Technology and System of Robust Noise Monitoring of Anomalous Seismic Processes

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Abstract— **Robust noise technology for analysis of seismic acoustic signal is offered, which allows using the noise in the signal as a carrier of information in the beginning 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 steel bores of 3-6 kilometers deep suspended oil wells, performing monitoring of the beginning of the latent period of earthquake formation. Experiments, which have been carried out on such 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, proved the reliability and adequacy of results of monitoring and identification of earthquakes within a radius of 300-500 kilometers 10-15 hours before earthquakes are detected by standard seismic stations.**

Keywords— seismic-acoustic system of monitoring; noise; anomalous seismic process; identification; indication; estimate

I. INTRODUCTION

Since 1950-1960s, studies have been carried out to establish causes of earthquakes and tectonic processes that lead to earthquakes [1-4]. Different devices and systems for receiving and processing of seismic signals were created and are created at present [5-9]. New methods of seismic signal processing were gradually developed, as well as new methods of seismic waves identification, and methods for automated extraction of characteristics of seismic signals [10-22]. Attempts were also made to simulate those processes to facilitate analysis of seismic signals [23-25]. Early warning systems have been created and are created up to this day [26-28]. Numerous academic and practical attempts of earthquake prediction have been made [29-33]. Determination of epicenter and hypocenter of earthquakes has been one of the main challenges for seismologists [34-37]. There have also been attempts to receive signals by means of geophones placed at a certain depth to receive seismic waves preceding earthquakes [38, 39].

Unfortunately, those methods do not meet all the requirements and are not widely applied in practice, which is the reason why development of a technology and a system, which would allow one to perform reliable short-term earthquake forecasting, is considered impossible, forming a pessimistic approach to the problem. Unlike the known works, the present paper considers one of the possible ways to deal with the monitoring of the beginning of anomalous seismic processes (ASP) by analyzing 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 deep strata of the earth within a radius of 300-500 km dozens of hours earlier than seismic waves registered by standard seismic stations on the earth's surface. However, conventional technologies of analysis of seismic-acoustic signals received by means of hydrophones at the heads of oil wells it do not allow one to detect the beginning of origin of anomalous seismic processes. The experiments carried out at Qum Island in the Caspian Sea from 01.07.2010 to 01.03.2012 demonstrated that the basics carrier of information about the beginning of anomalous seismic processes preceding an earthquake is noise of seismic-acoustic signals. The paper, therefore, offers technologies of analysis of noise as a carrier of useful information. By means of these technologies, such characteristics as 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 technologies for determination of noise estimates by means of relay correlation functions, which increases adequacy of monitoring results. Charts confirm reliability of results of monitoring performed with application of these technologies.

II. PROBLEM STATEMENT

Seismic monitoring systems do not allow at present to forecast earthquakes with disastrous consequences in due time [42].

Delayed registration of earthquakes by known types of standard ground seismic stations creates a grave problem for countries located in seismically active regions, which in its turn leads to serious casualties.

Outcomes of numerous earthquakes with high death toll and material damage [22] therefore require development of new and more effective technologies and systems for monitoring of the beginning of origin of anomalous seismic processes [40-42], which will allow one to perform short-term earthquake forecasting.

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

Another important problem of the task in question is related to the necessity to develop a technology of analysis of seismic acoustic noise. It is known that the existing conventional technologies of analysis of measurement information yield satisfactory results only under such classical conditions 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. Application of conventional technologies therefore cannot provide sufficient reliability and adequacy of obtained results. Thus, the second important problem of the task in question comes to development of a technology that takes into account peculiarities of a heavily noisy seismic acoustic signal in the period of ASP formation. Here, analysis of noise in 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], the time of normal seismic state T_0 between occasional ASP changes within the range of several weeks or months. The period of time of origin and formation of ASP T_1 can last several hours. The period of time of the critical state T_2, when seismic waves reach the surface of earth and an earthquake occurs, is estimated at minutes, after which a new period of rest T_0 begins. It is therefore appropriate to reduce the problem of monitoring and short-time forecasting of earthquakes to provision of reliable indication of the start of the latent period of ASP origin T_1. The known existing systems and widely applied seismic stations are designated for registration of the start of period T_2. Unfortunately, their functions do not include reliable and adequate monitoring of the start of period T_1, which is one of the graves shortcomings of the modern systems and means of both control and monitoring of seismic processes.

Thereby, let us consider the matter in more detail. Assume that in the normal seismic state in the period of time 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:

$$\omega_{T_0}[g(i\Delta t)] = \frac{1}{\sqrt{2\pi D_g}} e^{-\frac{(g(i\Delta t))^2}{2D_g}} \quad , \quad D_\varepsilon \approx 0 \quad , \quad D_g \approx D_X$$
$$R_{gg}(\mu) \approx R_{XX}(\mu); m_g \approx m_X; m_\varepsilon \approx 0$$

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

where $\omega_{T_0}[g(i\Delta t)]$ is $g(i\Delta t)$ signal distribution law; D_ε, D_X, D_g are the estimates of 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 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 $\varepsilon(i\Delta t)$.

However, when the latent period of ASP origin T_1 begins, the condition (1) is violated, i.e. [6-12]:

$$\omega_{T_0}[g(i\Delta t)] \neq \omega_{T_1}[g(i\Delta t)], \; D_\varepsilon \neq 0 \, , \; D_g \neq D_X$$
$$R_{gg}(\mu) \neq R_{xx}(\mu), \; m_g \neq m_x, \; R_{X\varepsilon}(\mu = 0) \neq 0 \, , r_{X\varepsilon} \neq 0 \tag{2}$$

The period of the normal seismic state T_0 ends and the period of ASP origin T_1 begins. As a result, due to the violation of the equality (1), statistical estimates of the seismic acoustic signal $g(i\Delta t)$ are determined with certain inaccuracy. Therefore, timely detection of the initial stage of ASP origin by means of conventional technologies is complicate in the period of time T_1 [44-48]. Meanwhile, the transition of ASP from the time cell T_1 into the time cell T_2 is registered adequately. Thus, standard seismic stations register the period of time T_2 only when an ASP reaches its critical state, when the earthquake occurs, which explains the delay in results of monitoring and short-term earthquake forecasting by means of conventional technologies. Registration of ASP origin in the period of time T_1 therefore requires development of a technology and a corresponding system, which would allow one to detect the moment of violation of the equality (1) by extracting the information contained in the noise.

With reference to the above-mentioned, solving of the problem of determining the time of ASP origin obviously requires creation of a system of receiving seismic acoustic information from the deep strata of the earth and development of robust noise technology, allowing analysis of noises as carriers of useful information.

The paper considers one of the alternative ways to solve those tasks.

III. Robust Noise Technology of Monitoring of the Beginning of ASP Origin

Theoretical and experimental researches demonstrated that when an ASP originates at the start of time T_1, estimates of noise correlation $R_{X\varepsilon\varepsilon}(\mu=0)$, noise variance D_ε, cross-correlation function $R_{X\varepsilon}(\mu=0)$, coefficient of correlation $r_{X\varepsilon}$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ change in the first place [44, 45]. The reason is that the noise $\varepsilon(i\Delta t)$ emerges due to random external factors, which have no correlation with the useful signal, in the time T_0 in the normal state of seismic processes. However, in the time T_1, when an ASP originates, the noise $\varepsilon(i\Delta t)$ emerges due to the influence of the seismic processes related to its deviation from the normal state. Therefore, in the period of time T_1, correlation arises between the noisy signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ and the inequalities $R_{X\varepsilon}(\mu)\neq 0$, $r_{X\varepsilon}\neq 0$ take place.

Thereby, let us consider one of the alternative methods of approximate calculation of the indicated estimates. For that end, the known expression

$$D_g = R_{gg}(\mu=0)=\frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)g(i\Delta t)=\frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t) \quad (3)$$

can be represented as follows:

$$R_{gg}(\mu=0)=\frac{1}{N}\sum_{i=1}^{N}\left[X(i\Delta t)+\varepsilon(i\Delta t)\right]^2 \quad (4)$$

It is obvious that by opening the brackets we will get the following

$$R_{gg}(\mu=0)=\frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t)+ +\frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\cdot\varepsilon(i\Delta t)\right]+\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t) \quad (5)$$

Assuming the following notations

$$\frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\varepsilon(i\Delta t)\right]+\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t)=R_{X\varepsilon\varepsilon}(\mu=0) \quad (6)$$

$$\frac{1}{N}\sum_{i=1}^{N} X^2(i\Delta t)=R_{XX}(\mu=0) \quad (7)$$

$$\frac{1}{N}\sum_{i=1}^{N} 2\left[X(i\Delta t)\varepsilon(i\Delta t)\right]=2R_{X\varepsilon}(\mu=0) \quad (8)$$

$$\frac{1}{N}\sum_{i=1}^{N}\varepsilon^2(i\Delta t)=R_{\varepsilon\varepsilon}(\mu=0)=D_\varepsilon \quad (9)$$

where $R_{X\varepsilon\varepsilon}(\mu=0)$ is the estimate of noise correlation value, $R_{X\varepsilon}(\mu=0)$ is the estimate of cross correlation function between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, $R_{\varepsilon\varepsilon}(\mu=0)=D_\varepsilon$ is the variance of noise $\varepsilon(i\Delta t)$, we get

$$R_{gg}(\mu=0)=R_{XX}(\mu=0)+2R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0) \quad (10)$$

Thereby, the approximate estimate of noise correlation value $R_{X\varepsilon\varepsilon}(\mu=0)$ and cross correlation function between $R_{X\varepsilon}(\mu=0)$ between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ can be determined by means of the following expressions:

$$R_{X\varepsilon\varepsilon}(\mu=0)=R_{gg}(\mu=0)-R_{XX}(\mu=0) \quad (11)$$

$$2R_{X\varepsilon}(\mu=0)=R_{gg}(\mu=0)-R_{XX}(\mu=0)-R_{\varepsilon\varepsilon}(\mu=0) \quad (12)$$

