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INTELLIGENT SEISMIC-ACOUSTIC SYSTEM FOR IDENTIFYING THE LOCATION OF THE FOCUS OF AN EXPECTED EARTHQUAKE

Analyzed the results of the noise monitoring of anomalous seismic processes (ASP) performed from 01.07.2010 to 01.03.2014 on nine seismic-acoustic stations built at the head of 10 m, 200 m, 300 m and 1400-5000 m deep wells. Based on the results of the experimental data obtained in the period covering over three years, an intelligent system has been built, which allows for identifying the location of the focus of an earthquake 10-20 hours in advance, using the combinations of time of change in the estimate of the correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ of the seismic-acoustic information received from different stations. In the long term, the system can be used by seismologists as a tool for determining the location of the focus of an expected earthquake.

Keywords: seismic acoustic signal, earthquake focus, noise dispersion, cross correlation function, knowledge base, expert system, intelligent system, neural set

1. Introduction. It is known that much research has been carried out on the causes and nature of earthquakes [1–3]. The possibility of receiving various types of seismic information from the deep strata of the earth also remains a popular research subject [3–7]. Methods, such as wavelet transform and finite elements [4, 8–11], are employed in analysing seismic signals received during earthquakes. In all of these research papers, the problems associated with earthquake prediction are the basic research trend [12–24]. Different models and technologies have been and are being developed [25–29]; numerous population-oriented early warning systems, models and technologies for the rapid response of rescue groups of relevant agencies have been developed and commissioned [30–38]. Regardless of the aforementioned research papers, earthquakes are not predicted in good time, which leads to massive disastrous consequences.

Papers [39–44] propose a seismic-acoustic system for monitoring the earthquake origin process. The system consists of a network of nine seismic-acoustic stations for the robust noise monitoring of anomalous seismic processes (RNM ASPs). The experiments that have been conducted on these stations since 01.07.2010 establish that a cross-correlation emerges between the useful signal and the noise of the seismic-acoustic information during the ASP origin.

The results of the operation of these stations have demonstrated that each of them separately performs reliable indication of ASP origin processes that precede earthquakes based on the variation of the cross-correlation function between the useful signal and the noise. However, it is impossible to determine the coordinates of an expected earthquake with sufficient accuracy by using these stations. The experimental research has demonstrated that it is possible, however, to create an intelligent neural network system, which would allow locating the ASP focus by means of these stations. We consider one possible way to create such a system in the following paragraphs.

2. Problem statement. It is known that in seismically active regions, after a certain period T_0 of the normal seismic state and at the end of a certain period T_1, an earthquake usually occurs due to originating ASPs.

Despite the difference in duration of T_0 and T_1, the problem of monitoring the beginning of the ASP origin comes down to providing a reliable indicator of the beginning of period T_1.

This matter has been considered in detail in [39–41].

Research [39] sets the problem for creating a technology and a system allowing one to register the starting instant of the period T_1. However, the experimental research [39–41] demonstrated that the beginning of T_1 does not take place only during the ASP origin. For this reason, besides the registration of the beginning of the period T_1, the monitoring of the beginning of the ASP origin also requires an indication of the change in the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$.

Thereby, the present paper sets up the problem of using the estimate $R_{X\varepsilon}(\mu)$ of the seismic-acoustic signal $g(i\Delta t)$ as an informative attribute for indicating the beginning of the ASP origin, which requires calculation of the estimate $R_{X\varepsilon}(\mu)$ during the monitoring process.

Furthermore, the practical application of a network of RNM ASP stations also requires developing a technology for determining the location of the earthquake focus. For this purpose, we should first consider the existing methods of calculating earthquake focuses [19–22, 45, 46] based on seismic information obtained by means of the network of existing standard ground stations.

It is known [19–22, 45, 46] that, in such cases, the difference between the amount of time it takes for the basic seismic waves P and S to reach the ground seismic stations is used to determine the earthquake focus. The propagation velocity of the P wave is higher than that of S wave. The P wave velocity in a homogeneous isotropic medium is determined by the expression

$$v_P = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}}, \tag{1}$$

where k is the volume coefficient, μ is the shear modulus and ρ is the density of the material penetrated by waves.

S wave propagation velocity is calculated by the following expression

$$v_S = \sqrt{\frac{\mu}{\rho}}, \tag{2}$$

where μ is the shear modulus and ρ is the density of the material penetrated by the waves.

The distance from the standard ground seismic station to the focus is found by multiplying the time difference by the velocity difference:

$$S = \Delta T(v_p - v_s). \tag{3}$$

After the distance between the epicentre and the different seismic stations has been determined, the coordinates of the focus are found geometrically. Unfortunately, in all known cases, the coordinates of epicentres and hypocentres in seismic monitoring systems are determined after actual earthquakes [19–28].

Our experimental research showed that, for many reasons, it is practically impossible to use the obtained results to calculate the coordinates of the ASP focus on RNM ASP stations by means of the said technology.

Therefore, the present paper poses the problem of developing an intelligent neural network system for monitoring the ASP origin, identifying the location of the focus and determining the approximate magnitude of an expected earthquake.

3. Technology for determining the informative attributes of the latent period of ASP origin. Our research demonstrated that when ASP arises at the start of period T_1, estimates of the cross-correlation function $R_{X\varepsilon}(\mu = 0)$ between the useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$, the noise variance D_ε and the noise correlation $R_{X\varepsilon\varepsilon}(\mu=0)$ change in the first place [39–41]. The reason is that in the beginning of period T_0, noise $\varepsilon(i\Delta t)$ forms due to the influence of the ASP. Therefore, in period T_1, correlation arises between the useful signal $X(i\Delta t)$ and noise $\varepsilon(i\Delta t)$ and the estimate $R_{X\varepsilon}(\mu)$ grows sharply. For this reason, the estimate $R_{X\varepsilon}(\mu)$ can be regarded as the main informative attribute, whose use is reasonable during the monitoring of the latent period of ASP origin.

