Technical Note

Seismic Monitoring of Distant Earthquakes for Studying Geodynamics and Estimating Environment's Stress

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ABSTRACT

The results of long-term seismic monitoring with use of natural sources conducted in the seismic dangerous area of the Caucasus mineral waters are presented. In order to study the subsurface geodynamics and its stress state in the study area, a technique has been developed based on studying energy of converted PS waves. The analysis of obtained data allowed middle-term criteria for predicting local tectonic earthquakes to be formulated proceeding from the model within the scope of the avalanche-unsteady crack formation (AUCF) theory. It has been shown that the catastrophic far earthquakes (distance up to 7000km) with M >7.0, after which intense surface waves had been recorded in the area of Caucasus Mineral Waters, changed anisotropic properties and stress state causing the increase of local seismic activity. This shows the induced seismicity. Induced process reduces the reliability of formulated criteria. This reveals the necessity to correct the model of earthquake origin in accordance with the AUCF theory.

Keywords:
Seismic monitoring;
Distant earthquakes;
Environment stress

1. Introduction

One of the most important problems in geo-ecology is to determine the intercommunication of geophysical fields with tectonic process when preparing an earthquake to reveal criteria for predicting a seismic activity. Such prediction for urban districts in seismic areas is of high priority to study the stress state of subsurface and the factors affecting its change. A geophysical monitoring is necessary as a priority in seismic monitoring.

Seismic observations within the area of Caucasus Mineral Waters (*CMW*) have been started in 1995 and are still in progress. Caucasus Mineral Waters area is characterized by seismicity. It applies to the zone where 7….8 point earthquakes (on the *MSK* scale) are possible. The seismic monitoring grid consists of 10 three-component stations equipped by the digital instruments, Alpha-Geon and Delta-Geon. The site of the grid is $70 \times 70 km$. The grid records local earthquakes within the range of 300*km* as well as far earthquakes (epicenter distance $>10°$) with the magnitude of $M > 4.7$.

2. Technique

In order to study subsurface geodynamics, a technique was developed which estimates the stress state of geological medium based on the estimation of converted wave energy from far earthquakes (*PS* waves), namely *Ev* energy for radial component *PSv* (the oscillations in the ray's plane) and the *Er* energy for tangential component *PSr* (the oscillations transversely to ray's plane). This energy depends on fracturing degree, porosity, and medium's anisotropic properties. For estimating the stress state, the total values of the radial component's energy (ΣEv) and tangential component's energy (ΣEr) are considered in the deep diapason 0-25*km*. In the deep diapason 0-25*km* (*CMW* region) the rays of *PS*- waves are close to vertical.

Medium stress state at some point can be estimated by following parameters [1-2]:

- The indicator of medium anisotropic properties change below each observation point.

$$\gamma = \sum Er / \sum Ev \qquad (1)$$

- The integral indicator of medium stress state on an observation area on the basis of γ distribution over the monitoring station grid:

$$S = \frac{\int_{X1}^{X2}\int_{Y1}^{Y2}\int_{\delta}^{\infty} \gamma(x,y)\,dx\,dy\,d\gamma}{\int_{X1}^{X2}\int_{Y1}^{Y2} \delta \cdot x \cdot y \cdot dx\,dy} \qquad (2)$$

Where *X*, *Y* are coordinates of an monitoring area; δ is the threshold level exceeding which indicates an increase of medium anisotropic properties and a stress state in area under investigation.

3. Results

The greater anisotropic properties of geological media under the recording station is, the more the level of γ indicator will be. The maps of the γ distribution over area of the monitoring grid and corresponding values of the indicator of medium stress state (*S*) for different time intervals [1-2] are shown in Figure (1-a) to (1-l). As usual the duration of each time interval is equal to one month at an average.

S(*t*) is shown in Figure (2), as a function of time for the whole 11-year observation interval. Here, the epicenters of local earthquakes with $M > 4.3$ happened with the distances up to 250-300*km* from the center of the station grid are also denoted. Average level of *S*(*t*) values substantially differs in the observation intervals 1995-2002 and 2003-2006. For these time intervals, the number of local earthquakes with $M > 4.3$ happened at distances up to 250-300*km* from center of the station grid is also different. The growth of the indicator of stress state *S* was particularly high after the catastrophic Sumatra earthquake (26.12.2004, $M = 9.0$) accompanied by tsunami. After this earthquake on the Terrestrial Globe, some destructive earthquakes with the magnitude $M > 7.0$ happened and the growth of indicator *S* was observed as well. It was assumed that besides local tectonic processes, the processes related to the global seismicity of the earth can affect the stress state of geological medium of