It is known [42, 43] that that with the corresponding sampling interval Δt and with the equality (1) being true, the following approximate equalities can be regarded as true:

$$\left.\begin{aligned} R_{gg}(\mu=1)&\approx R_{XX}(\mu=1)\\ R_{gg}(\mu=2)&\approx R_{XX}(\mu=2)\\ R_{gg}(\mu=3)&\approx R_{XX}(\mu=3)\end{aligned}\right\} \quad (13)$$

$$\left.\begin{aligned} &\Delta R_{gg}(\mu=1)=R_{gg}(\mu=0)-R_{gg}(\mu=1), \Delta R_{XX}(\mu=1)=R_{XX}(\mu=0)-R_{XX}(\mu=1)\\ &\Delta R_{gg}(\mu=2)=R_{gg}(\mu=1)-R_{gg}(\mu=2)\approx R_{XX}(\mu=1)-R_{XX}(\mu=2)=\Delta R_{XX}(\mu=2)\\ &\Delta R_{gg}(\mu=3)=R_{gg}(\mu=2)-R_{gg}(\mu=3)\approx R_{XX}(\mu=2)-R_{XX}(\mu=3)=\Delta R_{XX}(\mu=3)\end{aligned}\right\} \quad (14)$$

$$\left.\begin{aligned} \Delta R_{gg}(\mu=2)&\approx\Delta R_{XX}(\mu=2)\approx\Delta R_{XX}(\mu=1)\\ \Delta R_{gg}(\mu=3)&\approx\Delta R_{XX}(\mu=3)\approx\Delta R_{XX}(\mu=2)\end{aligned}\right\} \quad (15)$$

Under of equations (12)-(13), the following may be written

$$\left.\begin{aligned} R_{XX}(\mu=0) &= R_{XX}(\mu=1)+\Delta R_{XX}(\mu=1) \\ R_{XX}(\mu=0) &\approx R_{XX}(\mu=1)+\Delta R_{XX}(\mu=2) \end{aligned}\right\} \tag{16}$$

Taking into account expressions (10)-(14), the following may be written

$$\begin{aligned} R_{XX}(\mu=0) &\approx R_{XX}(\mu=1)+\Delta R_{XX}(\mu=1)\approx \\ &\approx R_{gg}(\mu=1)+[R_{gg}(\mu=2)-R_{gg}(\mu=3)] \end{aligned} \tag{17}$$

Expression (10) can therefore be represented as follows

$$\begin{aligned} R_{gg}(\mu=0) &= R_{gg}(\mu=1)+[R_{gg}(\mu=2)- \\ &-R_{gg}(\mu=3)]+2R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0) \end{aligned} \tag{18}$$

Taking into account that $R_{\varepsilon\varepsilon}(\mu=0)$ is the noise variance, the expression (18) can be represented as follows:

$$R_{X\varepsilon}(\mu=0)\approx\frac{1}{2}\left[R_{gg}(\mu=0)-\left[R_{gg}(\mu=1)+\left(R_{gg}(\mu=2)-R_{gg}(\mu=3)\right)\right]-D_\varepsilon\right] \tag{19}$$

The value of noise correlation $R_{X\varepsilon\varepsilon}(\mu=0)$ can be determined by means of the following expression

$$\begin{aligned} R_{X\varepsilon\varepsilon}(\mu=0) &= \frac{1}{2}\left[R_{gg}(\mu=0)-\left[R_{gg}(\mu=1)+\left(R_{gg}(\mu=2)-R_{gg}(\mu=3)\right)\right]\right]= \\ &= \frac{1}{2N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t)-\left[g(i\Delta t)g((i+1)\Delta t)+g(i\Delta t)g((i+2)\Delta t)-g(i\Delta t)g((i+3)\Delta t)\right]\right] \end{aligned} \tag{20}$$

It should be noted that the following expression can be used to calculate the estimate of noise variance in the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$

$$D_\varepsilon=\frac{1}{N}\sum_{i=1}^{N}\left[g(i\Delta t)g(i\Delta t)-2g(i\Delta t)g(i+2)\Delta t+g(i\Delta t)g(i+1)\Delta t\right] \tag{21}$$

In the presence of correlation, however, it is inappropriate to use this formula for determination of the estimate of the noise variance D_ε. The technology of determination of the estimate of the noise variance D_ε will therefore be considered in the following paragraphs.

In expressions (19), (20), readings of $g(i\Delta t)$, $g((i+1)\Delta t)$, $g((i+2)\Delta t)$, $g((i+3)\Delta t)$ are used to calculate the required estimates, similarly to the traditional algorithm. Formulas (19), (20) are therefore easily implemented in practice on widely used controllers and on personal computers. Naturally, after determination of the estimates of the noise variance D_ε, it will be also possible to calculate the coefficient of correlation $r_{X\varepsilon}$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, if necessary.

It is clear that in the period of time T_0 in the monitoring of ASP origin, estimates of the noise correlation $R^*_{X\varepsilon\varepsilon}(\mu=0)$, cross-correlation function $R_{X\varepsilon}(\mu=0)$ and the coefficient of correlation $r_{X\varepsilon}$ between the useful signal and the noise of the acoustic signal received from the deep strata of the earth will be close to zero due to the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. It is also obvious that when an ASP originates in the period of time T_1, the value of noise correlation estimate $R_{X\varepsilon\varepsilon}(\mu=0)$ will increase sharply due to the emergence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. Thus, the estimate $R_{X\varepsilon\varepsilon}(\mu=0)$ will be different from zero from the very start in the whole course of ASP, reflecting the presence of correlation.

IV. Technology of Determination of Estimates of Cross-Correlation Function and Coefficient of Correlation Between the Useful Seismic Acoustic Signal and Its Noise

Let us now consider one of possible methods of determination of cross-correlation function $R_{X\varepsilon}(\mu=0)$ between the useful seismic acoustic signal $X(i\Delta t)$ and its noise $\varepsilon(i\Delta t)$ using the technology of calculation of estimates of relay correlation functions $R^*_{gg}(\mu=0)$. For that end, let us first assume the following notations:

$$\operatorname{sgn} g(i\Delta t)=\operatorname{sgn} x(i\Delta t)=\begin{Bmatrix} 1, & g(i\Delta t)\ge 0 \\ 0, & g(i\Delta t)<0 \end{Bmatrix} \tag{22}$$

$$\left.\begin{aligned} &\frac{1}{N}\sum_{i=1}^{N} Sgn\, g(i\Delta t)\cdot\varepsilon(i+\mu)\Delta t=0, && \mu=0 \\ &\frac{1}{N}\sum_{i=1}^{N} Sgn\, g(i\Delta t)\cdot\varepsilon(i+\mu)\Delta t\ne 0, && \mu\ne 0 \\ &\frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\cdot\varepsilon(i\Delta t)\ne 0, && \mu=0 \\ &\frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\cdot\varepsilon(i+\mu)=0, && \mu\ne 0 \end{aligned}\right\} \tag{23}$$

The formula for determination of estimates of relay correlation functions $R^*_{gg}(\mu = 0)$ in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ can be represented as follows:

$$R^*_{gg}(\mu=0) = \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t) g(i\Delta t) = \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\cdot[X(i\Delta t) + \varepsilon(i\Delta t)] =$$

$$= \frac{1}{N}\sum_{i=1}^{N} [[\operatorname{sgn} g(i\Delta t)\cdot X(i\Delta t)] + [\operatorname{sgn} g(i\Delta t)\cdot \varepsilon(i\Delta t)]] =$$

$$= \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t) X(i\Delta t) + \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\cdot \varepsilon(i\Delta t) =$$

$$= \frac{1}{N}\sum \operatorname{sgn} X(i\Delta t) X(i\Delta t) + \frac{1}{N}\sum_{1} \operatorname{sgn} X(i\Delta t)\varepsilon(i\Delta t) = R^*_{XX}(\mu=0) + R^*_{X\varepsilon}(\mu=0) \tag{24}$$

It is known [42-48] that in the absence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, with conditions (22), (23) taken into account, the following approximate equalities can be regarded as true for estimates of relay correlation function:

$$R^*_{gg}(\mu=0) - R^*_{gg}(\mu=1) \approx R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2) \approx$$
$$\approx R^*_{gg}(\mu=2) - R^*_{gg}(\mu=3) \approx R^*_{gg}(\mu=3) - R^*_{gg}(\mu=4) \tag{25}$$

$$R^*_{XX}(\mu=0) - R^*_{XX}(\mu=1) \approx R^*_{XX}(\mu=1) - R^*_{XX}(\mu=2) \approx$$

$$\approx R^*_{XX}(\mu=2) - R^*_{XX}(\mu=3) \approx R^*_{XX}(\mu=3) - R_{XX}(\mu=4) \tag{26}$$

$$\Delta^* R_{gg}(\mu=0) \approx \Delta R^*_{gg}(\mu=1) \approx \Delta R^*_{gg}(\mu=2) \approx \Delta R^*_{gg}(\mu=3) \tag{27}$$

$$\Delta^* R_{XX}(\mu=0) = \Delta R^*_{XX}(\mu=1) \approx \Delta R_{XX}(\mu=1) \approx \Delta^* R_{XX}(\mu=2) \approx \Delta R^*_{XX}(\mu=3) \tag{28}$$

At the same time, when correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ takes place, the following expressions can be regarded as true

$$\Delta R^*_{gg}(\mu=0) - \Delta R_{gg}(\mu=1) \neq \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=2) \tag{29}$$

$$\left.\begin{array}{l} \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=2) \approx \Delta R_{gg}(\mu=2) - \Delta R_{gg}(\mu=3) \approx \Delta R_{gg}(\mu=3) - \Delta R_{gg}(\mu=4) \approx 0 \\ \Delta R_{XX}(\mu=1) - \Delta R_{XX}(\mu=2) \approx \Delta R_{gg}(\mu=2) - \Delta R_{gg}(\mu=3) \approx \Delta R_{gg}(\mu=3) - \Delta R_{gg}(\mu=4) \approx 0 \end{array}\right\} \tag{30}$$

It follows from the equality (24) that the estimate of relay correlation function $R^*_{X\varepsilon}(\mu=0)$ can be determined from the formula:

$$\Delta R^*_{gg}(\mu=0) \approx R^*_{XX}(\mu=0) + R^*_{X\varepsilon}(\mu=0) \tag{31}$$

$$R^*_{X\varepsilon}(0) \approx R_{gg}(\mu=0) - R_{XX}(\mu=0) \tag{32}$$

To calculate $R^*_{X\varepsilon}(\mu=0)$ by means of the expression (32), $R_{XX}(\mu=0)$ must be calculated. The equalities (24)–(29) imply that the estimate $R^*_{XX}(\mu=0)$ can be calculated by means of the following expression

$$R^*_{XX}(\mu=0) \approx R^*_{XX}(\mu=1) + \Delta R^*_{XX}(\mu=1) \approx R^*_{gg}(\mu=1) + \Delta R^*_{gg}(\mu=1) \approx R^*_{gg}(\mu=1) +$$

$$+ \left[R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2)\right] = 2R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2) \tag{33}$$

