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System of robust noise monitoring of anomalous seismic processes

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ABSTRACT

Robust noise technology is presented for the analysis of seismic-acoustic signals, which allows the use of noise in the signal as a carrier of information at the start of anomalous seismic processes preceding earthquakes. A station has been built based on this technology, which receives seismic-acoustic noises from the deep strata of the earth by means of 3–6 km deep steel bores suspended in oil wells, performing monitoring of the beginning of the latent period of earthquake formation. Experiments carried out at stations at Qum Island in the Caspian Sea since 01.05.2010 and in the town of Shirvan in the south of Azerbaijan since 20.11.2011 have proven the reliability and adequacy of results when monitoring and identifying earthquakes within a radius of 300–500 km, 10–15 h before the earthquakes are detected by standard seismic stations.

1. Introduction

Since the 1950–1960 s studies have been carried out to establish causes of earthquakes and the tectonic processes that lead to earthquakes [1–4]. Different devices and systems for the receiving and processing seismic signals were created and are presently being created [5–9]. New methods of seismic signal processing have been gradually developed, as well as new methods of seismic wave identification, and methods for the automated extraction of the characteristics of seismic signals [10–23]. Attempts have also been made to simulate those processes in order to facilitate the analysis of seismic signals [24–26]. Early warning systems have been created and are being created up to this day [27–29]. Numerous academic and practical attempts of earthquake prediction have been made [30–35]. The determination of the epicentre and hypocentre of earthquakes has been one of the main challenges for seismologists [36–38]. There have also been attempts to receive signals by means of geophones placed at a certain depth to receive the seismic waves preceding earthquakes [33,39].

Unfortunately, those methods do not meet all the requirements and are not widely applied in practice, which is the reason why the development of a technology and a system which would allow one to perform reliable short-term earthquake forecasting is considered impossible, establishing a pessimistic approach to the problem. Unlike the known works, the present paper considers one possible way to deal with the monitoring of the beginning of Anomalous Seismic Processes (ASP), by analysing the seismic-acoustic signals received from the deep strata of the earth [40–44].

Experiments carried out at seismic-acoustic stations installed at the heads of 3–6 km deep oil wells demonstrated that noisy seismic-acoustic waves spread in the deep strata of the earth within a radius of 300–500 km, dozens of hours earlier than the seismic waves registered by standard seismic stations on the earth's surface. However, conventional technologies for the analysis of seismic-acoustic signals received by means of hydrophones at the heads of oil wells do not allow the detection of the origin of ASP. The experiments carried out at Qum Island in the Caspian Sea from 01.07.2010 to 01.03.2012 demonstrated that the basic carrier of information at the beginning of ASP preceding an earthquake is the noise of seismic-acoustic signals. The paper, therefore, offers technologies for the analysis of noise as a carrier of useful information. By means of these technologies, characteristics such as the value of noise correlation $R_{X\varepsilon\varepsilon}(\mu=0)$, estimate of cross-correlation function $R_{X\varepsilon}(\mu=0)$ and coefficient of correlation $r_{X\varepsilon}$ of the useful signal and noise–noise variance $R_{\varepsilon\varepsilon}(\mu=0)$–are determined. These technologies are combined with those used for the determination of noise estimates by means of relay correlation functions, which increases the adequacy of monitoring results. Charts confirm the reliability of the results of monitoring performed with the application of these methods (Tables 1–4).

2. Problem statement

At present, seismic monitoring systems do not allow the forecasting of earthquakes, which has disastrous consequences in due time [42].

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The delayed registration of earthquakes by known types of standard ground seismic stations presents a grave problem for countries located in seismically-active regions, which in its turn leads to numerous casualties.

Due to the high death toll and material damage of many earthquakes [23] the development of new and more effective technologies and systems for the monitoring the beginning of ASP is required [40–42], which will allow one to perform short-term earthquake forecasting.

The monitoring of the beginning of ASP preceding earthquakes entails two specific problems. When an ASP arises, both infra-low frequency seismic waves and seismic-acoustic waves with a frequency within the sound range form. Both types of wave do not reach the surface of the earth for a long time before ASP reaches the critical state, which is explained by the fact that the frequency characteristics of the upper strata of the earth do not allow seismic-acoustic waves to reach the surface of earth. Seismic waves, in turn, only become powerful enough when ASP is in its critical state, i.e. when an earthquake is occurring. It implies that solving the given problem first of all requires obtaining seismic-acoustic noise from the deep strata of earth, this being the primary carrier of information on the incipient earthquake.

