Complexity of seismic process; measuring and applications — A review

T. Chelidze*, T. Matcharashvili

M.Nodia Institute of Geophysics, 1, Alexidze str., 0193, Tbilisi, Georgia

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Abstract

Recent methods of analysis of so called disordered systems show that many objects and processes that earlier were considered as completely random reveal clear evidence of having some ordered structure in both time and space. These new methods (fractals, percolation, nonlinear dynamics and complexity theories) allow visualization and quantitative assessment of the level of complexity (orderliness) of these structures, using both theoretical models and experimental data. We consider sequentially some aspects of structural and evolutionary complexity of dynamics of seismic process and the technique of measuring this property.

It is shown that the physical properties of geophysical medium are not always self-consistent and manifest fractal behavior on selected spatial and temporal scales. Mechanical percolation theory can be used for modeling geometry of fracture process. Namely, we consider fractal and connectivity aspects of delayed failure, including energy emission during fracturing. Special attention is paid to relating the intensity of geophysical anomalies to the strain in the framework of the pressure-induced anomalous strain-sensitivity (percolation) model, which explains naturally the observed heterogeneity of response of a geophysical media to the strain variation.

Different methods of measuring the dynamic complexity of seismological time series are applied to magnitude and waiting time sequences of Caucasian earthquakes. The fractal (correlation) dimension $d_2$ of the latter is high (larger than 8), but the former one has as low dimension as 1.6–2.5, which makes waiting time sequences a promising tool for revealing precursory changes.

The same nonlinear technique allow detecting significant changes in the seismic regime during external electromagnetc forcing by MHD pulses; similar tests on the laboratory scale show the possibility of triggering/controlling stick-slip process by relatively weak electromagnetic or mechanical forcing.

Lastly, the predictive potential of complexity analysis of seismological time series is considered. For example, percolation model predicts the increase of the number of large events and the scatter of magnitudes of events, decrease of the magnitude-frequency relation slope and appearance of multifractality at approaching the final rupture.

It seems that seismology can benefit from using the new techniques to cope with the complexity of earthquake machine; for example, the measures of complexity can be characteristic for a given region and change before strong earthquake.

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* Corresponding author.
E-mail address: chelidze@ig.acnet.ge (T. Chelidze).

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1. Introduction: Complexity of geophysical/seismic processes

XX-th century geophysics was focused on the accumulation of experimental data on Earth geophysical fields and their interpretation mainly using highly idealized spatio-temporal models. In other words, problems of mathematical physics were solved as applied to simple geometrical forms (spheres, layers, etc.) having homogeneous physical properties. The problem becomes geophysical after setting specific forms of geological bodies and their physical properties. The latter ones were also simplified — the physical properties of earth materials were supposed to be constant within a given elementary object and independent of its size.

This approach proved to be very fruitful and lead to the understanding of many global regularities, namely, the regularities that disregard the complexity of the real universe and allow to represent clouds as spheres, mountains as cones (Mandelbrot, 1982) and heterogeneous bodies as effective media with scale-independent properties.

As early as 1925 Perrin noted that scientists idealize natural objects too much and, striving for maximal mathematical rigor of analysis, wander far from reality. However, being aware of the complexity of natural objects and processes, scientists were lacking an exact mathematical formalism, allowing measuring, classifying and theoretically modeling this property.

The situation in geophysics was quite similar; as has been noted, the main approach was to simplify problems and to find the relevant solutions from the arsenal of mathematical physics. At the same time there was a growing understanding of the necessity to analyze both qualitatively and quantitatively the complexity in the geometry and evolution of nature.

In the past two decades, numerous publications dealt with robust mathematical methods of analysis of complexity both in space and time domain and their number grows steadily. Besides general publications (Mandelbrot, 1982; Berge et al., 1984; Feder, 1988; Abarbanel et al., 1993; Ott et al., 1994; Stauffer and Aharony, 1994; Sahimi, 1994) several books and reviews are devoted to application of new methods of analysis of complex systems to Earth sciences in general (Turcotte, 1992; Korvin, 1992; Sornette, 2000) and to seismic process in particular (Sadovski and Pisarenko, 1991; Main, 1996; Goltz, 1998; Kanamori and Brodsky, 2004).