Thus, the expression (32) can represented as follows:

$$R^*_{X\varepsilon}(\mu=0) = R^*_{gg}(\mu=0) - \left[2R^*_{gg}(\mu=1) - R^*_{gg}(\mu=2)\right] =$$
$$= R^*_{gg}(\mu=0) - 2R^*_{gg}(\mu=1) + R^*_{gg}(\mu=1) \tag{34}$$

The expression for calculation of the estimate of relay cross-correlation function $R^*_{X\varepsilon}(\mu=0)$ between the useful seismic acoustic signal $X(i\Delta t)$ and its noise $\varepsilon(i\Delta t)$ can therefore be written as follows:

$$R^*_{X\varepsilon}(\mu=0) \approx \frac{1}{N}\sum_{i=1}^{N} [\operatorname{sgn} g(i\Delta t) g(i\Delta t) -$$
$$- 2\operatorname{sgn} g(i\Delta t) g((i+1)\Delta t) + \operatorname{sgn} g(i\Delta t) g((i+2)\Delta t)] \tag{35}$$

As was indicated above, in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, it is impossible to determine estimates of noise variance D_ε of the seismic acoustic signal $g(i\Delta t)$, using the expression (21). Accordingly, we should consider the possibility of determining it by means of estimates $R_{X\varepsilon\varepsilon}(\mu=0)$, $R^*_{X\varepsilon}(\mu=0)$ and estimates of differences $\Delta R_{gg}(\mu=0)$ and $\Delta R^*_{gg}(\mu=0)$ in more detail.

Taking into account the conditions (25) – (30) and equalities (33) – (35), the following can be written:

$$\left.\begin{array}{l} R^*_{X\varepsilon}(\mu=0)+\Delta R^*_{XX}(\mu=0)\approx \Delta R^*_{gg}(\mu=0) \\ R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)+\Delta R_{XX}(\mu=0)\approx \Delta R_{gg}(\mu=0) \\ R_{X\varepsilon}(\mu=0)+R_{\varepsilon\varepsilon}(\mu=0)+\Delta R_{gg}(\mu=1)\approx \Delta R_{gg}(\mu=0) \end{array}\right\}. \tag{36}$$

It is known [48] that the correlation between the estimates $R^*_{X\varepsilon}(\mu=0)$; $R^*_{XX}(\mu=1)$ and $R_{X\varepsilon}(\mu=0)$; $\Delta R_{XX}(\mu=1)$, as well as the correlation between the estimates $R^*_{X\varepsilon}(\mu=0)$; $\Delta R^*_{gg}(\mu=1)$ and $R_{X\varepsilon}(\mu=0)$; $\Delta R_{gg}(\mu=1)$, allow one to assume that the following approximate equalities are true:

$$\left.\begin{array}{l} \dfrac{R^*_{X\varepsilon}(\mu=0)}{\Delta R^*_{XX}(\mu=1)}\approx\dfrac{R_{X\varepsilon}(\mu=0)}{\Delta R_{XX}(\mu=1)} \\ \dfrac{R^*_{X\varepsilon}(\mu=0)}{\Delta R^*_{gg}(\mu=1)}\approx\dfrac{R_{X\varepsilon}(\mu=0)}{\Delta R_{gg}(\mu=1)} \end{array}\right\} \tag{37}$$

In this case, we obtain the following equality: $R_{X\varepsilon}(\mu=0)\Delta R^*_{gg}(\mu=1)\approx R^*_{X\varepsilon}(\mu=0)\Delta R_{gg}(\mu=1)$.

Thus, in the presence of correlation between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$, the estimate $R_{X\varepsilon}(0)$ can be determined from the formula:

$$R_{X\varepsilon}(\mu=0)\approx\frac{R^*_{X\varepsilon}(\mu=0)\cdot\Delta R_{gg}(\mu=1)}{\Delta R^*_{gg}(\mu=1)} \tag{38}$$

It is clear that after the estimate $R_{X\varepsilon}(0)$ is determined, the estimate of noise variance D_ε can be determined both by means of the expression:

$$D_\varepsilon=R_{\varepsilon\varepsilon}(\mu=0)\approx\Delta R_{gg}(\mu=0)-\Delta R_{gg}(\mu=1)-R_{X\varepsilon}(\mu=0) \tag{39}$$

and by means of the expression:

$$D_\varepsilon=R_{X\varepsilon\varepsilon}(\mu=0)-R_{X\varepsilon}(\mu=0) \tag{40}$$

where $R_{X\varepsilon\varepsilon}$ is determined from the formula (20). It should be noted that when the conditions

$$\left\{\begin{array}{l} \dfrac{1}{N}\sum\limits_{i=1}^{N}g(i\Delta t)\varepsilon((i+1)\Delta t)\neq 0 \\ \dfrac{1}{N}\sum\limits_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon((i+1)\Delta t)=0 \end{array}\right. \tag{41}$$

do not take place for actual noisy signals, i.e. when

$$R_{X\varepsilon}(\mu=1)\neq 0 \tag{42}$$

then, assuming that the following equality is true

$$R_{X\varepsilon}(\mu=0)\approx R_{X\varepsilon}(\mu=1) \tag{43}$$

it can be demonstrated that even in the presence of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the expression (21) can be used for calculation of the approximate estimate of noise variance.

On the other hand, when the equality $R_{X\varepsilon}(\mu=1)\approx 0$ is true, then the estimate D_ε calculated from the expression (21) will be close to the estimate of noise correlation $R_{X\varepsilon\varepsilon}(0)$ calculated from the expression (20).

Naturally, having $R_{X\varepsilon}(\mu=0)$, D_ε , $R_{XX}(\mu=0)$ available, one can calculate the coefficient of correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, using the expression:

$$r_{X\varepsilon}\approx\frac{R_{X\varepsilon}(\mu=0)}{\sqrt{R_{XX}(\mu=0)\cdot D_\varepsilon}} \tag{44}$$

Experimental research demonstrated that with sampling interval $f=2000$ Hz, the following inequality takes place for the difference of estimates $R_{gg}(\mu)$ of the noisy seismic acoustic signal $g(i\Delta t)$

$$\begin{array}{l}\Delta R_{gg}(\mu=0)>\Delta R_{gg}(\mu=1)>\Delta R_{gg}(\mu=2)> \\ >\Delta R_{gg}(\mu=3)>\Delta R_{gg}(\mu=4)\approx\Delta R_{gg}(\mu=5)\approx\Delta R_{gg}(\mu=6)\end{array} \tag{45}$$

Here, taking into account that

$$\begin{cases} \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon(i\Delta t) = R_{\varepsilon\varepsilon}(\mu=0) = D_\varepsilon \\ \frac{1}{N}\sum_{i=1}^{N}\varepsilon(i\Delta t)\varepsilon(i+1)\Delta t = R_{\varepsilon\varepsilon}(\mu=1) = 0 \end{cases} \quad (46)$$

the differences of estimates

$\Delta R_{gg}(\mu=0)$, $\Delta R_{gg}(\mu=1)$,..., $\Delta R_{gg}(\mu=6)$ can be represented as follows:

$$\begin{cases} \Delta R_{gg}(\mu=0) \approx \Delta R_{XX}(\mu=0) + R_{\varepsilon\varepsilon}(\mu=0) + 2R_{X\varepsilon}(\mu=0) \\ \Delta R_{gg}(\mu=1) \approx \Delta R_{XX}(\mu=1) + 2R_{X\varepsilon}(\mu=1) \\ \Delta R_{gg}(\mu=2) \approx \Delta R_{XX}(\mu=2) + 2R_{X\varepsilon}(\mu=2) \\ \Delta R_{gg}(\mu=3) \approx \Delta R_{XX}(\mu=3) + 2R_{X\varepsilon}(\mu=3) \\ \Delta R_{gg}(\mu=4) \approx \Delta R_{XX}(\mu=4) \\ \Delta R_{gg}(\mu=5) \approx \Delta R_{XX}(\mu=5) \\ \Delta R_{gg}(\mu=6) \approx \Delta R_{XX}(\mu=6) \end{cases} \quad (47)$$

The experiments have shown that for the case under consideration, between the estimates

$R_{X\varepsilon}(\mu=0), R_{X\varepsilon}(\mu=1), R_{X\varepsilon}(\mu=2), R_{X\varepsilon}(\mu=3), R_{X\varepsilon}(\mu=4), R_{X\varepsilon}(\mu=5), R_{X\varepsilon}(\mu=6)$

$$\begin{cases} \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\varepsilon(i\Delta t) \approx R_{g\varepsilon}(\mu=0) \approx R_{X\varepsilon}(\mu=0) \neq 0 \\ \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\varepsilon(i+1)\Delta t \approx R_{g\varepsilon}(\mu=1) \approx R_{X\varepsilon}(\mu=1) \neq 0 \\ \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\varepsilon(i+2)\Delta t \approx R_{g\varepsilon}(\mu=2) \approx R_{X\varepsilon}(\mu=2) \neq 0 \\ \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\varepsilon(i+3)\Delta t \approx R_{g\varepsilon}(\mu=3) \approx R_{X\varepsilon}(\mu=3) \neq 0 \\ \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\varepsilon(i+4)\Delta t \approx R_{g\varepsilon}(\mu=4) \approx R_{X\varepsilon}(\mu=4) \approx 0 \\ \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t)\varepsilon(i+5)\Delta t \approx R_{g\varepsilon}(\mu=5) \approx R_{X\varepsilon}(\mu=5) \approx 0 \end{cases}$$

(48)

the following relation take place

$$R_{X\varepsilon}(\mu=0) \geq R_{X\varepsilon}(\mu=1) > R_{X\varepsilon}(\mu=2) > R_{X\varepsilon}(\mu=3) >$$
$$> R_{X\varepsilon}(\mu=4) \approx R_{X\varepsilon}(\mu=5) \approx R_{X\varepsilon}(\mu=6) \approx 0$$

(49)

Thus, according to the expressions (45)-(49), the formulae for calculating the estimates $D_\varepsilon, R_{X\varepsilon}(\mu=0)$ and $R_{X\varepsilon\varepsilon}(\mu=0)$ can be represented as follows:

$$\begin{cases} \Delta R_{gg}(\mu=0) - \Delta R_{gg}(\mu=1) \approx D_\varepsilon \\ \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=4) \approx \Delta R_{gg}(\mu=1) - \Delta R_{XX}(\mu=4) \approx 2R_{X\varepsilon}(\mu=0) \\ \Delta R_{gg}(\mu=0) - \Delta R_{gg}(\mu=4) \approx \Delta R_{gg}(\mu=0) - \Delta R_{XX}(\mu=4) \approx R_{X\varepsilon\varepsilon}(\mu=0) \end{cases}$$

(50)

It should be noted that prior information allows one to assume that the approximate expressions (45)-(50) hold true for noisy process variables in prevailing technical objects. These formulae can therefore find wide practical application due to their simplicity and convenience in implementation for determining the estimates $D_\varepsilon, R_{X\varepsilon}(\mu=0)$ and $R_{X\varepsilon\varepsilon}(\mu=0)$, i.e. they are of vital applied importance.