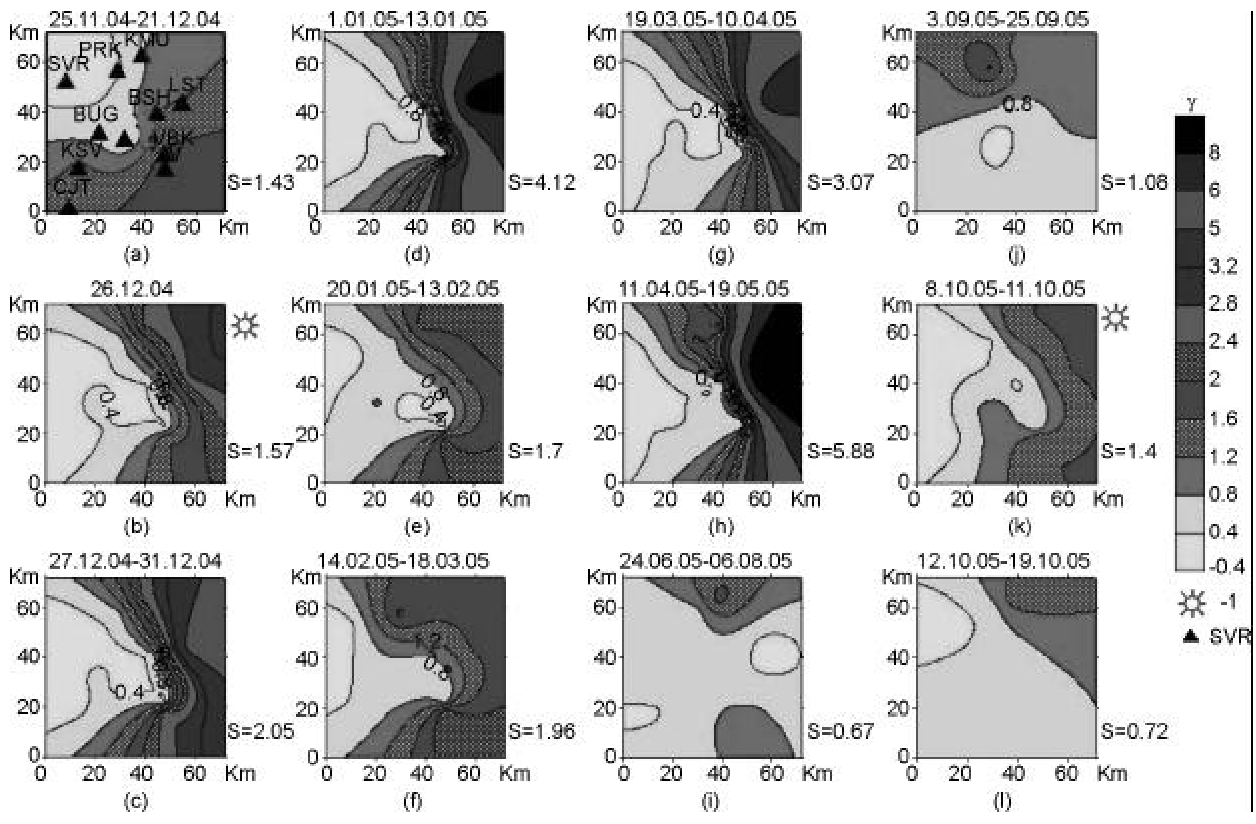

Figure 1. Maps of γ =Σ*Er*/Σ*Ev* distribution on the monitoring grid area in different observation intervals of time (contour interval 0.4). 1-Catastrophic far earthquake; 2-observation stations.