Since 01.07.2010, both conventional technologies and robust noise technologies have been used to register the beginning of the latent period of ASP origin on RNM ASP stations. We were unable to register period T_1 with sufficient reliability and authenticity by using estimates of conventional correlation and spectral technologies. When robust noise technology was put into practice, the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ would change abruptly in the beginning of period T_1. This turned out to be the crucial factor, which allows the monitoring of the beginning of ASP origin with sufficient reliability. With this in mind, the estimate $R_{X\varepsilon}(\mu)$ was taken as an informative attribute in solving the problem of monitoring the ASP origin during the building of the network of RNM ASP stations.

The expression for determining the estimates of the relay correlation function $R^*_{gg}(\mu=0)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ is given in [39] in the following form:

$$R^*_{X\varepsilon}(\mu=0) \approx \frac{1}{N}\sum_{i=1}^{N}\big[\operatorname{sgn} g(i\Delta t)g(i\Delta t) - 2\operatorname{sgn} g(i\Delta t)g((i+1)\Delta t) + \\ + \operatorname{sgn} g(i\Delta t)g((i+2)\Delta t)\big]. \tag{4}$$

It has also been shown that, with the estimates $R^*_{X\varepsilon}(\mu=0), R^*_{gg}(\mu=1), R_{gg}(\mu=1)$ available and using the equality of the relationship between $R^*_{gg}(\mu=1)$ and $R_{gg}(\mu=1)$ and $R^*_{X\varepsilon}(\mu=0)$ and $R_{X\varepsilon}(\mu=0)$

$$\frac{R^*_{gg}(\mu=1)}{R_{gg}(\mu=1)} = \frac{R^*_{X\varepsilon}(\mu=0)}{R_{X\varepsilon}(\mu=0)}, \tag{5}$$

and the estimate $R_{X\varepsilon}(\mu=0)$ can be determined by the formula:

$$R_{X\varepsilon}(\mu=0) = \frac{R_{gg}(\mu=1)R^*_{X\varepsilon}(\mu=0)}{R^*_{gg}(\mu=1)} \tag{6}$$

Our experiments demonstrated that to raise the reliability and authenticity of the monitoring results, it is reasonable to also use the estimates of the noise correlation value $R_{X\varepsilon\varepsilon}(\mu=0)$ and the noise variance D_ε, which are determined by the following expressions [39–44] as additional informative attributes:

$$R_{X\varepsilon\varepsilon}(\mu) = R_{X\varepsilon}(\mu) + D_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left[g^2(i\Delta t) + g(i\Delta t)g((i+2)\Delta t) - 2g(i\Delta t)g((i+1)\Delta t)\right] \tag{7}$$

$$D_\varepsilon = R_{X\varepsilon\varepsilon}(\mu=0) - R_{X\varepsilon}(\mu=0) \tag{8}$$

Thus, it is possible to use formulas (4), (6), (7) and (8) to determine the estimates $R^{*}_{X\varepsilon}(\mu=0)$, $R_{X\varepsilon}(\mu=0)$, $R_{X\varepsilon\varepsilon}(\mu=0)$, and D_{ε}, by means of which the monitoring of the ASP can be undertaken with sufficient reliability.

4. Intelligent technology and systems for identifying the location of the focus of ASP origin. It is known that when an ASP enters its critical state, an earthquake occurs. Boundaries of the earthquake's focus and magnitude depend on the structure and nature of the strain–stress distribution in the rocks in the particular place. Rock deformation is uneven and transmits elastic waves. The volume of deformed rocks is an important factor determining the strength of the seismic impact and the formation of seismic-acoustic noise $g(i\Delta t)$. Each main burst is preceded by quite a long period of time T_1 of earthquake preparation. This period can last up to several dozens of hours [39].

The analysis of seismic information, received by means of acoustic sensors installed at the heads of suspended oil wells, has demonstrated that when ASPs arise, seismic-acoustic noise spreads in the deep strata of the Earth for several dozens of hours T_1 before the expected earthquake [39–41]. It has been experimentally established that monitoring the beginning of time T_1 by means of the technology described above is carried out quite reliably by RNM ASP stations (Figs. 1, 2) [39, 40]. In the following paragraphs, we discuss the possibility of developing intelligent technology to identify the location of the ASP focus by means of the information received from the stations built in nine (9) seismically active Caspian regions
(Fig. 1).

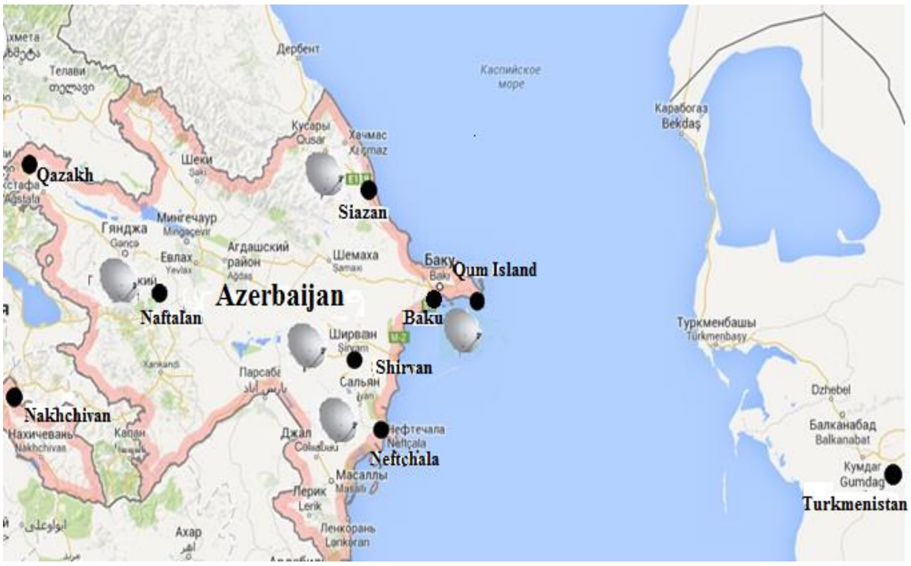


Fig. 1. *Map of the locations of RNM ASP stations in the Caspian seismically active region.*