The carried out research showed that, taking into consideration high reliability and adequacy requirements of ASP monitoring results, it is appropriate to carry out the analysis of seismic acoustic noise with parallel application of several technologies. Thereby, offered below are several technologies, which are applied side by side, allowing one to obtain informative attributes for indication of the start of ASP origin.

V. Robust Spectral Indicators of ASP Origin

The following is speculation on the possibility of indication of the start of ASP origin by means of the robust spectral analysis technology.

As was mentioned before, spectral characteristics of the signal $g(i\Delta t)$ do not change in the normal seismic state during the period of time T_0. It is also obvious that at the start of time T_1, when anomalous seismic processes (ASP) originate, spectra of both the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ of the noisy seismic acoustic signal $g(i\Delta t)$ change. Analyses showed that when spectral methods of monitoring at the start of time T_1 of ASP, it is appropriate to use as informative attributes estimates a_ω^*, b_ω^*; a_ω^{**}, b_ω^{**} for the spectrum ω^* of the signal $g(i\Delta t)$, for which the following conditions are true in the normal state during the period of time T_0:

$$\left.\begin{aligned} a^{*}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N} g(i\Delta t)\cos\omega^{*}(i\Delta t) \geq 0 \\ b^{*}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N} g(i\Delta t)\sin\omega^{*}(i\Delta t) \geq 0 \end{aligned}\right\} \quad (51)$$

$$\left.\begin{aligned} a^{**}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\operatorname{sgn}\cos\omega^{*}(i\Delta t) \approx 0 \\ b^{**}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\operatorname{sgn}\sin\omega^{*}(i\Delta t) \approx 0 \end{aligned}\right\} \quad (52)$$

where a^{*}_{ϖ}, b^{*}_{ϖ}; a^{**}_{ϖ}, b^{**}_{ϖ} are coefficient of the spectrum ω^{*}, which are close to zero in the time cell T_0.

It will be demonstrated below that informative value of estimates of the spectrum with frequency ω^{*} is explained by the fact that inaccuracy of obtained results is reduced to the minimum in that case. Those important properties allow one to use them as a reliable indicator of the beginning of ASP origin. In this respect, let us consider the peculiarity of characteristics of those spectra. It is clear that in the normal seismic state in the time cell T_0, estimates $a^{*}_{\omega T_0}$, $b^{*}_{\omega T_0}$, $a^{**}_{\omega T_0}$, $b^{**}_{\omega T_0}$ of the signal $g(i\Delta t)$ can be represented as:

$$\left.\begin{aligned} a^{*}_{\omega T_0} &= a_{\omega T_0}{}^{++} + a^{--}_{\omega T_0} - (a^{+-}_{\omega T_0} + a^{-+}_{\omega T_0}) \\ a^{0*}_{\omega T_0} &= a_{\omega T_0}{}^{++} + a^{--}_{\omega T_0} - (a^{+-}_{\omega T_0} + a^{-+}_{\omega T_0}) \end{aligned}\right\} \quad (53)$$

$$\left.\begin{aligned} a^{**}_{\omega T_0} &= a'^{++}_{\omega T_0} + a'^{--}_{\omega T_0} - (a'^{+-}_{\omega T_0} + a'^{-+}_{\omega T_0}) \\ a^{**}_{\omega T_0} &= a_{\omega T_0}{}'^{++} + a'^{--}_{\omega T_0} - (a'^{+-}_{\omega T_0} + a'^{-+}_{\omega T_0}) \end{aligned}\right\} \quad (54)$$

where $a^{++}_{\omega T_0}$, $a^{--}_{\omega T_0}$, $a^{+-}_{\omega T_0}$, $a^{-+}_{\omega T_0}$, $b^{++}_{\omega T_0}$, $b^{--}_{\omega T_0}$, $b^{+-}_{\omega T_0}$, $b^{-+}_{\omega T_0}$, $a_{\omega T_0}{}'^{++}$, $a'^{--}_{\omega T_0}$, $a'^{+-}_{\omega T_0}$, $a'^{-+}_{\omega T_0}$ are determined from the following expressions:

$$\left.\begin{aligned} a^{++}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\cos^{+}\omega^{*}(i\Delta t) \\ a^{--}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{--}}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\cos^{-}\omega^{*}(i\Delta t) \\ a^{+-}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\cos^{-}\omega^{*}(i\Delta t) \\ a^{-+}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\cos^{+}\omega^{*}(i\Delta t) \end{aligned}\right\} \quad (55)$$

$$\left.\begin{aligned} b^{++}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\sin^{+}\omega^{*}(i\Delta t) \\ b^{--}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{--}}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\sin^{-}\omega^{*}(i\Delta t) \\ b^{+-}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\sin^{-}\omega^{*}(i\Delta t) \\ b^{-+}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\sin^{+}\omega^{*}(i\Delta t) \end{aligned}\right\}$$

$$\left.\begin{aligned} a'^{++}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\operatorname{sgn}\cos^{+}\omega^{*}(i\Delta t) \\ a'^{--}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{--}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\operatorname{sgn}\cos^{-}\omega^{*}(i\Delta t) \\ a'^{+-}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\operatorname{sgn}\cos^{-}\omega^{*}(i\Delta t) \\ a'^{-+}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\operatorname{sgn}\cos^{+}\omega^{*}(i\Delta t) \end{aligned}\right\} \quad (56)$$

$$\left.\begin{aligned} b'^{++}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\operatorname{sgn}\sin^{+}\omega^{*}(i\Delta t) \\ b'^{--}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{--}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\operatorname{sgn}\sin^{-}\omega^{*}(i\Delta t) \\ b'^{+-}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{+}(i\Delta t)+\varepsilon^{+}(i\Delta t)\right]\operatorname{sgn}\sin^{-}\omega^{*}(i\Delta t) \\ b'^{-+}_{\omega T_0} &= \frac{2}{N}\sum_{i=1}^{N^{++}}\operatorname{sgn}\left[\overset{\circ}{X}{}^{-}(i\Delta t)+\varepsilon^{-}(i\Delta t)\right]\operatorname{sgn}\sin^{+}\omega^{8}(i\Delta t) \end{aligned}\right\}$$

where N^{++}, N^{--}, N^{+-}, N^{-+} are the quantity of products $g(i\Delta t)\cos\omega^*(i\Delta t)$, $g(i\Delta t)\sin\omega^*(i\Delta t)$ with signs of multipliers ++, – –, + –, – + respectively.

It can be shown that results obtained from the expressions (47) – (50) will not change in the stable normal seismic state during the time cell T_0, which is due to the fact that according to the expressions (51), (52), the quantity of products $g(i\Delta t)\cos\omega^*(i\Delta t)$, $g(i\Delta t)\sin\omega^*(i\Delta t)$ with positive and negative signs will be equal in the period of time T_0. Errors of products caused by $\varepsilon(i\Delta t)$ will therefore compensate one another, i.e.

$$\lambda^*_{a_\omega} \approx \frac{2}{N}\left[\sum_{i=1}^{N^{++}}\left[\varepsilon^+(i\Delta t)\cos^+\omega^*(i\Delta t)\right]+\left[\varepsilon^-(i\Delta t)\cos^-\omega^*(i\Delta t)\right]\right]-$$
$$-\left[\sum_{i=1}^{N^{+-}}\left[\varepsilon^+(i\Delta t)\cos^-\omega^*(i\Delta t)\right]+\left[\varepsilon^-(i\Delta t)\cos^+\omega^*(i\Delta t)\right]\right]\approx 0 \tag{57}$$

$$\lambda^*_{b_\omega} \approx \frac{2}{N}\left[\sum_{i=1}^{N^{++}}\left[\varepsilon^+(i\Delta t)\sin^+\omega^*(i\Delta t)\right]+\left[\varepsilon^-(i\Delta t)\sin^-\omega^*(i\Delta t)\right]\right]-$$

$$-\left[\sum_{i=1}^{N^{--}}\left[\varepsilon^+(i\Delta t)\sin^-\omega^*(i\Delta t)\right]+\left[\varepsilon^-(i\Delta t)\sin^+\omega^*(i\Delta t)\right]\right]\approx 0 \tag{58}$$

For this reason, the start of time T_1 of ASP origin is reflected in the given estimates fault-free. On the other hand, errors in estimates of other spectra are commensurable at that moment with changes in the characteristic of the signal $g(i\Delta t)$. Thereby, estimates a_n, b_n of other spectra in the monitoring of transition from the time cell T_0 into the time cell T_1 do not possess such degree of sensitivity. Thus, results of the analysis obtained from the expressions (45)-(46) can be used as spectral noise indicators of the origin of the center of a powerful earthquake. This is due to the fact that during ASP origin, when the signal enters the time cell T_1 and proceeds further to T_2, T_3, characteristics of the noise $\varepsilon(i\Delta t)$ change, the normalcy of distribution law is violated, correlation between the useful signal $X(i\Delta t)$ and the noise is different from zero, etc. From that moment, changes in the estimates $a^{++}_{\omega T_0}$, $a^{--}_{\omega T_0}$, $a^{+-}_{\omega T_0}$, $a^{-+}_{\omega T_0}$, $b^{++}_{\omega T_0}$, $b^{--}_{\omega T_0}$, $b^{+-}_{\omega T_0}$, $b^{-+}_{\omega T_0}$, $a_{\omega T_0}{}^{'++}$, $a_{\omega T_0}{}^{'--}$, $a_{\omega T_0}{}^{'+-}$, $a_{\omega T_0}{}^{'-+}$, $b_{\omega T_0}{}^{'++}$, $b_{\omega T_0}{}^{'--}$, $b_{\omega T_0}{}^{'+-}$, $b_{\omega T_0}{}^{'-+}$ prove to be inevitable and become a source of forecasting. For instance, if $g(i\Delta t)$ is subject to the normal law, then the following equalities will be true in the normal state of the object under monitoring, according to the conditions (45), (46), (51), (52):

$$\left.\begin{array}{l} a^{++}_{\omega T_0}\approx a^{--}_{\omega T_0}\\ a^{+-}_{\omega T_0}\approx a^{-+}_{\omega T_0}\\ b^{++}_{\omega T_0}\approx b^{--}_{\omega T_0}\\ b^{+-}_{\omega T_0}\approx b^{-+}_{\omega T_0}\end{array}\right\},\quad \left.\begin{array}{l} a'^{++}_{\omega T_0}\approx a'^{--}_{\omega T_0}\\ a'^{+-}_{\omega T_0}\approx a'^{-+}_{\omega T_0}\\ b'^{++}_{\omega T_0}\approx b'^{--}_{\omega T_0}\\ b'^{+-}_{\omega T_0}\approx b'^{-+}_{\omega T_0}\end{array}\right\} \tag{59}$$