In following we shall use the term complexity in order to address both non-Euclidean spatial forms and nonlinear time-depending processes.

2. Complexity of the geophysical medium

2.1. Theory of effective media

It was common knowledge in geophysics that if the size \( L \) of so called elementary representative volume (ERV) is much larger than the characteristic size \( l \) of heterogeneities in the ERV, the physical properties of material are self-consistent (invariant to translation). In other words, the physical properties of a heterogeneous material are the same for any chosen ERV and, what is more important, they do not depend on the size of the probe volume, if it is larger than \( L \). The concept of ERV or self-consistency is a basic one in the effective medium theory (EMT), allowing calculation of physical properties of the heterogeneous medium provided that the properties, the partial volumes and form of components are known (Hanai, 1968; Shermegor, 1977; Christensen, 1979). It has to be stressed that the EMT is applicable only if the properties of components do not differ too much and the concentration of inclusions is not too high (Gueguen et al., 1997; Chelidze et al., 1998).

2.2. Fractal media

Recent experimental data show that physical properties of medium in certain conditions vary in a regular (self-similar) manner with the size of the tested volume; these objects are defined as fractals. The property of scaling can be very important in interpretation of earthquake anomalies: it implies that the properties of geological formations can depend on the size of the tested volume. This means that in material relations such as Ohm’s, Fick’s and Hooke’s laws it is necessary to take into account scaling. For example, the elastic modulus of a fractal system is:

\[
M = M_0 L^{-f/v},
\]

where \( L \) is the size of the system and the ratio \( f/v \) is the characteristic exponent for mechanical percolation (Chelidze, 1993; Sahimi, 1994). Of course, this does not mean that all geological objects are fractal at any scale. In real systems fractal regime can be realized only in the finite range of scales.

2.3. Percolation theory and fracture

Besides fractality there is another important property of heterogeneous material, namely, the degree of connectivity of a given component. In other words the medium can be fractal but its elements can be either...
Functions of damage

The mechanical percolation model (Sahimi, 1994) can consider a regular or random lattice, the elements of which can be either intact with probability $q$ or broken with probability $x = 1 - q$. Probability $x$ can be related to the applied stress and/or duration of loading (Chelidze, 1982, 1987, 1993; Chelidze et al., 2006a). The progress of the fracture process means that $x$ increases and the solid (consolidated) lattice becomes more and more diluted (damaged). Nearest damaged elements form local clusters — microcracks and macrocracks. The size of clusters increases with $x$ and at some critical concentration of defects ($x_c$) an infinite cluster (IC) of destroyed elements (main rupture) appears in the lattice, meaning that the lattice becomes unconsolidated. Besides this limiting value, it is possible to consider earlier stages of the damage process by means of characteristic percolation functions of damage $x$ such as the mean number of defects per cluster $s(x)$, the correlation length $L(x)$, elastic moduli, conductivity, etc. The process of nucleation, interaction and merging of elementary defects inevitably changes the properties of the medium long before appearance of the main rupture: consequently, the percolation model inherently contains the potential of predicting impending collapse of the system by monitoring its physical properties and energy emission patterns (Chelidze, 1982, 1987, 1993). Analysis of experimental precursory data shows that they can be approximated by percolation characteristic functions that are power functions of the “distance” to the threshold $\Delta x = (x - x_c)$; these results can be considered as a first tests of the criticality hypothesis (Chelidze, 1982).

Theoretical analysis of percolation model of fracture shows that near the percolation threshold the process becomes multifractal. This is a clear indication of multifractality of the local stress distribution (Arcangelis, 1990). Fractal analysis of field data (Dimitriu et al., 2000) clearly shows increasing multifractality in the spatial distribution of shocks prior to a strong earthquake confirming theoretical prediction of Arcangelis.