Those stations have the following geographical coordinates and their wells have the following depths:

1.	(Qum Island):	40.310425º	50.008392º	3500 m	July	2010
2.	Siazan:	41.046217º	49.172058º	3145 m	November	2011
3.	Naftalan:	40.609521º	46.791458º	4000 m	May	2012
4.	Shirvan:	39.933170º	48.920745º	4900 m	November	2011
5.	Neftchala:	39.358333°	49.246667°	1430 m	June	2012

6.	Nakhchivan:	39.718000°	44.876000°	1800 m	March	2013
7.	Qazakh	41,311889°	45,108611°	200 m	August	2013
8.	Turkmenistan	40,223252°	49,800833°	300 m	August	2013
9.	Baku Cybernetic	38,530089°	56,654472°	10 m	February	2014

The experiments carried out on the RNM ASP stations (Fig. 2) have demonstrated that the seismic-acoustic noises received by hydrophones from the deep strata of the Earth are direct precursors of the earthquake preparation process.

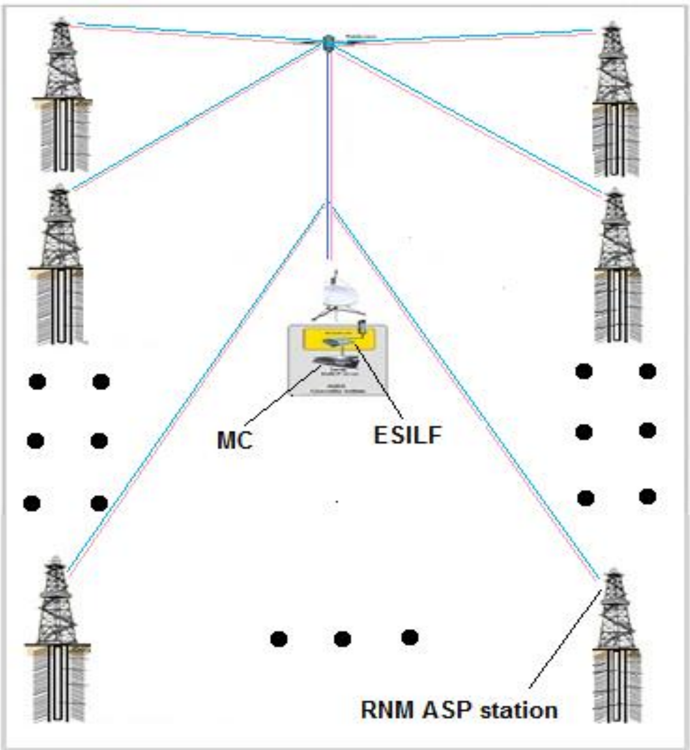


Fig. 2. *Intelligent seismic-acoustic system for identifying the location of the focus of an expected earthquake*

ESILF- Expert System for Identifying the Location of the Focus

The results of the measuring and analysis of those noises were sent from each station to the server of the seismic-acoustic monitoring centre (MC) via a high speed radio channel with satellite communication. The system is also capable of transferring received data to servers of other MCs in the neighbouring countries of seismic-acoustic regions.

To carry out large-scale experiments on ASP monitoring, as Fig. 1 shows, since 01.07.2010 RNM ASP stations have been made operational, one by one, at Qum Island, in Shirvan, Siazan, Naftalan, Neftchala, Nakhchivan (on the borders with Turkey and Iran), Kopetdag (Turkmenistan), Qazakh (on the border with Georgia), and Cybernetic (Baku). The last three stations have been built on 300-m, 200-m and 10-m deep water wells, respectively. The stations were built on the wells, in which pipes are naturally filled with water. Hydrophones were placed inside at the depth of 10–20 m from the water level. The analysis of seismic-acoustic signals received by these stations has demonstrated that seismic-acoustic noises emerge during ASP origin. Those noises spread within a radius of 300–500 km dozens of hours before the seismic waves are registered by ground seismic stations.

Synchronous robust analysis of seismic-acoustic signals received from all stations via satellite communication is undertaken in the process of the network operation. Estimates of the noise characteristics $R_{X\varepsilon}(\mu)$, $R_{X\varepsilon\varepsilon}(\mu)$, D_ε are transmitted to the server of the MC from the stations every 5 s (Fig. 2). The changes in them are used to indicate, for instance, the beginning of the ASP origin T_{1i} and T_{1j} for the *i*-th and *j*-th stations.

The operating experience of the stations demonstrates that each of them separately allows for reliable indication of the process of origin of ASP, which precedes an earthquake [39]. It also demonstrates that the results obtained by means of the network of those stations opens the way to developing an intelligent technology for identifying the location of the focus of an expected earthquake. To do that, we first determine the combinations of moments of indication T_{1i} and T_{1j} by means of the network of these stations. Those combinations and the coordinates of their location are source data to solve the problem of identifying the location of ASP origin. To raise the level of authenticity and reliability of the obtained results, it is reasonable to use time differences T_{1i}-T_{1j} for each selected pair of stations, alongside the combination of time of indication. In other words, solving the problem at hand requires determining not only the combination T_{1i}, T_{1j} but also the time of indication of ASP between the stations, i.e. the difference $\Delta\tau_{ij} = \left(\mathrm{T_{1i}} - \mathrm{T_{1j}}\right)$, as source data.