Another important problem of the task in question is related to the necessity of developing a technology of analysis of seismic-acoustic noise. It is known that the existing conventional technologies for the analysis of measurement information only yield satisfactory results under classical conditions such as normally distributed law, stationary state, absence of correlation between the useful signal and the noise, etc. [42]. Those conditions are, however, violated in seismic-acoustic noises when ASP arise and form. The application of conventional technologies cannot therefore provide the sufficient reliability and adequacy of the obtained results. Thus, the second key issue of the task in question concerns the development of a technology that takes into account the peculiarities of a heavily noisy seismic-acoustic signal in the period of ASP formation. Here, the analysis of noise in the seismic-acoustic signal as a carrier of useful diagnostic information is of prime importance [42–48].

It is known that in seismically-active regions [42–48] time T_0 of the normal seismic state between occasional ASP changes within the range of several weeks or months. Time period T_1 of the origin of ASP and formation can last several hours. The time period of the critical state T_2, when the seismic waves reach the surface of earth and an earthquake occurs, is estimated in minutes, after which a new period of rest T_0 begins. It is therefore appropriate to reduce the problem of monitoring and short-term forecasting of earthquakes to the provision of a reliable indication of the latent period start of ASP, T_1. The known existing systems and widely-applied seismic stations are designated for registering the start of period T_2. Unfortunately their functions do not include the reliable and adequate monitoring of the start of period T_1, which is one of the severe shortcomings of modern systems and means of both the control and monitoring of seismic processes.

Therefore let us consider the matter in more detail. Assume that in the normal seismic state in the time period T_0, the known classical conditions hold true for noisy seismic-acoustic signals $g(i\Delta t)=X(i\Delta t)+\varepsilon(i\Delta t)$ received as the output of corresponding acoustic sensors, for instance hydrophones, i.e. the equalities [40,41] are true: $\omega_{T_0}[g(i\Delta t)] = (1/\sqrt{2\pi D_g})e^{-(g(i\Delta t))^2/2D_g}$, $D_\varepsilon \approx 0$, $D_g \approx D_X$; $R_{gg}(\mu) \approx R_{XX}(\mu)$; $m_g \approx m_X$; $m_\varepsilon \approx 0$;

$$R_{X\varepsilon}(\mu=0) \approx 0,\ r_{X\varepsilon} \approx 0 \tag{1}$$

where $\omega_{T_0}[g(i\Delta t)]$ is $g(i\Delta t)$ the signal distribution law; D_ε, D_X, D_g are estimates of the variance of the noise $\varepsilon(i\Delta t)$, the useful signal $X(i\Delta t)$ and the sum signal $g(i\Delta t)$ respectively; $R_{XX}(\mu)$, $R_{gg}(\mu)$ are the estimates of the correlation functions of the useful signal $X(i\Delta t)$ and the sum signal $g(i\Delta t)$; m_ε, m_X, m_g are mathematical expectations of the noise $\varepsilon(i\Delta t)$, the useful signal and the sum signal; $R_{X\varepsilon}(\mu=0)$, $r_{X\varepsilon}$ are the cross-correlation function and the coefficient of correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$.

Table 1
Seismic events.

#	Region	Magnitude	Date	Time	Coordinates	*d* (km)
a	Azerbaijan	ML 3.0	2012.06.10	22:30:19.7 UTC	38.84N; 48.54E	15
b	Azerbaijan	ML 3.2	2012.06.20	00:59:14.0 UTC	41.52N; 46.66E	12
c	Azerbaijan	ML 4.0	2012.06.25	20:05:59.0 UTC	41.21N; 47.21E	5
d	Azerbaijan	ML 3.2	2012.06.27	16:24:25.0 UTC	41.21N; 48.44E	45

Table 2
Seismic events.

#	Magnitude	Region	Date	Time	Location	*D* (km)
5 a,b	ML 5.6	Eastern Turkey	2011.10.23	11:00:25.0 UTC	38.09N; 42.87E	10
5c,d	ML 3.8	Eastern Turkey	2011.10.24	01:57:59.0 UTC	38.79N; 43.55E	2

Table 3
Seismic events.

Magnitude	**mb 4.7**
Region	**NORTHWESTERN IRAN**
Date time	**2012-11-16 03:58:28.0 UTC**
Location	**38.62N; 46.84E**
Depth	**10 km**
Distances	76 km NE Tabriz (pop 1,424,641; local time 07:28:28.5 2012-11-16) 25 km NW Ahar (pop 94,348; local time 07:28:28.5 2012-11-16)

Table 4
Seismic events.

Magnitude	**ML 3.1**
Region	**EASTERN TURKEY**
Date time	**2012-11-23 18:28:15.0 UTC**
Location	**38.84N; 43.57 E**
Depth	**5 km**
Distances	169 km SW Yerevan (pop 1,093,485; local time 22:28:15.5 2012-11-23) 42 km N Van (pop 371,713; local time 20:28:15.5 2012-11-23) 27 km SE Ercis (pop 91,915; local time 20:28:15.5 2012-11-23)