Nucleation and coalescence of defects implies some energy emission, as each such act causes redistribution of local stresses. A model of elastic/electromagnetic wave emission and amplitude distribution for percolation failure was first suggested in (Chelidze and Kolesnikov, 1984). This assumes that the emergence of each new defect is associated with an emission event and that the (conventional, effective) emission amplitude generated by the addition of a single elementary event depends directly on the increment of the size of the resulting (offspring) defect cluster induced by this event. In contrast to other models, where the total number of finite clusters is considered as a proxy of emitted energy pulses (earthquakes), we presume that emission occurs only when the increment of the size of merging clusters of defects takes place. In the framework of this model of “activated clusters” the effective emission amplitude $A$, generated by each elementary fracture depends directly on the increment of the size of the resulting (offspring) cluster of defects, induced by the addition of a single defect:

$$A = A_0((\sum_{i=1}^{k} s_i)^2 - (\sum_{i=1}^{k} s_i^2))^{1/2},$$

where $k$ is the number of clusters linked by the elementary defect, $s$ is the number of sites in the $i$-th merging cluster, and $A_0$ is a conventional amplitude, generated by the nucleation act of a single isolated defect in the intact lattice. The model predicts drastic increase of the number of large events and scatter of magnitudes of events as well as decrease of the slope of the magnitude-frequency relation at approaching percolation threshold (Chelidze and Kolesnikov, 1984); later the same results was obtained by Kanamori and Brodsky (2004).

2.4. Strain-sensitivity and nonregularity of predictors

One of most important problems in earthquake forecast is the analysis of the response of the geophysical medium to tectonic stress. In order to correctly relate the amplitude of the observed precursor to strain it is necessary to know the local strain sensitivity of the measured quantity.

The mechanical impact, which results in anomalies of transport properties, is transferred through the complex geologic formation. This irregularity/complexity of medium makes relating amplitudes of precursors or post-seismic effects to the strain intensity extremely difficult (Silver and Wakita, 1996). The most vivid experimental illustration of this statement is given by King et al. (1999), who reported earthquake-related water level changes at 16 closely clustered wells (all within 0.6 km). The authors conclude that large differences in the response of close wells cannot be explained by the strain-field variations, which are calculated on the basis of poroelastic dislocation models. The observed changes require local permeability changes and near-critical hydrological conditions of well-surrounding media.
These observations present the essence of the difficulties in interpretation of earthquake precursors, namely the ambiguity of physical model, relating the amplitude of precursors to the strain intensity. The heterogeneity of response in transport properties is usually explained in terms of local stress-intensity variation. Nevertheless, it seems that the spatial variability of a tectonic stress field is not the main or the only source of response heterogeneity: there is another important factor that defines the amplitude of a precursor, namely, the strain-sensitivity \( k \) of the physical properties of crustal material. The parameter \( k \) can be defined as the ratio: 
\[
\frac{dg}{dl/l},
\]
where \( dg \) is the increment of the physical property \( g \) under strain and \( dl/l \) is the strain (Chelidze, 1987; Chelidze et al., 1998). The physical property \( g \) in general can be any structure-sensitive (transport) property of rock which should be considered as a sensor of a tectonic strain field.

Calculation of stress-induced effects in transport properties of systems with wide, fully saturated interconnected pores can be carried out in the framework of EMT. In this case, the connectivity of pore space changes under stress insignificantly, and the strain-sensitivity even for large strain increments is not large. For example, the variation of conductivity of saturated sandstones with wide pores does not exceed 10–20\% in the range of axial stress from 0 to 100 MPa (Glover et al., 1996). Transitions, related to the connectivity of transport channels, are correctly described by the percolation theory (Chelidze and Gueguen, 1998) which predicts that these transitions occur at the percolation threshold. Such transitions lead to strong variation of a transport property at a small change of porosity as near the percolation threshold the heterogeneous system is extremely sensitive to any external impact affecting the pore space connectivity. Such an impact can be produced by tectonic stress.