Our experiments have demonstrated that it is difficult to determine the beginning of the time of indication T_{1i} with sufficient accuracy using the values of the estimates of noise characteristics. Thus, considering the importance and necessity of enhancing the accuracy, the proposed system provides for duplication of the process of determining $\Delta\tau_{ij}$. It was also found to be reasonable to use the extreme value of the estimate of the cross-correlation function $R_{g_i g_j}(\mu_{\max})$ between the signals $g_i(i\Delta t)$ and $g_j(i\Delta t)$ obtained through different combinations of the RNM ASP stations to determine the time difference $\Delta\tau_{ij} = \left(\mathrm{T_{1i}} - \mathrm{T_{1j}}\right)$ by the following expressions:

$$R_{g_i g_j}(\mu_{\max}) = \frac{1}{N}\sum_{i=1}^{N} g_i(i\Delta t) g_j(i+\mu)\Delta t \tag{9}$$

$$R^*_{g_i g_j}(\mu_{\max}) = \frac{1}{N}\sum_{i=1}^{N} g_i^2(i\Delta t) g_j^2(i+\mu)\Delta t \tag{10}$$

$$R^*_{g_i g_j}(\mu_{\max}) = \frac{1}{N}\sum_{i=1}^{N} g_i(i\Delta t) g_j^2(i\Delta t) \tag{11}$$

In that case, the procedure for determining the difference in the time of monitoring between different stations on the MC server comes down to the following:

1. determining when the beginning of period T_{1i} of the ASP origin is registered by the first station Qum Island;
2. determining the time of monitoring for the second (Shirvan), third (Siazan), fourth (Naftalan), etc. stations;
3. determining the sets of estimates of cross-correlation functions $R_{g_v g_j}(i\Delta t)$, $R^*_{g_v g_j}(i\Delta t)$ by the expressions (9–11) and further, selecting from the obtained estimates those time shifts $\mu \cdot \Delta t$, at which the curve of the cross-correlation function has the peak value, i.e. the extreme value; these

time shifts are used to determine $\Delta\tau_{ij} = \left(\mathrm{T}_{1\mathrm{i}} - \mathrm{T}_{1\mathrm{j}}\right)$, i.e. the time difference in registration of ASP by the *i*-th and *j*-th stations, respectively;

4. using the found time differences $\Delta\tau_{1i} = \left(\mathrm{T}_{1\mathrm{i}} - \mathrm{T}_{1\mathrm{j}}\right)$ as source data to identify the location of the ASP focus.

Thus, in the proposed system (Fig. 2), the estimates of the noise characteristics $R_{X\varepsilon}(\mu)$, $R_{X\varepsilon\varepsilon}(\mu)$ and D_ε obtained as a result of ASP monitoring performed by the Qum Island, Shirvan, Siazan, Naftalan, Neftchala, Nakhchivan, Kopetdag (Turkmenistan), Qazakh and Cybernetic (Baku) RNM ASP stations are synchronously transmitted via satellite communication to the MC server. The obtained results are used to form the combination of sequences of indication times $T_{1i}\ T_{1j}$ and the combinations of time differences $\Delta\tau_{ij}$, which are used as source data to identify the location of an expected earthquake.

The experiments on the said stations carried out in the period from 01.07.2010 to 01.06.2014 have demonstrated the following active earthquake focuses in Azerbaijan and neighbouring regions within a radius of 500–600 km around the network of the RNM ASP stations.

1. Turkmen coast of the Caspian Sea;
2. in the Caspian Sea south of the Apsheron peninsula;
3. in the Caspian Sea north of the Apsheron peninsula;
4. in the Shirvan region of Azerbaijan;
5. in the north-western regions of Azerbaijan;
6. in the southern regions of Azerbaijan;
7. south of the Caucasus region of the Russian Federation;
8. in the north-eastern regions of the Republic of Iran;
9. in the north-western regions of the Republic of Iran (near Tabriz);
10. on the Iranian–Iraqi–Turkish border;
11. in the northern regions of Iran;
12. in the eastern regions of Turkey;
13. in the western regions of Georgia (Black Sea).

Some of the results of the registration of ASP in those focuses by the RNM ASP stations are given in [39].

Numerous earthquakes with magnitudes of 3,4 have occurred in those regions in the last 1.5–2 years. For each focus, the combinations of the sequence of the times of the ASP registration by Qum Island, Shirvan, Siazan, Neftchala, Naftalan and Nakhchivan by the RNM ASP stations practically repeated themselves. Our analysis of the recorded charts has demonstrated that each sequence combination of the time of the indication of the current ASP corresponds to one of the concrete earthquake focuses. After studying the problem of interpretation of the experimental materials for over 2 years, we have learned to identify the location of the focus of an expected earthquake, error-free intuitively, using these combinations of time. It then became obvious that the problem of identifying the location of an expected earthquake can be solved by using expert systems (ESs). This, in its turn, demonstrated the possibility of creating an ES which will allow seismologists to use the network of the RNM ASP stations as a tool to determine the focus of an expected earthquake.

The experimental version of the ES for identifying the location of the ASP focus (ESILF) proposed in this paper is based on the knowledge base (KB) comprising the totality of the sets $W_1, W_2, W_3, \ldots W_{13}$ of the locations of the respective focuses. The elements of each of these sets are formed from the data of the charts recording the parameters of all earthquakes registered by the RNM ASP stations in all 13 focuses from 01.07.2010 to the present day. Each element of the KB consists of the combination of the sequence of times of the ASP indication by the stations T_{1i}, T_{1j}, the combination of the differences in times of the indication $\Delta\tau_{ij}$, and from the combination of the estimates of the cross-correlation function $R_{X\varepsilon}(\mu=0)$. Each element of the KB also contains the value of magnitude M_i determined during the corresponding earthquakes by ground seismic stations. The date of the earthquake is also specified in each element. In the case when there is only one element, the KB appears as follows:

$$W_1\begin{Bmatrix} \mathrm{T}_{11}^{1(1)} & \mathrm{T}_{11}^{2(1)} & \dots & \mathrm{T}_{11}^{6(1)} & M_1 \\ \Delta\tau_{11}^{1} & \Delta\tau_{21}^{1} & \dots & \Delta\tau_{61}^{1} & M_1 \\ \mathrm{R}_{X\varepsilon}^{1(1)}(\mu=0) & \mathrm{R}_{X\varepsilon}^{2(1)}(\mu=0) & \dots & \mathrm{R}_{X\varepsilon}^{6(1)}(\mu=0) & M_1 \end{Bmatrix}$$