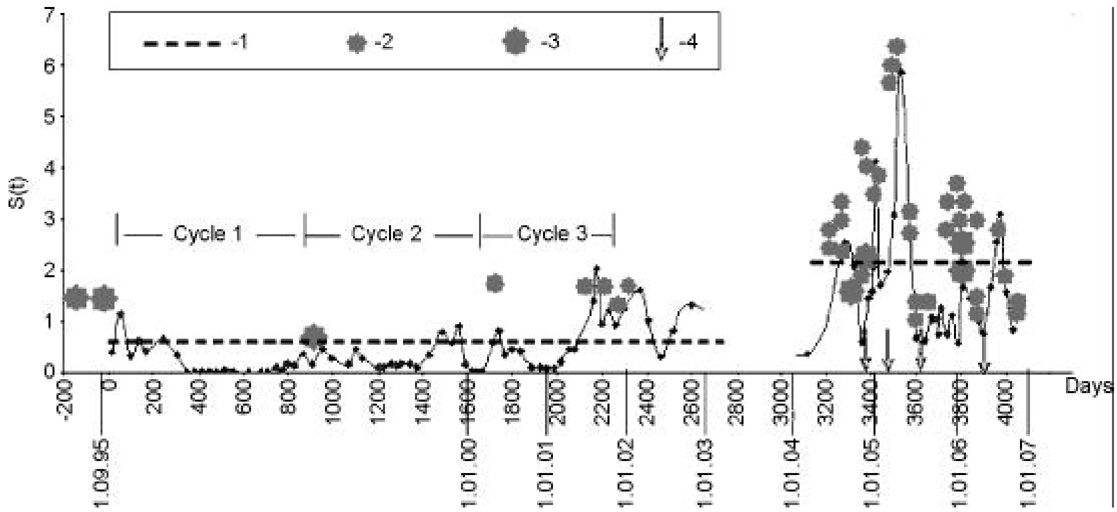

Figure 2. General S(t) dependence over the whole monitoring period 25.08.1995-25.9.2006. 1- Average level of S values; 2- local earthquakes with M=4.3-4.8; 3- local earthquakes with M=4.9-5.9; 4- time-registration of far catastrophic earthquake manifestation in the region CMW.

Caucasus Mineral Waters testing area.

$S(t)$ dependences were considered separately for the periods of 1995-2002 and 2004-2006. The $S(t)$ dependence and the averaged $S(t)$ dependence for the period 1995-2002 are presented in Figure (3). The analysis of these dependences together with the maps of $\gamma = \Sigma Er/\Sigma Ev$ distribution and local seismicity data in the area of the Caucasus Mineral Waters makes it possible to conclude that the change of the medium stress state during this period was related only to the tectonic processes in the area under study [1-2]. The cycles of the earthquake preparation with the magnitude of $M > 4.3$ stand out. It is particularly well seen on the average $S(t)_{ave}$ dependence. The cycle duration is 2-3 years. Each cycle consists of three phases. The first phase is the decay of stress state after pronounced seismic activity in the area. The second phase is a low value of stress state. The third phase is the growth of stress state. These three phases conform with three phases in the tectonics earthquake preparation cycle in terms of the theory of an avalanche-unsteady crack formation [3-4]: “discharging”, “regular state”, and “activization” correspondingly.

The discharging phase is characterized by the maximum S values and the maximum degree of

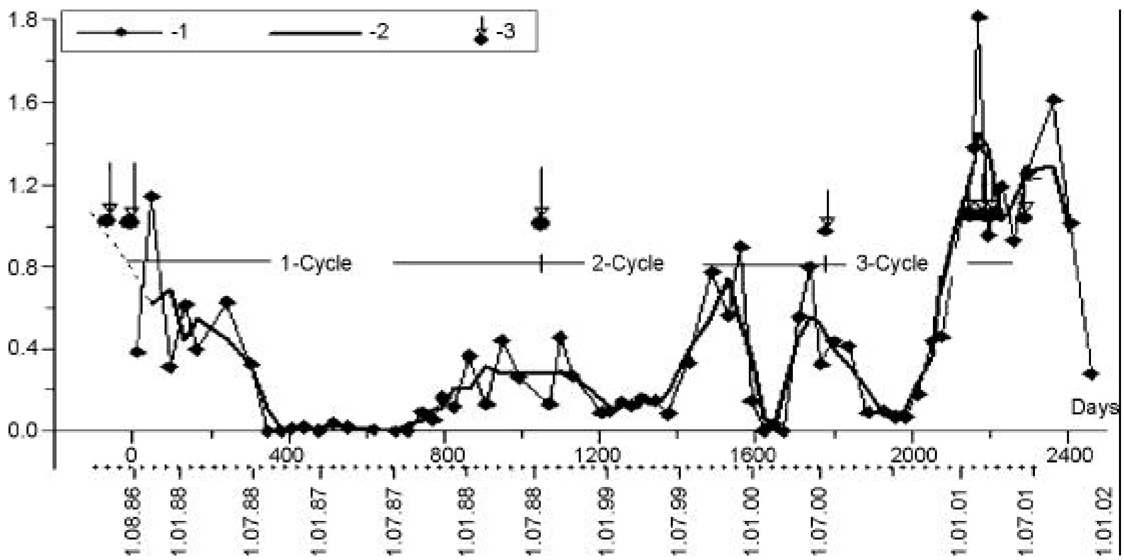

Figure 3. $S(t)$ dependence over the time period 1995-2002. 1- $S(t)$ dependence; 2-averaged dependence $S(t)_{ave}$; 3- earthquakes with M >4.3.