Thus, sensitivity to the impact can be quite different depending on the state of the system. Below the percolation threshold, the system is just impermeable or hardly permeable. Above the threshold and far enough from it the increment of porosity leads to an addition of transport channels which are parallel to the existing ones of an infinite cluster. Appearance of such channels affects the global transport in the system much less than cutting (or addition) of singly connected channels. Therefore, far from the percolation threshold the strain-sensitivity is relatively low. Actually such systems are bad (though, possibly, linear) strain sensors. On the contrary, systems which are close to the percolation state manifest strong response to a weak impact; they are very sensitive though, probably, nonlinear strain sensors.

The phenomenon is illustrated in the paper of King et al. (1999), which explains the high sensitivity of a specific well (SN-3) with a closeness of an aquifer-barrier system to the critical state, where “relatively weak seismic shaking or stress change may be sufficient to create enough interconnected fissures in the aquifers and fault zone to allow water to flow rapidly...”. This is the almost exact description of a pressure-driven percolation transition model (Chelidze, 1987; 1993, Chelidze and Gueguen, 1998).

The percolation model of strain-sensitivity can explain the striking difference in volumetric strain assessment from seismological and hydrological measurements. For example, King et al. (1999) reported that strains, calculated from the water-level data, which are an order of magnitude larger strains than from the dislocation model of Okada (1992). Kitagawa and Koizumi (1996) argue that groundwater temperature changes reveal \( 10^3 – 10^4 \) larger strains than the seismological assessment. The possible explanation is that hydrological methods monitor the changes both in the stress and in the transport properties (state) of the medium, the latter depending strongly on the connectivity of pore/crack space.

It should be mentioned that there are several additional factors that may significantly affect the strain-sensitivity, such as anisotropy of rocks, the character of the applied stress (hydrostatic, deviatoric), the scale of observation base, etc.

The latter effect, namely, the scale-dependence of geophysical fields, is a relatively new phenomenon (Chelidze, 1987; Savich, 1983/1984; Jones, 1995; Schulze-Makuch, 1997; Bonnet et al., 2001) which is also explained by fractal/percolation theory. The strain-dependence potentially may be affected by the scale-dependence. For example, the high strain-sensitivity, corresponding to the situation when the correlation range of the network of channels \( L_c \) and the observation base \( l \) are comparable, may disappear if this condition is violated. This is the result of the finite size scaling effect, which is well known in percolation theory. The stress-induced redistribution of transport channels can also affect fractal dimension of a fracture network. We conclude that scale-dependence introduces additional response heterogeneity in the strain-related field data.

The strain-sensitivity may also depend on the time due to tectonic stress variations.

Thus strain-sensitivity \( k \) in a general case is a state-, scale- and time-dependent parameter; this means that it is necessary to control it permanently in order to correctly relate strain change to the observed geophysical anomaly.
3. Dynamic complexity; time series

As a rule, geophysical time series are rather complicated; we will understand dynamic complexity as a set of quantitative features and quantitative parameters characterizing the orderliness of time series. The problem is that between total randomness and strict periodicity there are many intermediate states that reveal some degree of orderliness. Till recently both qualitative and quantitative analysis of these intermediate states was impossible due to the absence of a corresponding mathematical formalism. Now new methods of nonlinear analysis of time series (Packard et al., 1980; Berge et al., 1984; Eckmann and Ruelle, 1985; Theiler et al., 1992; Abarbanel et al., 1993; Rapp et al., 1993; Theiler and Prichard, 1997; Kantz and Schreiber, 1997, etc.) allow solving this problem. Owing to their universality, these methods are applicable to a very broad range of time-dependent processes with different dynamic characteristics. The level of complexity of a given process can be assessed both qualitatively and quantitatively.

For the qualitative evaluation of seismic process dynamics, it is possible to use several approaches, e.g. two and three dimensional phase portrait reconstruction, Poincare sections, iterated function systems (IFS) and recurrent plot (RP) methods (Eckmann et al., 1987; Jeffrey, 1992). They preserve the general topological peculiarities of investigated dynamics and are suitable for visual, qualitative analysis of unknown dynamical process.