$$W_2\begin{Bmatrix} \mathrm{T}_{11}^{1(2)} & \mathrm{T}_{11}^{2(2)} & \dots & \mathrm{T}_{11}^{6(2)} & M_2 \\ \Delta\tau_{11}^{2} & \Delta\tau_{21}^{2} & \dots & \Delta\tau_{61}^{2} & M_2 \\ \mathrm{R}_{X\varepsilon}^{1(2)}(\mu=0) & \mathrm{R}_{X\varepsilon}^{2(2)}(\mu=0) & \dots & \mathrm{R}_{X\varepsilon}^{6(2)}(\mu=0) & M_2 \end{Bmatrix}$$

$$W_{13}\begin{Bmatrix} \mathrm{T}_{11}^{1(13)} & \mathrm{T}_{11}^{2(13)} & \dots & \mathrm{T}_{11}^{6(13)} & M_{13} \\ \Delta\tau_{11}^{13} & \Delta\tau_{21}^{13} & \dots & \Delta\tau_{61}^{13} & M_{13} \\ \mathrm{R}_{X\varepsilon}^{1(13)}(\mu=0) & \mathrm{R}_{X\varepsilon}^{2(13)}(\mu=0) & \dots & \mathrm{R}_{X\varepsilon}^{6(13)}(\mu=0) & M_{13} \end{Bmatrix}$$

Each set $W_1 - W_{13}$ of the experimental version of the KB consists of several dozens of such elements and new elements are added during each new earthquake. During the operation of the ES, after the monitoring and indication of the time of the beginning of the current ASP has been completed, the stations form the current combinations of the sequence of times of indication T_{1i}, T_{1j}, the combinations of differences in times of indication $\Delta\tau_{ij}$, and the combinations of the values of estimates $R_{X\varepsilon}(\mu)$.

On 05.01.2014, the experimental phase of the identification of the location of earthquake focuses by ESILF was launched. This phase is carried out as follows. The current element is formed based on the results of monitoring of the network of RNM ASP stations. After that, the current element is compared with all elements of the sets $W_1, W_2, W_3, \dots W_{13}$ in the identification unit of the expert system (IUES). If it matches any element of any set, the location of the focus of an expected earthquake is identified based on the number of the current element. The number of the ASP focus is saved in the decision-making unit (DMU) of the ES. At the same time, the current element is entered into the set of the KB. Thus, new elements are continuously written into the KB during the ESILF operation and the network of RNM ASP stations and ESILF operate as a single system.

To check the authenticity and reliability of the identification of the location of the ASP focus, the described ESILF was tested during all subsequent earthquakes. The obtained results have demonstrated the real possibility of practical application of the experimental version of ESILF to identify the location of the ASP focus, which creates prerequisites for using the system in question as a tool in determining the location of the focus of an expected earthquake. Taking this prospect into account, a function of forming the following information and providing it to seismologists was included in the list of basic functions of the DMU of ESILF:

1. date of the current ASP and the number of the focus of the expected earthquake;
2. results of the current monitoring performed by the RNM ASP stations;
3. estimated lead time at the beginning of ASP monitoring compared with the time of registration of

the expected earthquake by ground seismic stations;

4. list of all elements previously registered in the corresponding set during the origin of the previous ASP in the estimated location of the focus of the expected earthquake (with dates);
5. the amount of elements matching the current elements;
6. magnitudes of previous earthquakes;
7. minimum magnitude of the expected earthquake;
8. if the KB contains no elements matching at least some of the elements in the sets $W_1 \div W_{13}$, information on the impossibility of identifying the earthquake focus is formed in the DMU.

5. Technology for determining the approximate value of magnitude of an expected earthquake using a neural network. The analysis of the results of the experimental identification of the location of the ASP focus has demonstrated that, with the current estimates $R_{X\varepsilon}(\mu)$, $R_{X\varepsilon\varepsilon}(\mu)$, D_ε and knowing the distance from the focus to the RNM ASP stations, it is possible to determine the approximate value of the minimum magnitude of an expected earthquake using a neural network. Research shows that neural networks can be used for this purpose [47, 48]. It was found that it is appropriate to use the information contained in the sets $W_1 \div W_{13}$ to train neural networks. Fig. 3 shows the block diagram of the neural network (N3=1) functioning in the following way. The content of the corresponding elements of the sets $W_1, W_2, W_3, \dots W_{13}$ is transmitted to the outputs $X_1, X_2, \dots, X_{N1}$ of the neuron, i.e. the combinations of times of the ASP indication T_{1ij}, differences of indication time $\Delta\tau_{ij}$ and the estimate $R_{X\varepsilon}(\mu = 0)$ are received at the inputs of the neuron one by one; the magnitude M_i of the earthquake registered by ground stations is established at the output of the neuron. The training is carried out successively from earthquake focus I to earthquake focus XIII. For instance, during the training of the neuron on focus III, i.e. during the earthquake with the focus in the Caspian Sea, the monitoring results obtained at the stations in Siazan, Qum Island, Neftchala and Kopetdag (Turkmenistan) are successively transmitted from the KB to the inputs of the neuron. The value of the magnitude M_3 is given to the output.

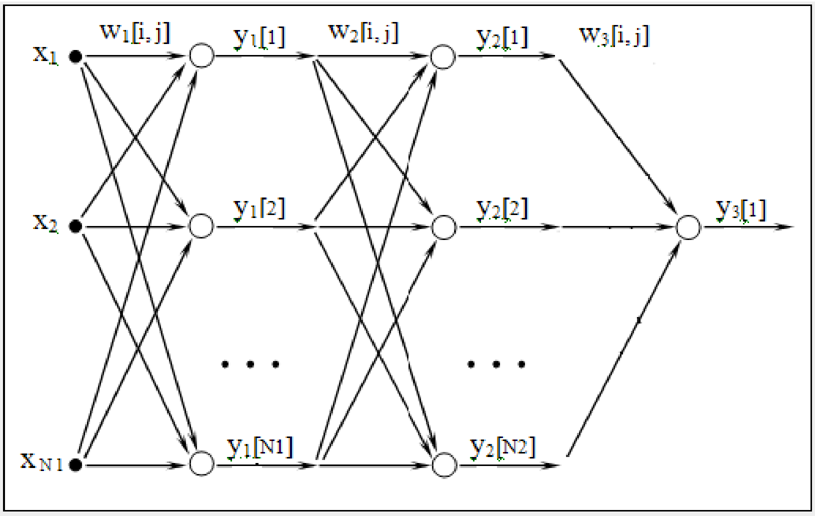


Fig. 3. *Structure of the neural network of the intelligent seismic-acoustic system*