a medium anisotropy. The regular state phase corresponds to the decrease of a medium anisotropy degree. At this, the *PS*-wave energy is also decreased at all observation points. This fact makes it possible to assume that medium fluidization grows at the regular state phase. A gradual increase of $S(t)_{ave}$ and accordingly medium anisotropy degree at the activization phase can be explained by a fracturing increase. The natural increase of the $S(t)_{ave}$ dependence after a sufficiently long-duration period of low values can be considered as a middle-term criteria of seismic activity. The level of S_{ave} growth depends on a magnitude of a preparing earthquake and closeness of a hypocenter to the location area of the monitoring station grid. The longer the regular state (or quiescent state) phase, the greater magnitude of a preparing event to come can be presumed.

In the study area, strong events with $M \geq 5.0$ happened within approximately 6-11 months from the commencement of stress state growth phase. On the basis of the above statements, following criteria of middle-term prediction of strong earthquakes with the magnitude of $M \geq 4.3$ can be formulated in the study area.

- The presence of a sufficiently long term period of low values (the phase of regular state) of the $S(t)_{ave}$ dependence;
- A stable growth of $S(t)_{ave}$ function; the growth gradient and the maximum values of $S(t)_{ave}$ depend on the magnitude of preparing earthquake and its distance from the grid.

With a long term phase of low values of $S(t)_{ave}$ dependence (approximately 1 year) and a high gradient of $S(t)_{ave}$ dependence growth up to high absolute values, a strong earthquake with the magnitude of $M \geq 5.0$ can be predicted in the vicinity of grid location station or immediately within the grid namely in its part where maximum values are noted on the maps of the $\gamma = \Sigma Er/\Sigma Ev$ distribution. If the phase of the $S(t)_{ave}$ low values are 3-4 months, the earthquakes with the magnitude of $M = 4.3$-4.7 can be predicted. Depending on the growth gradient and maximum values of $S(t)_{ave}$ function, the distance from the observation station grid can be presumed.

As stated above, the indicator of medium stress state *S* grew sharply after recording the far Sumatra earthquake (00*h*58', 26.12.04). The similar phenomena were also noted after recording other catastrophic events which had happened worldwide during the time period 2004-2006 (second Sumatran earthquake (28.03.2005), Pakistani (8.10.2005), Koryakian earthquake (20.04.2006) and Indonesian one (17.06.2006)).

The analysis of seismic signals recorded by the stations of monitoring grid revealed that intensive low-frequency surface waves with the period of 15-20*s* had been observed after all catastrophic earthquakes during some time. Other local and far earthquakes were also recorded against their background. In Figure (4), the records of far earthquake (the Nicolas Islands 2*h*30', 26.11.2004) are shown against the low-frequency surface waves from the first Sumatran earthquake. The amplitudes of surface waves are several times higher than those of Nicolas earthquake. Record time of the surface waves after the first Sumatran earthquake was about 6 hours, after the second Sumatran earthquake about 3 hours, Pakistani and Koryakian earthquakes 1 hour and 30 minutes, and after the Indonesian one about 2 hours.

After all catastrophic earthquakes, γ distribution which characterizes anisotropic properties of the medium Caucasus' Mineral Waters was sharply changed. After the first Sumatran earthquake, the reconstruction of medium anisotropic properties took place. The increased γ value region was moved to the east of the area, see Figure (1b). The surface waves from the catastrophic earthquake had arrived from this direction. The medium anisotropy degree was sharply increased within 3 days after 26.12.04, see Figure (1c).

