 1998, 861–871.

Johansen, A., Sornette, D., Acoustic Radiation Controls Dynamic Friction: Evidence from a Spring-Block Experiment', *Physical Review Letters*, 82, 1999, 5152–5155.

Marwan, N, Wessel, N., Meyerfeldt, U., Schirdewan, A., Kurths, J., Recurrence-plot-based-measures of complexity and their application to heart rate variability data. *Physical* Review E, 66, 2002, 026702.1-026702.8.

Marwan, M., Encounters with neighborhood, PhD Thesis, 2003.

Matcharashvili, T., Chelidze, T., Javakhishvili, Z., 'Nonlinear analysis of magnitude and interevent time interval sequences for earthquakes of Caucasian region', *Nonlinear Processes in Geophysics*, 2000, 7, 9–19.

Matcharashvili, T., Chelidze, T., Peinke, J., Increase of order in seismic processes around large reservoir induced by water level periodic variation, Nonlinear Dynamics, 399-407, 51, 3, 2008.

McAllister, R., Uchida, A., Meucci, A., Roy, R., 'Generalized synchronization of chaos: experiments on a two-mode microchip laser with optoelectronic feedback', *Physica D* 195, 2004, 244–262.

Nascimento, A, F., Cowie, P.A., Lunn, R, J., Pearce, G., 'Spatio-temporal evolution of induced seismicity at Açu reservoir, NE Brazil', *Geophysical Journal International*, 158, 2004, 1041–1052.

Pazo,D., Zaks, M.A., Kurths. J., Role of unstable periodic orbits in phase and lag synchronization between coupled chaotic oscillators, *Chaos*, 13, 2003, 309–318.

Peinke, J., Matcharashvili, T., Chelidze, T., Gogiashvili, J., Nawroth, A., Lursmanashvili, O., Javakhishvili, Z., 'Influence of Periodic Variations in Water Level on Regional Seismic Activity Around a Large Reservoir: Field and Laboratory Model', *Physics of the Earth and Planetary Interiors*, 156/1-2, 2006, 130–142.

Pikovsky, A., Rosenblum, M.G., Kurth. J., *Synchronization: Universal Concept in Nonlinear Science*, Cambridge University Press, Cambridge, 2003.

Postnov, D.E., Sosnovtseva, O.V., Mosekilde, E., Holstein-Rathlou, N.-H., 'Synchronization of Tubular Pressure Oscillations in Interacting Nephrons' *Chaos, Solitons and Fractals*, 15, 2, 2003, 343–369.

Rosenblum, M., Pikovsky, A., Kurth, J., 'Phase synchronization of chaotic oscillators, *Physics Review Letters'*, 76, 1996, 1804–1807.

Rundle, J., Turcotte, D., Klein, W., (eds),. *GeoComplexity and the Physics of Earthquakes*, American Geophysical Union, Washington, 2000.

Simpson, D. W., 'Triggered earthquakes', *Annual Reviews of the Earth and Planetary Sciences.* 14, 1986, 21–42.

Simpson, D., Leith, W., Scholz, C. 'Two types of reservoir-induced seismicity', *Bulletin of Seismological Society America*, 78, 1988, 2025–2040.

Smirnov, V.B., 'Fractal properties of seismicity of Caucasus', *J. of Earthq. Prediction Res.* 4, 1995, 31–45.

Talwani, P., 'On nature of reservoir-induced seismicity', *Pure and Applied Geophysics*, 150, 1997, 473-492.

Trifu, C.I. (ed)., The mechanism of induced seismicity, Special Volume, *Pure & Applied Geophysics*, 159, 2002.

Zbilut, J.P., Webber, C.L. Jr., Embeddings and delays as derived from quantification of recurrence plots. *Physics Letters A*, 171,1992, 199–203.