During the training of the neuron to determine the magnitude in focus XII, i.e. in East Turkey, then the monitoring data of Qazakh, Naftalan, Shirvan and Nakhchivan are sent to the input of the neuron and the magnitude M_{12} goes to the output. Thus, the parameters of the ASP monitoring previously registered by the

RNM ASP stations are used for the neural network training. At the same time, the coordinates of the location of the earthquake focus are used in the DMU to determine the approximate distance S_I between the stations and the focuses, which are also transmitted to the inputs of the neural network. Based on the source data written in the elements of the sets $W_1 - W_{13}$ and the distances $S_1 - S_9$ from the ASP focus to each station, the neural network learns to determine the approximate magnitude of an expected earthquake. Owing to this, after the training stage and in the process of the current monitoring of the ASP, when the current combinations of corresponding estimates are transmitted to the neuron outputs, the code of the corresponding magnitude M of the expected earthquake forms on the output y_3[1]. The result is sent to the input of the DMU of ESILF.

During the operation of the neural network and the ES, every time the coordinates and approximate magnitude of every expected earthquake have been identified, the obtained results are compared with the coordinates and magnitude of actual earthquakes registered by ground seismic stations. The obtained difference is further used to correct the KB and in the training of the neural network. Therefore, the KB is improved in the course of time, with the training level of the neural network constantly improving. This results in increased reliability, authenticity and adequacy of identification of the location and magnitude of expected earthquakes.

Analysing the experience of the use of the ES in identifying the location of the focus of the expected earthquake and of the neural network in determining its magnitude has demonstrated that improved reliability and authenticity of the obtained results requires increasing the number of RNM ASP stations. Taking this into account, since the beginning of 2013, a station in the Nakhchivan Autonomous Republic near the border with Turkey and Iran (Fig. 1) and Kopetdag station in Turkmenistan (Fig. 1) have been commissioned. On 01.07.2013, another station was built in the Qazakh region on the border with Georgia (See Fig. 1) and at the Institute of Cybernetics (Baku).

It should be noted that the results of the experimental monitoring of the station built in the basement of the Institute of Cybernetics in a 10-m deep well practically match the readings of the Qum Island station built in a 3500-m deep well.

6. Results obtained by the intelligent system identifying focuses of expected earthquakes from 01.01.2014 to 02.07.2014. As was mentioned earlier, the test operation of the system under discussion started on 06.01.2014. In this period, some identification errors were detected during weaker earthquakes (less than 2.5÷3.5 points). Besides, we also detected erroneous identification results at 2–3 RNM ASP stations simultaneously during a malfunction of the power supply system, communication systems and hydrophone, controller and other units. In the normal state of operation of all RNM ASP stations, no errors were detected in the results of the identification of the location of focuses of expected earthquakes with strength exceeding 5 points.

The list of the location of focuses of expected earthquakes identified from the archived monitoring results in 2013–2014 is very long, which is why Table 1 below contains only the results of 11 identified focuses of expected earthquakes with magnitude over 5 points from 01.01.2013 to 06.07.2014. Figs. 4–13 are the recorded ASP charts that preceded those earthquakes. The data in the first column in Table 1 are taken from the website of the Euro-Mediterranean Seismological Centre (EMSC) (http://www.emsc-csem.org/#2).

The time of the earthquakes in Table 1 is given in UTC as provided by the EMSC website. The charts show the local time (Baku time), which is UTC+4 in the winter and UTC+5 in the summertime.

Column 22 of Table 1 provides information on the locations of the identified focuses of expected earthquakes. To demonstrate the validity of those results, each row of the table is accompanied by relevant charts (Figs. 4–13) recorded by the RNM ASP stations during the origin of the respective ASPs.

In column 2 of the table, the earthquake magnitudes are given in **ML, mb,** Mw. (In 1935, Charles Richter developed the local magnitude, ML scale for moderate-size (3 < ML < 7) earthquakes in southern California. The ML scale is often called the “Richter scale” by the press and the public. Other units are determined relative to the Richter scale for different situations.

Sign "*" in Table 1 means that the station gave a weak reaction to the origin of the ASP of the expected earthquake. Sign "-" means that the value of the registered value of $R_{\chi_\varepsilon}(\mu)$ is lower than the threshold level.

Table 1. Identified focuses of expected earthquakes

№	**Date, time, coordinates, magnitudes and depth of earthquake epicenter**	$\Delta\tau_{12}$	$\Delta\tau_{13}$	$\Delta\tau_{14}$	$\Delta\tau_{15}$	$\Delta\tau_{16}$	$\Delta\tau_{17}$	$\Delta\tau_{18}$	$\Delta\tau_{19}$	$R_{1\chi\varepsilon}$
1	**2**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	2013-03-26 23:35:24.0 UTC 43.219 N;41.637 E mb 5.1; 10 km	35	-120	-	135	*	-	*	-	300
2	2013-05-28 00:09:52.0 UTC 43.22 N; 41.58 E mb 5.2; 2 km	-115	-150	-250	-	*	-	*	-	150
3	2013-09-17 04:09:14.0 UTC 42.17 N; 45.89 E mb 5.0; 10 km	-	-150	-	390	*	120	*	-	100
4	2013-09-17 04:09:13.0 UTC 42.13 N; 45.80 E Mw 5.1; 2 km	-	-150	-	390	*	120	*	-	100
5	2013-11-24 18:05:41.0 UTC 34.06 N; 45.52 E mb 5.6; 2 km	-	*	-	-10	-60	*	*	-	160
6	2014-01-10 00:45:32.0 UTC 41.77 N; 49.31 E ML 5.0; 87 km	-	20	-	110	*	-	-10	-	110
7	2014-01-14 13:55:02.0 UTC 40.38 N; 52.97 E mb 5.1; 50 km	-	-45	*	-120	*	*	-	-	160
8	2014-01-28 23:47:38.0 UTC 32.52 N; 49.98 E ML 5.1; 33 km	-135	-	-	100	-300	-	-	-	120
9	2014-02-10 12:06:48.0 UTC 40.23 N; 48.63 E Mw 5.4; 55 km	-300	-	-	-	45	75	-	-	75