At the beginning of change in the seismic situation at the start of the time cell T_1, the normalcy of distribution law is violated, the equalities (59) being transformed into inequalities:

$$\left.\begin{array}{l} a^{++}_{\omega T_1}\neq a^{--}_{\omega T_1}\\ b^{++}_{\omega T_1}\neq b^{--}_{\omega T_1}\\ a^{+-}_{\omega T_1}\neq a^{-+}_{\omega T_1}\\ b^{+-}_{\omega T_1}\neq b^{-+}_{\omega T_1}\end{array}\right\},\quad \left.\begin{array}{l} a'^{++}_{\omega T_1}\neq a'^{--}_{\omega T_1}\\ b'^{++}_{\omega T_1}\neq b'^{--}_{\omega T_1}\\ a'^{+-}_{\omega T_1}\neq a'^{-+}_{\omega T_1}\\ b'^{+-}_{\omega T_1}\neq b'^{-+}_{\omega T_1}\end{array}\right\} \tag{60}$$

which leads to the following differences:

$$\left.\begin{array}{l} \Delta a^{++}_{\omega T_1}=a^{++}_{\omega T_0}-a^{--}_{\omega T_1}\\ \Delta a^{+-}_{\omega T_1}=a^{+-}_{\omega T_1}-a^{-+}_{\omega T_1}\\ \Delta b^{++}_{\omega T_1}=b^{++}_{\omega T_1}-b^{--}_{\omega T_1}\\ \Delta b^{+-}_{\omega T_1}=b^{+-}_{\omega T_1}-b^{-+}_{\omega T_1}\end{array}\right\},\quad \left.\begin{array}{l} \Delta a'^{++}_{\omega T_1}=a'^{++}_{\omega T_1}-a'^{--}_{\omega T_1}\\ \Delta a'^{+-}_{\omega T_1}=a'^{+-}_{\omega T_1}-a'^{-+}_{\omega T_1}\\ \Delta b'^{++}_{\omega T_1}=b'^{++}_{\omega T_1}-b'^{--}_{\omega T_1}\\ \Delta b'^{+-}_{\omega T_1}=b'^{+-}_{\omega T_1}-b'^{-+}_{\omega T_1}\end{array}\right\} \tag{61}$$

$$\left.\begin{array}{l} \Delta a_{\omega T_1}=\left(a^{++}_{\omega T_1}+a^{--}_{\omega T_1}\right)-\left(a^{+-}_{\omega T_1}+a^{-+}_{\omega T_1}\right)\\ \Delta b_{\omega T_1}=\left(b^{++}_{\omega T_1}+b^{--}_{\omega T_1}\right)-\left(b^{+-}_{\omega T_1}+b^{-+}_{\omega T_1}\right)\\ \Delta a'_{\omega T_1}=\left(a'^{++}_{\omega T_1}+a'^{--}_{\omega T_1}\right)-\left(a'^{+-}_{\omega T_1}+a'^{-+}_{\omega T_1}\right)\\ \Delta b'_{\omega T_1}=\left(b'^{++}_{\omega T_1}+b'^{--}_{\omega T_1}\right)-\left(b'^{+-}_{\omega T_1}+b'^{-+}_{\omega T_1}\right)\end{array}\right\} \tag{62}$$

reflecting the information on the start of violation of normal seismic state, owing to which they can be regarded as reliable indicators of the start of ASP origin.

On the basis of the equalities (61), (62), the expressions determining the estimates of spectral noise indicators $\Delta a^*_{\omega T_0 T_1}$, $\Delta b^*_{\omega T_0 T_1}$, $\Delta a^{**}_{\omega T_0 T_1}$, $\Delta b^{**}_{\omega T_0 T_1}$ can also be reduced to the following form:

$$\begin{aligned} \Delta a^{*}_{\omega T_0 T_1} &= a^{*}_{\omega T_0} - a^{*}_{\omega T_1} \\ \Delta b^{*}_{\omega T_0 T_1} &= b^{*}_{\omega T_0} - b^{*}_{\omega T_1} \\ \Delta a^{**}_{\omega T_0 T_1} &= a^{**}_{\omega T_0} - a^{**}_{\omega T_1} \\ \Delta b^{**}_{\omega T_0 T_1} &= b^{**}_{\omega T_0} - b^{**}_{\omega T_1} \end{aligned} \quad (63)$$

It is obvious from the above-given that obtained estimates of indicators $\Delta a^{*}_{\omega T_0 T_1}$, $\Delta b^{*}_{\omega T_0 T_1}$, $\Delta a^{**}_{\omega T_0 T_1}$, $\Delta b^{**}_{\omega T_0 T_1}$ have robustness property, allowing reliable detection of the moment of transition of ASP from the time cell T_0 into the time cell T_1, since they will change in the first place. It is therefore reasonable to use them as reliable indicators of ASP origin, too.

VI. Robust Correlation Indicators of the Beginning of ASP Origin

Let us consider the possibility of registration of the beginning of the period T_1 of ASP from estimates of auto- and cross-correlation functions $R_{gg}(\mu)$ and $R_{g_j g_\nu}(\mu)$. Analysis of the peculiarity of calculation of those estimates demonstrates that their inaccuracy depends on the change in the spectrum of the noise $\varepsilon(i\Delta t)$, which is why they do not meet the conditions of robustness [42, 49]. However, with increase of time shift $\mu \cdot \Delta t$ between $g(i\Delta t)$ and $g((i+\mu)\Delta t)$, as well as between $g_j(i\Delta t)$ and $g_\nu((i+\mu)\Delta t)$, there comes a moment when obtained estimates turn out to be equal to zero. If we denote that time shift by $\mu' \cdot \Delta t$, the following obvious equalities will take place:

$$R_{gg}(\mu') = \frac{1}{N}\sum_{i=1}^{N} g(i\Delta t) g((i+\mu')\Delta t) \approx 0 \quad (64)$$

$$R_{g_j g_\nu}(\mu') = \frac{1}{N}\sum_{i=1}^{N} g_j(i\Delta t) g_\nu((i+\mu')\Delta t) \approx 0 \quad (65)$$

With the time shift $\mu' \cdot \Delta t$, inaccuracy of estimates $R_{gg}(\mu)$ forms from the sum of errors of products $g(i\Delta t) g((i+\mu')\Delta t)$ with positive and negative signs in the quantity N^{+}, N^{-} respectively. Only in that case, the equality $N^{+} = N^{-}$ takes place. Owing to that, the condition of robustness holds true, positive and negative errors of products practically compensate one another. The following equality can therefore be regarded as true:

$$\begin{aligned} R^{+}_{gg}(\mu = \mu') &\approx \frac{1}{N}\sum_{i=1}^{N^{+}} g(i\Delta t) g((i+\mu')\Delta t) = \\ &= \frac{1}{N}\sum_{i=1}^{N^{-}} g(i\Delta t) g((i+\mu')\Delta t) \approx R^{-}_{gg}(\mu = \mu') \end{aligned} \quad (66)$$

It is clear that estimates of cross-correlation functions, i.e. $R_{g_j g_\nu}(\mu')$ will also have robustness property and the following can also be written for them:

$$R^{+}_{g_j g_\nu}(\mu = \mu') = R^{-}_{g_j g_\nu}(\mu = \mu') \quad (67)$$

With the reference to the above-mentioned, the equalities (60), (61) will be violated at the moment of start of the period T_1 of ASP, i.e.

$$R^{+}_{gg}(\mu = \mu') \neq R^{-}_{gg}(\mu = \mu'),\ R^{+}_{g_j g_\nu}(\mu = \mu') \neq R^{-}_{g_j g_\nu}(\mu = \mu') \quad (68)$$

Estimates obtained in the time shift $\mu = \mu'\Delta t$ will therefore be different from zero at the start of ASP origin, i.e.

$$R_{gg}(\mu') = R^{+}_{gg}(\mu') - R^{-}_{gg}(\mu') \neq 0 \quad (69)$$

$$R_{g_j g_\nu}(\mu') = R^{+}_{g_j g_\nu}(\mu') - R^{-}_{g_j g_\nu}(\mu') \neq 0 \quad (70)$$

Thus, in virtue of the equalities (66), (67), the influence of the noise on the obtained estimates in the period of time T_0 is compensated, thereby ensuring their robustness. Estimates $R_{gg}(\mu')$ will be different from zero due to violation of the condition (1) only in the beginning of ASP, i.e. at the start of the time cell T_1. Estimates $R_{gg}(\mu)$, $R_{g_j g_\nu}(\mu')$ can therefore be regarded as reliable indicators, calculation of which can be easily parallelized with determination of estimates $R_{X\varepsilon\varepsilon}(\mu = 0)$, $R_{X\varepsilon}(\mu = 0)$, D_ε.

Accordingly, in the operation process of a station of RNM ASP (Robust Noise Monitoring of Anomalous Seismic Processes), characteristics of seismic acoustic signals $g_1(i\Delta t)$ calculated from the expressions (64) are used to form estimates of robust auto-correlation indicators $R_{g_1 g_1}(\mu')$, which are equal to zero in the normal seismic state T_0. They will be different from zero at the start of ASP origin in T_1.