The contrast of increased γ value region has became more evident, see Figure (1d). This indicates the sharp growth of medium stress state degree, too. The contrast of medium anisotropic properties somewhat decreased within the next two months, see Figures (1e) and (1f), but structure of γ distribution maps remained. The second catastrophic Sumatran earthquake had taken place at the end of March 2005, after which a sharp growth of the medium's anisotropy degree was also noted during nearly two months, see Figures (1g) and (1h). Afterwards, the medium stress decay was seen well on the γ distribution maps, see Figures (1i) and (1j), and the structure of γ maps characterizing the medium anisotropic properties changed. After the Pakistani, Koryakian and Indonesian earthquakes, the reconstruction of medium anisotropic properties was also fixed. However, the change contrast was sufficiently weaker in comparison with what was observed after

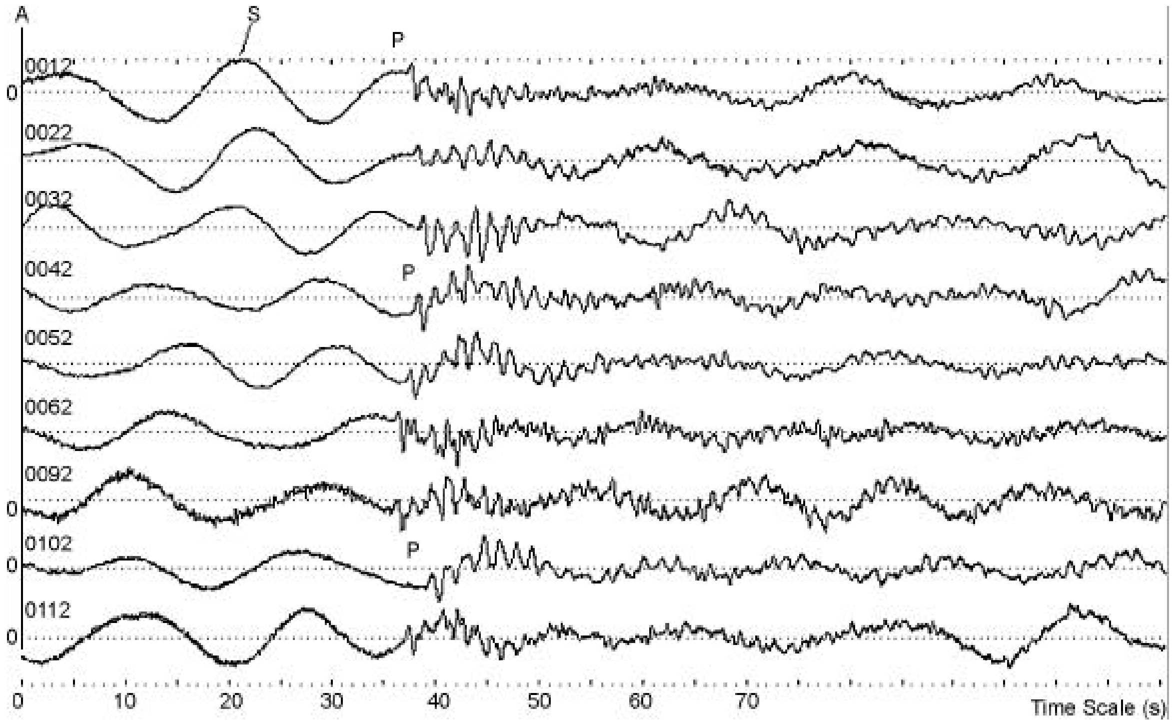

Figure 4. Records of amplitudes (A) of the vertical component of the earthquake (2h 30", M = 7.2 the Nicolas islands) against surface waves from the Sumatran earthquake (00h 58' 26.12.04 M = 9.0) at different observation stations (00z … 011z). (Arrival of the P-wave from the Nicolas earthquake denoted by P, surface wave denoted by S, amplitudes A are given in reading of the analog-to-digital converter.

the Sumatran earthquakes, see Figure (1k).

The indicator *S* of medium stress state for the time intervals after the catastrophic earthquakes calculated on γ distribution maps increased sharply, see Figure (2). Such growth of the anisotropy and stress degree of medium Caucasus's Mineral Waters test field after the catastrophic earthquakes was assumed to be related to the arrival of the intensive low-frequency surface waves. When surface waves are not long-durations, the medium stress state changes to a lesser degree. As a result of increased medium stress state after all catastrophic earthquakes at a distance from the grid, up to 300*km*, the increase of local seismic activity is fixed with the magnitude of $M \geq 4.3$, see Figure (2).

4. Conclusion

The obtained results conclude that far catastrophic earthquakes after which intensive long-duration surface waves are recorded, may change the structure of medium anisotropic properties and stress state of distant regions resulting in the growth of seismic activity of the area. This reveals the induced seismicity [5]. The criteria of local earthquakes prediction in the area formulated for the regular case became less accurate due to induced process. These show the necessity to correct the model of original earthquake according to the avalanche-unsteady crack formation theory using accumulated new experimental data and mathematical modeling.

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