There are also several ways for the quantitative evaluation of complexity of analyzed dynamics by analyzing available one-dimensional time series. Namely, evolution of phase space trajectories may be analyzed by means of Lyapunov exponent \( \lambda \) (often by its maximal value, \( \lambda_{\text{max}} \)) calculation. Geometry of structures reconstructed in the phase space can be characterized by calculation of fractal dimensions e.g. correlation dimension \( d_2 \) of seismic time series. Lyapunov-exponent and correlation-dimension calculation methodologies are very sensitive to the length of time series. At the same time the length of real seismic data sets are usually restricted. Therefore sometimes use of the not so sensitive to time-series length recurrent quantification analysis (RQA), Lempel and Ziv (LZ) algorithmic complexity measure and Shannon entropy calculation methodology may be preferable (Kaspar and Schuster, 1987; Zbilut and Webber, 1992; Kantz and Shreiber, 1997).

A low value of correlation dimension, LZ complexity and Shannon entropy values, as well as a low positive value of Lyapunov exponent testify to a high level of orderliness in a time series; processes with LZC close to 1, \( d_2 \) larger than 5 and large positive \( \lambda_{\text{max}} \) mark closeness to random processes.

Several recent publications are devoted to the nonlinear analysis of the seismic process (Keilis-Borok, 1990; Pisarenko and Pisarenko, 1991; Korvin, 1992; Turcotte, 1992; Keilis-Borok, 1994; Kagan, 1994; Goltz, 1998). The main results can be summarized in the following way: the qualitative methods (IFS, recurrence plots) testify to the presence of some non-random

![Fig. 1. IFS visualizations (a, c, e, k) and recurrence plots (b, d, f, h) of Caucasian earthquakes: (a, b) magnitudes, (c, d) interearthquake distances and (e, f) waiting times sequences; (k, h) Random numbers sequences.](image-url)
nonlinear structure in energetic, spatial and temporal distributions of earthquakes (Fig. 1).

Fractal dimension of magnitude time series is high (i.e. \( d_2 > 5 \)), \( d_2 \) as a rule is larger than 8 (Matcharashvili et al., 1996), at the same time the fractal dimension for the distribution of epicentral distances is low (Sadovsky and Pisarenko, 1991). Recently Goltz (1998) and Matcharashvili et al. (2000) almost simultaneously discovered that the fractal dimension of time intervals between earthquakes (waiting times) also assumes low values of \( d_2 \) of the order of 1.6 – 2.5. In the Table 1 are presented correlation dimension and maximal Lyapunov’s exponent \( \lambda_{\text{max}} \) and LZC values of waiting times for Caucasus and some sub-areas of the region. The tested nonlinear properties can be characteristic for a given region and give new tools for seismic regionalization.

The sensitivity of the correlation dimension of earthquakes’ temporal distribution (Figs. 2 and 3), together with the variation of the spatial distribution before and after large events (Matcharashvili et al., 2002) indicate that measuring the complexity of time series may have a precursory meaning and can be used for earthquake forecast.

### 4. Complexity and artificial control of nonlinear structure of seismic/acoustic regime

One of the signs of complexity (nonlinearity) of a system is its high sensitivity to relatively weak external excitations, implying that the object is in or close to the critical state. According to recent investigations, the Earth’s crust in seismically active regions can be in the critical state or close to it (Bak et al., 1988; Scholtz, 1990). This can explain the known phenomena of tidal variations of acoustic/seismic emission in the Earth crust, seismic activation during the filling of large reservoirs and pumping of water into boreholes (Sibson, 1994) as well as remote aftershocks of the Landers earthquake (Gomberg et al., 2001, Hill et al., 1995). In the experiments (1975–1996), initially aimed at finding resistivity precursors to strong earthquakes in the upper layers of Earth crust by MHD-sounding, an unexpected effect of microseismicity activation after these discharges was discovered in the Bishkek test area in Central Asia (Tarasov, 1997; Tarasov et al., 1999). In order to test the possibility of man-made impact on the seismic regime, the dynamics of temporal distribution of earthquakes around the test area was analyzed. For this purpose, sequences of time intervals in seconds between