VII. Technology of Sampling of Noisy Seismic Acoustic Signals

In accordance with the technologies offered above, the noise $\varepsilon(i\Delta t)$ of the signal $g(i\Delta t)$ is considered as a carrier of useful information in solving the problem of monitoring of the start of ASP origin. This, in its turn, requires determining sampling interval Δt_ε of the source seismic acoustic signal $g(i\Delta t)$ with provision for high-frequency spectra of both the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$. Let us consider one of the possible ways to solve this task by means of frequency characteristics of low order $q_0(i\Delta t)$ of readings of the seismic acoustic signal $g(i\Delta t)$ being analyzed [42].

Let us assume that the signal under analysis is exposed to analog-digital conversion with current frequency f_v, which exceeds significantly the sampling rate f_c found by means of conventional methods [40, 42,44,49]. In this case, time sampling interval Δt_v

Equation

$$\Delta t_v = \frac{1}{f_v} \tag{71}$$

will be considerably lower than the quantization step

$$\Delta t_c \le \frac{1}{2f_c} \tag{72}$$

As a result, the following inequality between the cutoff frequency f_C found from sampling theorem and the current frequency f_v will take place

$$\left.\begin{aligned} f_v &>> f_C \\ \Delta t_v &<< \Delta t_C \end{aligned}\right\} \tag{73}$$

Values of binary k-bits of readings of the signal $g(i\Delta t)$ in each successive interval will be repeated with high degree of probability, i.e. the following equality will take place:

$$P[X(i\Delta t)] \approx P[X((i+1)\Delta t)] \tag{74}$$

where P is the sign of probability.

This being the case, frequency f_{q_0} of low order $q_0(i\Delta t)$ of reading of $g(i\Delta t)$ can be determined through the quantity N_{q_0} of its transition from one state to null state in a time unit. For that end, N of readings of the seismic acoustic signal $g(i\Delta t)$ should be written into computer memory in the process of analog-digital conversion with frequency f_v, after which frequency f_{q_0} and sampling interval Δt_ε can be determined from the following expressions:

$$f_{q_0} = \frac{N_{q_0}}{N} f_v \tag{75}$$

$$\Delta t_\varepsilon \approx \frac{1}{f_{q_0}} \tag{76}$$

In that case, the value of frequency f_{q_0} will obviously be lower than the current sampling rate f_v, and software determination of the sampling interval Δt_ε can be reduced to the following:

seismic acoustic signal $g(i\Delta t)$ with redundant frequency f_v is converted to digital code in the monitoring period T, and a file forms from N of its readings;

f_{q_0} is determined from the formula $f_{q_0} = \frac{N_{q_0}}{N} f_v$;

sampling interval Δt_ε is determined from the formula

$$\Delta t_\varepsilon \le \frac{1}{(2 \div 5) f_{q_0}}$$

This being the case, unlike conventional methods, in the process of determining the sampling interval Δt_ε, high-frequency spectra of the sum signal $g(i\Delta t)$ and metrological performance of the analog-digital converter (ADC) itself are taken into account automatically. Numerous experiments in coding of seismic acoustic signals $g(i\Delta t)$ proved the efficiency of application of the above-mentioned technology. Simplicity of its implementation is of particular importance in terms of wide practical use.

VIII. Station of Robust Noise Monitoring of Anomalous Seismic Processes (RNM ASP)

The diagram of the station of robust noise monitoring of ASP is given in Fig. 1. The basic difference of the station from all other known prototypes is that steel bores of suspended oil wells filled with water are used in it for receiving seismic information from the deep strata of earth. Unit 1 is the equipment for receiving of seismic acoustic noise from the deep strata of earth, based on a hydrophone installed at the head of a 3-6 kilometers deep well. Seismic acoustic signals are analyzed by means of the above-discussed technology and corresponding estimates are determined in Unit 2. Unit 3 is standard seismic equipment, which allows one to register and assess the intensity of seismic vibrations. The function of Unit 4 and the server of monitoring center are to identify the results of ASP monitoring at the RNM ASP station with registered earthquakes at seismic stations of seismological service [50].

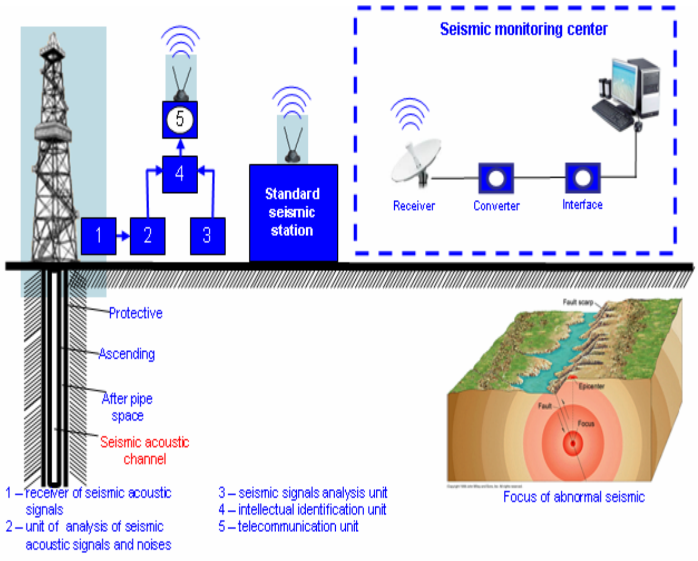

Figure 1. Station of robust noise monitoring of ASP (RNM ASP)

At the initial stage, corresponding estimates of seismic signals received from hydrophones of Unit 1 are determined by means of algorithms (19), (20), (35), (43)-(46), (63), (64) in Unit 2. Those estimates are forwarded to the monitoring server, where they are saved. Estimates form and are saved both in Unit 2 and on the server during the long period of time T_0. At the same time, estimates of seismic signals coming from ground seismic equipment 3 are also determined during the time T_0 and registered in the same manner. This process continues to the moment when current estimates of the signals received from corresponding sensors will differ from previous ones by a value, which is higher than the set threshold levels.

At the same time corresponding information is sent to the server of the monitoring center. Thus, information on the beginning of anomalous seismic processes forms in the system at the start of the time T_1 from the estimates of seismic acoustic signals received at the output of hydrophones. Standard ground seismic stations, meanwhile, register corresponding signals and determine magnitudes of seismic vibrations only at the start of the time T_2 (intense vibrations). That information is also sent both to Unit 4 and to the server, where the difference between moments of receiving the corresponding signals in Units 2 and 3 respectively is determined. Training and identification of ASP are carried out simultaneously both in Unit 4 and on the server in the operation process, with known technologies of recognition being used, including neural network technologies. After a certain training period on the server and in Unit 4, the minimum time of registration of the moment of the expected earthquake by standard seismic stations is determined as a result of monitoring of ASP.

IX. Results of Monitoring Experiments at the Station of RNM ASP at Qum Island in the Caspian Sea

An experimental version of RNM ASP station was installed at the head of 3,500 m deep suspended oil well # 5 on 01.07.2010. The well is filled with water and for this reason, a BC 312 hydrophone is used as a sensor. Fig. 2 shows the external appearance of the station after its installation. A building was constructed afterwards to protect the station from the sun, wind and other external factors.

Figure 2. Appearance of the station after installation

The station includes the following equipment:

System unit;

Fastwell Micro Pc controller;

GURALP LTD CMG 5T seismic accelerometer;

BC 321 hydrophone, made in Zelenograd;

Reinforcing and normalizing elements;

Siemens MC35i terminal forming an Internet channel via GPRS.

The following earthquakes have been registered by Azerbaijan seismic stations during the operation of the station from 01.07.2010 to 15.01.2011.

09.10.2010, town of Masally 00:58:11, M:3.5, d:12 км

11.10.2010, town of Shirvan, 22:50:23, M:3.9, d:37 км

17.10.2010, town of Imishli, 07:20:38, M:3.4, d:18 км

20.11.2010, Caspian Sea, 05:05:48-08:29:29, M:3.5, d: 50 km

25.11.2010, Baku, Sangachal, 09:15:21, M: 3.04, d: 36 km

Given below in the Fig. 3a, 3b, 3c, 3d, 3e are the results of ASP monitoring by means of RNM ASP. The records show that the estimates between the useful signal and the noise of the seismic acoustic signal received at the output of the hydrophone increase sharply over 5-10 hours before the earthquake, which continues till the end of the earthquake. It should be noted that the distance from a RNM ASP station to remotest earthquakes is over 200-300 km.

Fig. 3f demonstrates records of the estimate of cross-correlation function $R_{x\varepsilon}(\mu)$ between the useful signal $R_{x\varepsilon}(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ related to the earthquakes in Azerbaijan (21.01.2011, 01:58:54), Georgia (23.01.2011, 07:51:23), Tajikistan (24.01.2011, 06:45:29) and on the border with Turkey, Armenia and Iran (3 earthquakes - 25.01.2011, 03:56:12, 04:02:32, 07:40:04). As is clear from the results of the given charts of ASP monitoring, their lead over the beginning of the earthquake is over 5-10 hours. For instance, Fig. 3g gives the expanded record of the estimate of cross-correlation function during the earthquake in Georgia (near Kutaisi) on 23.01.2011. It is obvious from the chart that the beginning of ASP 07:51:23 was clearly registered 5-6 hours before the beginning of the earthquake. The charts show Baku time.

Experimental research demonstrated that in the analysis of seismic acoustic signals, clear identification of the beginning of the time T_1 by means of conventional technologies is impossible. Application of robust technology of noise analysis of estimates $R_{X\varepsilon\varepsilon}$, $R_{X\varepsilon}$ and D_ε, on the other hand, allow one to detect the beginning of origin of anomalous seismic processes reliably and adequately.

Thus, initial results of experiments show that it is possible to perform monitoring within a radius of over 200-300 km 5-15 hours before the earthquake by means of RNM ASP. Those results imply that the difference in time between ASP origin and its critical state depends on the location of the earthquake center. One can assume, based on the obtained results, that, when spreading from the earthquake center, seismic acoustic waves are reflected due to the resistance of certain upper strata of the earth and change horizontally. One can also assume that sufficient intensity of those waves allows them to travel to long distances (300-500 km).