10	2014-06-07 06:05:32.1 UTC 40.32 N; 51.55 E mb 5.6; 50 km	145	20	-	-70	-	-	-	120	80
11	2014-06-29 17:26:10.4 UTC 41.62 N; 46.68 E mb 5.1; 20 km	305	-85	-	-	-	315	*	-	100

№	$R_{2\chi\varepsilon}$	$R_{3\chi\varepsilon}$	$R_{4\chi\varepsilon}$	$R_{5\chi\varepsilon}$	$R_{6\chi\varepsilon}$	$R_{7\chi\varepsilon}$	$R_{8\chi\varepsilon}$	$R_{9\chi\varepsilon}$	**Number and location of the focus of expected earthquake**
13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
1	50	100	-	140	-	-	-	-	Georgia (Sak'art'velo)
2	150	160	250	-	-	-	-	-	Georgia (Sak'art'velo)
3	-	40	-	80	-	80	-	-	Caucasus Region, Russia
4	-	40	-	80	-	80	-	-	Caucasus Region, Russia
5	-	-	-	150	250	-	-	-	Iran-Irag Border
6	-	110	-	110	-	-	40	-	Caspian Sea, Offshore Azerbaijan
7	-	100	-	120	-	-	-	-	Turkmenistan
8	110	-	-	-	180	-	-	-	Western Iran
9	130	-	-	-	260	230	-	-	Azerbaijan
10	25	40	-	100	-	-	-	80	Offshr Turkmenistan
11	20	120	-	-	-	25	-	-	Azerbaijan

The first row of the table shows the results of the identification of the focus of the earthquake that occurred in Georgia on 26.03.2013. It follows from Fig. 4 that its beginning was indicated by the RNM ASP stations in the following order: Siazan – 04:15; Qum Island – 04:30; Shirvan – 06:50; Neftchala – 08:30. Even though the Naftalan station was not operating at the time, the system identified that such an indication corresponded to focus VII. The indication was 8–10 hours in advance of the earthquake.

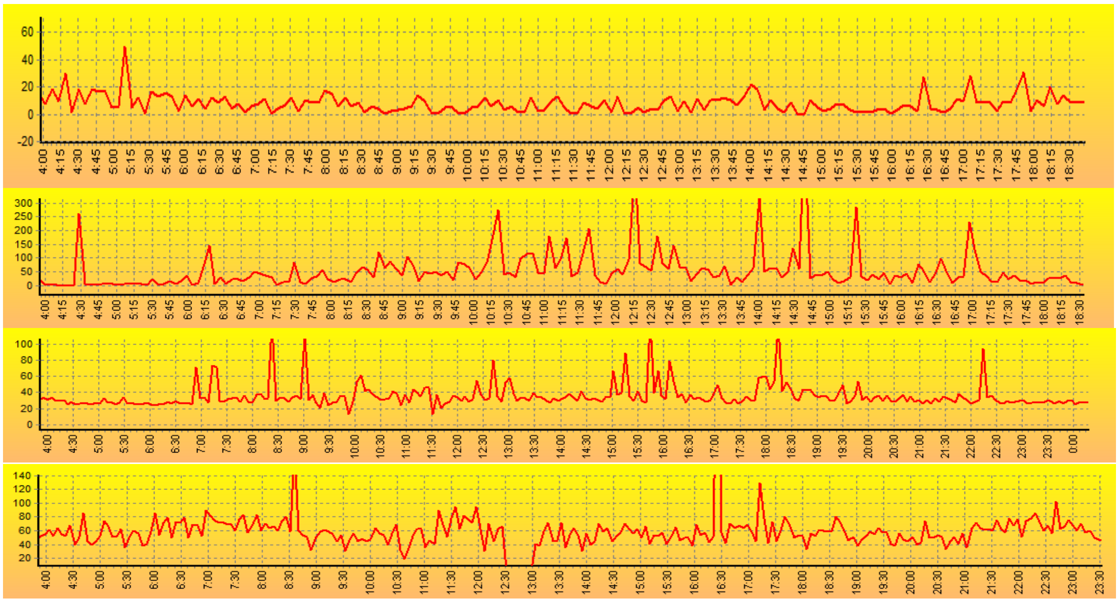


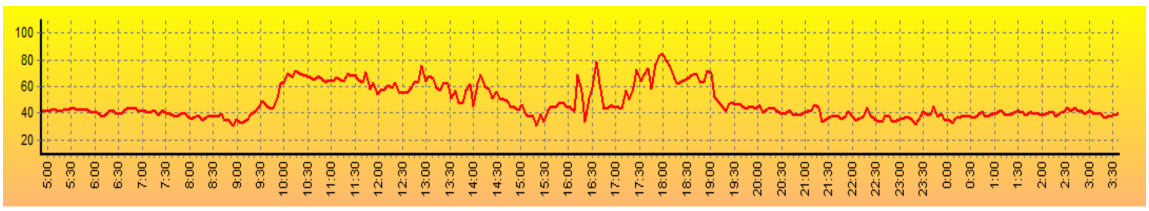
Fig 4. *VII – Siazan, Qum Island, Shirvan, Neftchala 2013-03-26 Georgia-Russia*

Row 2 of the table gives the results of the identification of the focus of the earthquake that occurred in Georgia on 27.05.2013/28.05.2013. According to the chart, the RNM ASP stations Siazan, Naftalan, Shirvan and Qum Island registered the ASP origin more than 20 hours before the earthquake, despite the malfunction of the Naftalan station. It is clear from the charts that the northern (Siazan) and north-western (Qum Island) stations detected an anomaly earlier than the rest of the stations. The beginning of the anomalous processes was indicated by the RNM ASP stations in the following order: Naftalan – 07:30; Siazan – 09:10; Shirvan – 09:45; Qum Island – 11:40. Thus, the earthquake focus was identified by the system by approximately 18:00 Baku time, which is almost 10–11 hours earlier than the time of registration by the ground stations.