<table>
<thead>
<tr>
<th>Region</th>
<th>Larger Caucasus</th>
<th>Javakhety plateau</th>
<th>Focal area of Racha earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_2 )</td>
<td>1.65±0.42</td>
<td>1.70±0.51</td>
<td>1.82±0.13</td>
</tr>
<tr>
<td>( \lambda_{\text{max}} )</td>
<td>0.241±0.018</td>
<td>0.539±0.041</td>
<td>0.784±0.026</td>
</tr>
<tr>
<td>LZC</td>
<td>0.85±0.07</td>
<td>0.71±0.08</td>
<td>0.95±0.01</td>
</tr>
</tbody>
</table>

Fig. 2. Variation of correlation dimension \( d_2 \) for sliding window containing 1000 earthquake waiting times sequences versus embedding space dimension \( p \) for Paravani earthquake (M.5.6) area at 50 event steps.

Fig. 3. Correlation dimension as a function of an embedding dimension \( p \) for: Spitak (a) and Paravani (b) earthquake waiting time sequences. Black circles, triangles and squares correspond to waiting times before the earthquake, their Gaussian scaled random and phase shuffled surrogates, respectively. White circles, triangles and squares correspond to time interval sequences after the earthquake, their Gaussian scaled random and phase shuffled surrogates, respectively.
consecutive earthquakes from the seismic catalogue compiled by the Institute of Physics of Earth (Moscow) were investigated using nonlinear time series analysis tools (Chelidze and Matcharashvili, 2003). The time periods before experiment (1975–1983), the period of cold and hot runs (1983–1988), the period immediately after accomplishment of the experiments (1988–1992), as well as the time period long after the experiment (1992–1996) were considered separately. Waiting time sequences, corresponding to these periods, have approximately equal lengths (about 3660 events).

In Fig. 4 we present qualitative recurrence plot analysis of the mentioned time series. Plots of Fig. 4 show that after beginning of experiments the temporal distribution of earthquakes changes significantly. This conclusion is confirmed by Lempel Ziv algorithmic complexity (LZC) measure analysis (Kaspar and Schuster, 1987), which is a useful tool for analysis of relatively short time series. Indeed, calculated values of LZC measure are $C_{LZ} = 0.98 \pm 0.09$; $C_{LZ} = 0.65 \pm 0.05$; $C_{LZ} = 0.99 \pm 0.97$, before, during and long after the beginning of experiments, respectively (note that $C_{LZ} = 0.04$ for periodic and $C_{LZ} = 1$ for random processes). To the same conclusion leads also the calculation of quantitative RQA characteristics such as $RR(t)$ — the probability of the recurrence of a certain state in the phase space, and $DET(t)$ — proportion of recurrence points forming long diagonal structures in R, which are typical for regular processes. From our analysis it follows that $RR(t) = 9.6$, $DET(t) = 3.9$ before experiments, $RR(t) = 25$, $DET(t) = 18$ during and $RR(t) = 3$, $DET(t) = 1.5$ after experiments.

A quantitative measure, correlation dimensions versus embedding dimension of these time series are plotted in Fig. 5. Interevent time series before beginning of experiment is characterized by the correlation dimension $d_2 = 3.50 \pm 0.63$ which is below the low dimensionality threshold ($d_2 = 5.0$). During experiments correlation dimension of waiting times’ sequence decreases to $d_2 = 1.71 \pm 0.09$; after termination of experiments it increases to $d_2 > 5$.

After beginning of EM discharges the behavior of seismicity is more regular in spatial domain too, which is evident considering the results of Shannon entropy calculation (Fig. 6).

In addition to the comparative analysis of the seismic catalogue with field electromagnetic (EM) tests, laboratory experiments that mimic the situation on the large scale have been carried out (Chelidze et al., 2002; Chelidze and Lursmanashvili, 2003). Two kinds of experiments were performed: (i) initiation of mechanical instability by EM impact on the sample, placed on an
inclined plane at the angle less than the critical one; (ii)
synchronization of micro-slip events in slider-spring
system with weak periodic (EM or mechanical) impact,
superimposed on the much larger dragging force. In both
cases the samples were roughly finished basalt blocks.