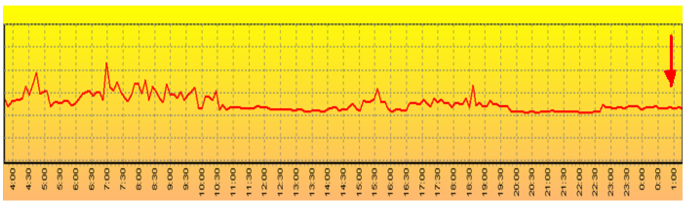

Figure 3a. 08.10.2010 Masally 00:58:11 M:3.5 d:12 km Noise variance

Start of ASP approximately at 04:30, 08.10.2010, earthquake at 00:58:11, 09.10.2010

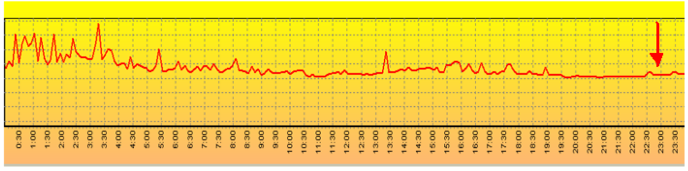

Figure 3b. 11.10.2010 Shirvan 22:50:23 M:3.9 d:37 km Noise variance

Start of ASP approximately at 00:30,11.10.2010, earthquake at 22:50:23,11.10.2010

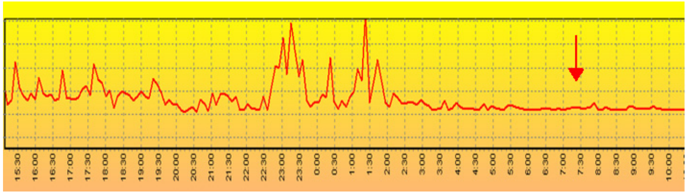

Figure 3c. 16-17.10.2010 Imishli 07:20:38 M:3.4 d:18 km. Noise variance

Start of ASP approximately at 15:30, 16.10.2010, earthquake at 07:20:38, 17.10.2010

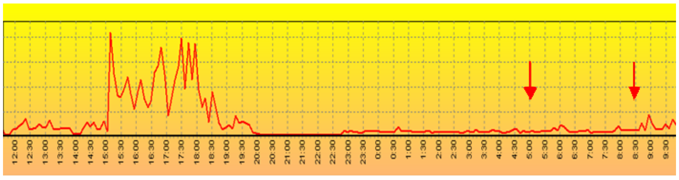

Figure 3d. 19-20.11.2010 At sea 05:05:48--08:29:29 20.11.2010 M:3.5 d: 50 km. Noise variance.

Start of ASP approximately at 12:20, 19.11.2010 г., two earthquakes at 05:05:48, 08:29:29 20.11.2010

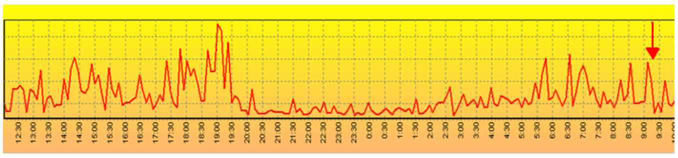

Figure 3e. 25.11.2010 Baku, Sangachal 09:15:21 M: 3.04 d: 36 km. Noise variance

Start of ASP approximately at 12:10 24.11.2010, earthquake at 09:15:21 25.11.2010

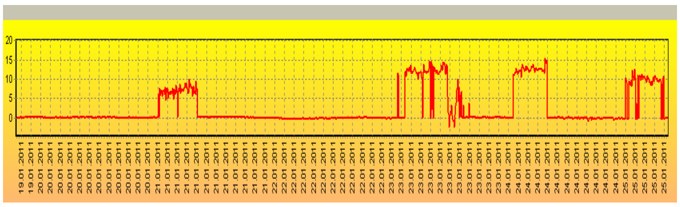

Figure 3f. In Azerbaijan (21.01.2011, 01:58:54), in Georgia (23.01.2011, 07:51:23.0), in Tajikistan (24.01.2011, 06:45:29.0) and on the border between Turkey and Iran (3 earthquakes 25. 01.2011, 03:56:12.; 04:02:32.; 07:40:04.)

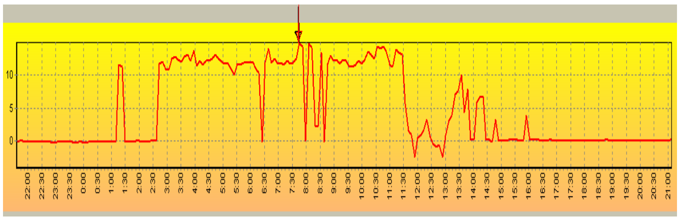

Figure 3g. 23.01.2011 Georgia, near Kutaisi 07:51:23 M: 4.5 d: 10 km
Estimates of cross-correlation function

These experimental results show the expediency of building such stations of RNM ASP. Creation of another two stations is near completion at the present time, one at well # 427 of Shirvan Oil, and the other at a well of Siazan Oil. A fourth station is to be built in the town of Naftalan, Qoranboy region. Four RNM ASP stations will make it possible to determine the direction and coordinates of the earthquake center.

In the long term, integration of RNM ASP stations with standard seismic stations will allow one to create robust intellectual systems of noise monitoring, which will be capable of carrying out short-term earthquake forecasting with sufficient degree of reliability and adequacy after a certain training period.

X. CONCLUSION

Obtained experimental results allow one to conclude that the lead in the time of registration of ASP origin by seismic acoustic stations of RNM ASP over widely used standard seismic equipment is conditioned by two factors. First, high-frequency seismic acoustic waves, which arise at the start of origin of anomalous seismic processes deep below the surface of earth, spread through some strata horizontally in the form of noise, which reaches the steel bore of the oil well at a depth of over 3-6 kilometers. Serving as acoustic channels, the steel bores filled with water transmit seismic acoustic noise at the velocity of sound to the surface of earth, where it is received by means of a hydrophone in Unit 1. At the same time, infra-low frequency seismic waves gain the required capacity in a certain amount of time, when seismic processes reach their critical state and an earthquake occurs, which is why they are registered by seismic receivers of standard ground equipment much later. Second, application of robust noise technology allows one to analyze noises as information carriers, which makes it possible to register anomalous seismic processes at the start of their origin, and their detection by means of estimates of characteristics of useful signals starts considerably earlier. Thus, those two factors made it possible to detect the indication time of the start of ASP of the coming earthquake by means of robust noise analysis of obtained seismic acoustic data considerably earlier that it is registered by stations of seismological service. An earthquake is usually detected no less than 5-10 hours before its beginning, which can give a chance to warn the population in due time about the danger of a powerful earthquake. It was proved after the start of operational testing of the second station at the 4,400 m deep well # 427 in Shirvan Oil on 20 November, 2011. First experimental monitoring results given below in Fig. 4 were obtained by this station on 23.10.2011 and 24.10.2011 more than 10-12 hours before the beginning of the earthquake. The similar record was made at the Qum Island station.

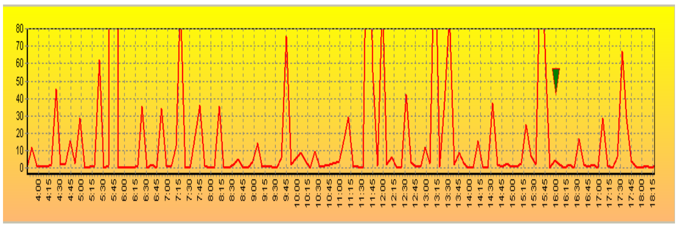

Figure 3h. Shirvan 23 October 16:00:25 East Turkey M=5.6

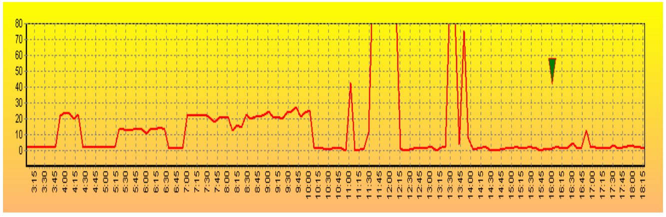

Figure 3i. Qum Island 23 October 16:00:25 East Turkey M=5.6

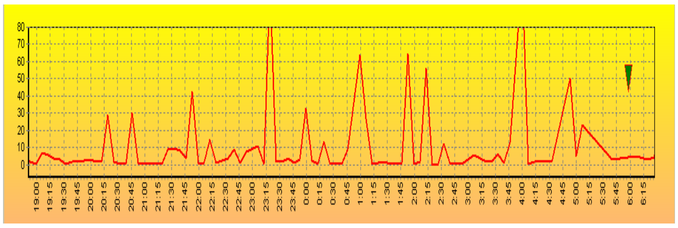

Figure 3j Shirvan 24 October 06:57:59 East Turkey M=3.8 prolonged earthquakes

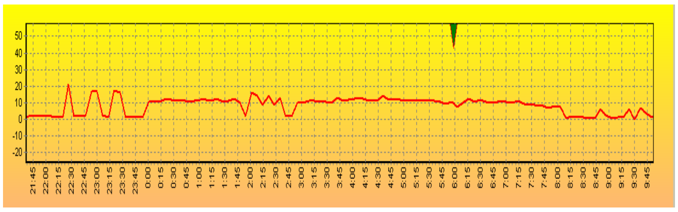

Figure 3k Qum Island 24 October 06:57:59 East Turkey M=3.8 prolonged earthquakes

The experiments demonstrated that determination of the coordinates and magnitude of an expected earthquake requires creation of networks consisting of at least four stations and their integration with standard seismic stations. For that end, another three stations are built in 2011 in addition to the station at Qum Island in the Caspian Sea: in the town of Shirvan in the south of the country, in the town of Siazan in the north and in the town of Naftalan in the west.