It has been found that the EM impact initiates the slip
with the probability \( P \approx 0.07 \) at the voltage \( \Delta V = 1300 \) V
and with the probability \( P \approx 0.2 \) at \( \Delta V \approx 10 \) kV, when
the electric field is nearly parallel to slip plane. On the
other hand, application of electric field normal to the slip
plane hampers the slip.

Experiments carried out on the slider-spring system,
where the large pulling force was modulated by a weak
periodical force of EM or mechanical nature, also show
high sensitivity of critical or “nearly critical” nonlinear
systems to a small external impact. The regimes of slip
vary from the perfect synchronization of slip events
(acoustic emission) with the perturbing periodical
mechanical or EM impact to the complete desynchroni-
zation of these phenomena depending on the amplitude
and the frequency of the applied weak perturbations. For
example, synchronization of microslip events with EM
periodical perturbance became visually evident when the
amplitude of applied voltage exceeds 400 V (Fig. 7). In
(Chelidze et al., 2005; Chelidze et al., 2006b) we show
that it is possible to measure the strength of slip control
by the applied forcing using new tools of synchroniza-
tion theory (Pikovsky et al., 2003).

We consider the above results as an evidence that it is
possible to control slip by application of weak periodical
perturbations that are orders of magnitude less that the
dragging force; the effect is due to the complexity/
nonlinearity of the slip process both on laboratory and
natural fault scale.

5. Earthquake forecast and critical phenomena

The problem of predicting/forecasting the behavior
of a dynamic system is a touchstone for any serious
science; that is why it is necessary to find reliable a
physical basis of earthquake forecast. Lately the
discussion on the fundamental problem of predictability
of earthquakes became very intensive. The main
argument against the possibility of earthquake forecast
is (see Geller, 1997; Kagan, 1997): the Earth’s crust is in
the state of self-organized criticality or SOC (Bak et al.,
1988; Scholtz, 1990) and because of the strong
nonlinearity of the system, the smallest change in initial
conditions may cause a totally different response. This
leads to the conclusion of the inherent implausibility of
reliable earthquake forecast as any small shock can grow
into a large event without any preparatory stage.

On the other hand, it has been shown theoretically
that the behavior of a nonlinear system on a limited time
interval \( T \) is predictable. The limit of the predictability
time is given by the Kolmogorov–Sinai (KS) entropy \( h(X) \),
where \( X \) is a set of states. The system becomes
unpredictable only after the passage of time \( T \approx 1/h(X) \)
(Abarbanel et al., 1993).

Besides, from the experimental mechanics of solids we
know that if a system manifests strain relaxation

![Fig. 6. Variation of Shannon entropy of IVTAN test area \( (M=2.0) \) time
series for 400 data sliding windows. a) Magnitude time series, b)
waiting time series, c) interevent distances time series. On the left from
dashed line—time period before experiments, between dashed lines—
time period of experiments, on the right from the dashed line—time
period after experiments.](image-url)
(nonlinearity) after releasing the applied load then it reveals a strain build-up process of nearly the same duration also. Applying this universal observation to the seismic process we can state: if there are no predictors of the strong event then there should also be no after-event effects. The most obvious and indisputable examples of after-effects are aftershock activity, which lasts months or years, and water level relaxation in deep wells, of similar duration. Then, if there is clear evidence of long strain relaxation periods after strong events, why should the possibility of prolonged strain accumulation before it be rejected? If the relaxation of stress takes several years, why the build-up process does not need any time? In laboratory tests of delayed fracture of rocks, both intact and containing artificial fracture, as well as in stick-slip experiments, a plethora of precursors of main rupture has been found on the basis of simultaneous monitoring of acoustic, electric, local strain fields, gas emission and other phenomena (Sobolev and Ponomarev, 2003). What is so specific in the seismic process that leads to a taboo on precursors to earthquake?