With all four stations operating, results of processing of seismic acoustic signals will be sent at the moment of monitoring of ASP origin, i.e. in the transition from the time cell T_0 into the time cell T_1, from each station to the server of the monitoring center by means of all the proposed technologies. As a result, a set of informative attributes will form:

$$W_{NM_1} = \left\{ \begin{matrix} R_{X_1\varepsilon_1\varepsilon_1}(0) & R_{X_2\varepsilon_2\varepsilon_2}(0) & R_{X_3\varepsilon_3\varepsilon_3}(0) & R_{X_4\varepsilon_4\varepsilon_4}(0) \\ R_{X_1\varepsilon_1}(0) & R_{X_2\varepsilon_2}(0) & R_{X_3\varepsilon_3}(0) & R_{X_4\varepsilon_4}(0) \\ R^*_{X_1\varepsilon_1}(0) & R^*_{X_2\varepsilon_2}(0) & R^*_{X_3\varepsilon_3}(0) & R^*_{X_4\varepsilon_4}(0) \\ D_{\varepsilon_1} & D_{\varepsilon_2} & D_{\varepsilon_3} & D_{\varepsilon_4} \\ R_{g_1g_1}(\mu') & R_{g_2g_2}(\mu') & R_{g_3g_3}(\mu') & R_{g_4g_4}(\mu') \\ a^*_{T_1\omega_1^*}, b^*_{T_1\omega_1^*} & a^*_{T_1\omega_2^*}, b^*_{T_1\omega_2^*} & a^*_{T_1\omega_3^*}, b^*_{T_1\omega_3^*} & a^*_{T_1\omega_4^*}, b^*_{T_1\omega_4^*} \\ \Delta a^*_{\omega_1^* T_0 T_1} & \Delta a^*_{\omega_2^* T_0 T_1} & \Delta a^*_{\omega_3^* T_0 T_1} & \Delta a^*_{\omega_4^* T_0 T_1} \\ \Delta b^*_{\omega_1^* T_0 T_1} & \Delta b^*_{\omega_2^* T_0 T_1} & \Delta b^*_{\omega_3^* T_0 T_1} & \Delta b^*_{\omega_4^* T_0 T_1} \end{matrix} \right\} \tag{79}$$

The starting point of indication time of ASP monitoring will be transmitted from each RNM ASP to the server in the following form:

$$W_{NM_2} = \left((T_0 \to T_1)t_1; (T_0 \to T_1)t_2; (T_0 \to T_1)t_3; (T_0 \to T_1)t_4\right) \tag{80}$$

These expressions will also be used to determine sets of differences in monitoring time of all seismic stations in the following form:

$$W_{NM_3} = \left\{ \begin{matrix} \Delta T_{12} = (t_1 - t_2) & \Delta T_{13} = (t_1 - t_3) & \Delta T_{14} = (t_1 - t_4) \\ \Delta T_{23} = (t_2 - t_3) & \Delta T_{24} = (t_2 - t_4) & \Delta T_{21} = (t_2 - t_1) \\ \Delta T_{34} = (t_3 - t_4) & \Delta T_{31} = (t_3 - t_1) & \Delta T_{32} = (t_3 - t_2) \\ \Delta T_{41} = (t_4 - t_1) & \Delta T_{42} = (t_4 - t_2) & \Delta T_{43} = (t_4 - t_3) \end{matrix} \right\} \tag{81}$$

After every ASP monitoring cycle, all stations form sets W_{NM_1}, W_{NM_2}, W_{NM_3} on the server of the monitoring center based on the obtained results and their system analysis is carried out. Results of analysis of obtained experimental data, as well as results of tests and operation of equipment of RNM ASP stations will be used to determine final requirements with regard both to hardware and to models, algorithms and software of the server and the whole system in general. First of all, they must be capable of determining the coordinates of an earthquake center within a radius 300-400 lm with sufficient accuracy, using the difference in time of receipt and indication of ASP between four stations. After determination of the distance between the earthquake center and the stations, software of the system must allow one to calculate the estimate of minimum magnitude of an expected earthquake.

Seismic-acoustic stations of ASP monitoring can also be used for monitoring of the latent period of volcano formation well before the eruption. Their use will also allow one to perform monitoring of testing of minor and major nuclear bombs and other experiments related to manufacture of military equipment on a regional basis. A network of such stations will make it possible to fully control such tests and various military maneuvers.

Experiments carried out at seismic-acoustic stations installed at the heads of 3-6 km deep oil wells in the period from 01.05.2010 to 01.03.2012 demonstrated that conventional technologies of analysis of seismic-acoustic signals received by means of hydrophones do not allow one to detect the beginning of ASP origin. The experiments also demonstrated that the basics carrier of information about the beginning of ASP preceding an earthquake is noise of seismic-acoustic signals. The offered technologies of analysis of noise as a carrier of useful information determine such its characteristics as value of noise correlation, correlation functions and coefficient of correlation of the useful signal and noise, noise variance. These technologies are combined with relay technologies for determination of noise estimates, which increases adequacy of monitoring results both in the presence of correlation between the useful signal and the noise and in the absence of such. Given below is the list of these technologies.

$$\left. \begin{aligned} R_{X\varepsilon\varepsilon}(\mu=0) &\approx \frac{1}{N}\sum_{i=1}^{N}\left[\left[g(i\Delta t)g(i\Delta t) - g(i\Delta t)g((i+1)\Delta t)\right] - \left[g(i\Delta t)g((i+2)\Delta t) - g(i\Delta t)g((i+3)\Delta t)\right]\right] \\ R_{X\varepsilon\varepsilon}(\mu=0) &\approx \frac{1}{N}\sum\left[\left[g(i\Delta t)g(i\Delta t) - g(i\Delta t)g((i+1)\Delta t)\right] - \left[g(i\Delta t)g((i+3)\Delta t) - g(i\Delta t)g((i+4)\Delta t)\right]\right] \\ R_{X\varepsilon\varepsilon}(\mu=0) &\approx \frac{1}{N}\sum_{i=1}^{N}\left[\left[g(i\Delta t)g(i\Delta t) - g(i\Delta t)g((i+1)\Delta t)\right] - \left[g(i\Delta t)g((i+4)\Delta t) - g(i\Delta t)g((i+5)\Delta t)\right]\right] \end{aligned} \right\} \tag{82}$$

$$R^*_{X\varepsilon}(\mu=0) \approx \frac{1}{N}\sum_{i=1}^{N}\left[\operatorname{sgn} g(i\Delta t)g(i\Delta t) - 2\operatorname{sgn} g(i\Delta t)g((i+1)\Delta t) + \operatorname{sgn} g(i\Delta t)g((i+2)\Delta t)\right] \tag{83}$$

$$\left. \begin{aligned} R_{X\varepsilon\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=0) - \Delta R_{gg}(\mu=1) \\ R_{X\varepsilon\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=0) - \Delta R_{gg}(\mu=2) \\ R_{X\varepsilon\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=0) - \Delta R_{gg}(\mu=3) \\ R_{X\varepsilon\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=0) - \Delta R_{gg}(\mu=4) \end{aligned} \right\} \tag{84}$$

$$\left. \begin{aligned} R_{X\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=2) \\ R_{X\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=3) \\ R_{X\varepsilon}(\mu=0) &\approx \Delta R_{gg}(\mu=1) - \Delta R_{gg}(\mu=4) \end{aligned} \right\} \tag{85}$$

$$\left. \begin{aligned} R^*_{X\varepsilon}(\mu=0) &\approx \Delta R^*_{gg}(\mu=0) - \Delta R^*_{gg}(\mu=1) \\ R^*_{X\varepsilon}(\mu=0) &\approx \Delta R^*_{gg}(\mu=0) - \Delta R^*_{gg}(\mu=2) \\ R^*_{X\varepsilon}(\mu=0) &\approx \Delta R^*_{gg}(\mu=0) - \Delta R^*_{gg}(\mu=3) \\ R^*_{X\varepsilon}(\mu=0) &\approx \Delta R^*_{gg}(\mu=0) - \Delta R^*_{gg}(\mu=4) \end{aligned} \right\} \tag{86}$$

where

$$\left.\begin{aligned}
\Delta R_{gg}(\mu=0)&=R_{gg}(\mu=0)-R_{gg}(\mu=1)\\
\Delta R_{gg}(\mu=1)&=R_{gg}(\mu=1)-R_{gg}(\mu=2)\\
\Delta R_{gg}(\mu=2)&=R_{gg}(\mu=2)-R_{gg}(\mu=3)\\
\Delta R_{gg}(\mu=3)&=R_{gg}(\mu=3)-R_{gg}(\mu=4)\\
\Delta R_{gg}(\mu=4)&=R_{gg}(\mu=4)-R_{gg}(\mu=5)\\
\Delta R^{*}_{gg}(\mu=0)&=R^{*}_{gg}(\mu=0)-R^{*}_{gg}(\mu=1)\\
\Delta R^{*}_{gg}(\mu=1)&=R^{*}_{gg}(\mu=1)-R^{*}_{gg}(\mu=2)\\
\Delta R^{*}_{gg}(\mu=2)&=R^{*}_{gg}(\mu=2)-R^{*}_{gg}(\mu=3)\\
\Delta R^{*}_{gg}(\mu=3)&=R^{*}_{gg}(\mu=3)-R^{*}_{gg}(\mu=4)\\
\Delta R^{*}_{gg}(\mu=4)&=R^{*}_{gg}(\mu=4)-R^{*}_{gg}(\mu=5)
\end{aligned}\right\} \tag{87}$$

$$R_{X\varepsilon}(\mu=0)\approx\frac{R^{*}_{X\varepsilon}(\mu=0)\cdot\Delta R_{gg}(\mu=1)}{\Delta R^{*}_{gg}(\mu=1)} \tag{88}$$

$$D_{\varepsilon}\approx R_{X\varepsilon\varepsilon}(\mu=0)-R_{X\varepsilon}(\mu=0) \tag{89}$$

$$\begin{aligned}
2R_{X\varepsilon}(\mu=0)&\approx\Delta R_{gg}(\mu=1)-\Delta R_{gg}(\mu=2)\\
2R_{X\varepsilon}(\mu=0)&\approx\Delta R_{gg}(\mu=1)-\Delta R_{gg}(\mu=3)\\
2R_{X\varepsilon}(\mu=0)&\approx\Delta R_{gg}(\mu=1)-\Delta R_{gg}(\mu=4)
\end{aligned} \tag{90}$$

$$\begin{aligned}
D_{\varepsilon}&\approx\Delta R_{gg}(\mu=0)-\Delta R_{gg}(\mu=1)-R_{X\varepsilon}(\mu=0)\\
D_{\varepsilon}&\approx\Delta R_{gg}(\mu=0)-\Delta R_{gg}(\mu=2)-R_{X\varepsilon}(\mu=0)\\
D_{\varepsilon}&\approx\Delta R_{gg}(\mu=0)-\Delta R_{gg}(\mu=3)-R_{X\varepsilon}(\mu=0)\\
D_{\varepsilon}&\approx\Delta R_{gg}(\mu=0)-\Delta R_{gg}(\mu=4)-R_{X\varepsilon}(\mu=0)
\end{aligned} \tag{91}$$

Synchronic analysis of noise of seismic-acoustic signals from deep strata of the earth performed by means of the above-mentioned technologies confirmed that seismic-acoustic waves of ASP spread within a radius of 300-500 km dozens of hours earlier than seismic waves registered by ground seismic stations, which is a prerequisite of their wide application in seismology.

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