It seems that the contradiction between the competing paradigms of unpredictable nonlinearity and predictable strain- or damage-accumulation (also nonlinear) models can be resolved by decoupling these two approaches. This means that both are valid, but have different limits of validity. Such models as SOC and cellular automata are mainly focused on simulation and prediction of fundamental features of the seismic regime as a whole that is for modeling seismic catalogues and are less helpful for prediction of the next strong event. These models do not allow understanding the nature of strain build-up/relaxation anomalies in seismic regime.

Besides, preparation of the strong earthquake is not a purely seismic process. Even during the earthquake only a small part of the released energy is transformed into seismic waves. During build-up/relaxation processes the seismic component plays an even lesser role: the main feature here is mostly aseismic deformation, which may cause, nevertheless, strong anomalies in strain-sensitive geophysical, geochemical and geodynamical fields, due, say, to the evolution of the fracture network before the strong event and redistribution of pore fluid.

The last but not least in the nonlinear approach to the forecast is the problem of connectivity. Analysis of connectivity may be very important if, say, fluid pore pressure is decisive in nucleation of earthquakes (Sibson, 1994; Muir Wood, 1994). If the connectivity factor is essential, percolation theory seems to be the best tool for assessment of closeness to the critical state, as it is focused on the analysis of connectivity of elementary objects, such as pores, fractures or just overstressed volumes (Chelidze, 1987, 1993). Percolation fracture model (Chelidze, 1987; Herrmann and Roux, 1990; Chelidze, 1993) with some simple kinetic assumptions permits to understand the physics of the process of nucleation, coagulation and growth of clusters of microfractures during delayed fracture and predict evolution of physical properties of system during destruction as well as the time to failure (Chelidze, 1982; Main, 1999; Chelidze et al., 2006a). The model of pressure-induced percolation transitions explains
The fractal (correlation) dimension and waiting time sequences of Caucasian earthquakes. The physical properties of geophysical medium are not always self-consistent and manifest fractal behavior. Mechanical percolation theory can be used for modeling fractal and connectivity aspects of fracture process, including energy emission during fracture. Special attention is paid to relating the intensity of geophysical anomalies to strain in the framework of pressure-induced anomalous strain-sensitivity (percolation) model. Model explains the observed heterogeneity of response of geophysical media to the strain process.

6. Conclusions

As it has been established in the recent years, many objects and processes that earlier were considered as completely random reveal clear evidence of having some ordered structure in the time and space domain. Based on new methods of analysis we carried out visualization and quantitative assessment of the level of complexity (orderliness) of real-systems structures and dynamics. In this connection we consider the heterogeneity of geological formations, strain sensitivity of transport processes, nonlinear structures in seismic time series, their relation to the problem of earthquake forecast and the possibility of human control of the seismic process.

It is shown that the physical properties of geophysical medium are not always self-consistent and manifest fractal behavior. Mechanical percolation theory can be used for modeling fractal and connectivity aspects of fracture process, including energy emission during fracture. Special attention is paid to relating the intensity of geophysical anomalies to strain in the framework of the pressure-induced anomalous strain-sensitivity (percolation) model. Model explains the observed heterogeneity of response of geophysical media to the strain variation.

Different methods of measuring the dynamic complexity of seismological time series are applied to magnitude and waiting time sequences of Caucasian earthquakes. The fractal (correlation) dimension \( d_2 \) of the latter is high (larger than 8), but the former one has as low dimension as 1.6–2.5, which makes waiting time sequences a promising tool for revealing precursory changes.

The same nonlinear technique allows detecting significant changes in the seismic regime during external electromagnetic forcing; similar tests on the laboratory scale show the possibility of triggering/controlling stick-slip process by relatively weak electromagnetic of mechanical forcing.

Lastly, the predictive potential of complexity analysis of seismological time series is considered. For example, the percolation model predicts the increase of the number of large events and the scatter of magnitudes of events, decrease of the magnitude-frequency relation slope and appearance of multifractality at approaching the final rupture.

We conclude that measuring spatio-temporal complexity of seismic, hydraulic, electromagnetic and other geophysical fields in space and time gives new tools for finding and quantitative assessment of regional complexity and pre-seismic anomalies; comparison of these anomalies with predictions of mechanical percolation theory and other direct models of seismic process will test their validity.

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References