Fig. 5. *VII – Siazan, Naftalan, Shirvan, Qum Island 2013-05-27 2013-05-28 00:09:52.0 UTC mb 5.2 Georgia (Sak'art'velo)*

Rows 3 and 4 of the table show the results of the identification of the focus of the earthquakes that occurred in South Russia on 16.09.2013.

According to the charts of the third and fourth earthquakes (Fig. 6), the ASP originated in the south-east of the Caucasus region and registered in the following order: Siazan – 05:30, Qum Island – 08:00, Qazakh – 10:00, Neftchala – 14:30. Based on this sequence of registration times, the system identified earthquake focus VII, which corresponds to the north-east of Azerbaijan, where an earthquake actually occurred at 16:00/17:00 Baku time. The time of the focus identification was approximately 15 hours in advance of the earthquake.



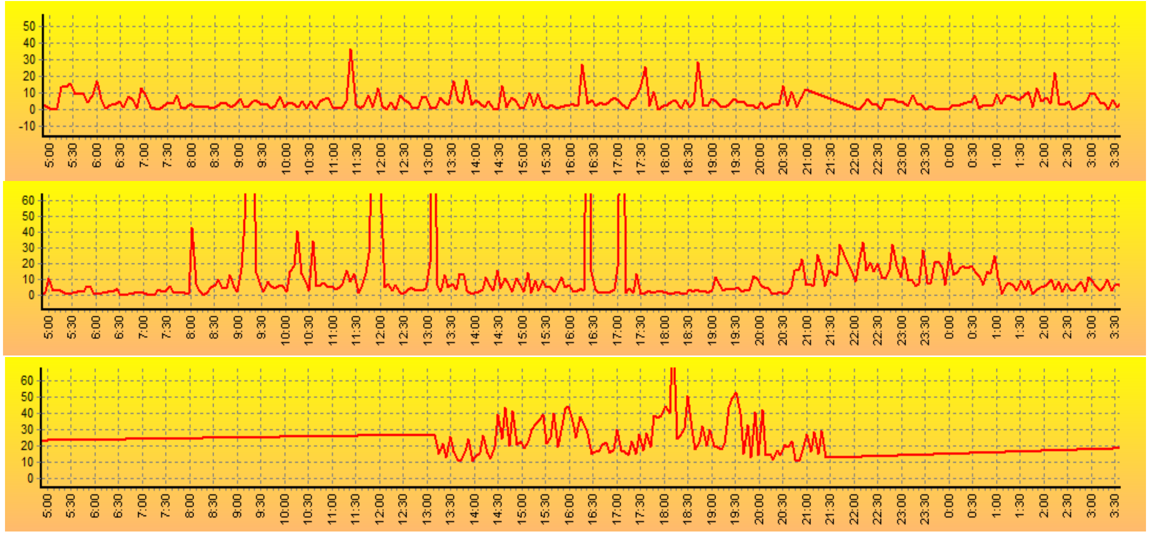


Fig. 6. *VII - Qazakh, Siazan, Qum Island, Neftchala 2013-09-16 42.17 N ; 45.89 E Russia*

According to the chart in Fig. 7, based on the combination of times of registration by the stations Nakhchivan – 08:00; Qum Island – 09:00; Neftchala – 08:50, the system identified the focus of the expected earthquake on the Iran–Iraq border 12 hours beforehand.

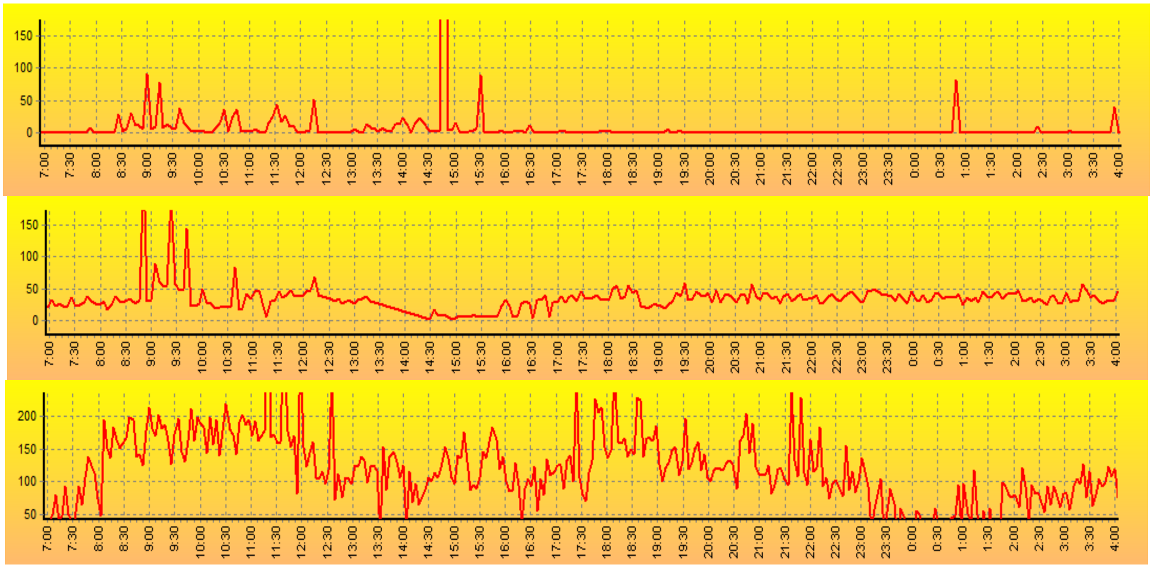


Fig. 7. *X - Qum Island, Neftchala, Nakhchivan 2013-11-21 Iran-Iraq border*

Fig. 8 shows the results of the identification of the focus of the earthquake that occurred on 2014-01-09, at about 12:00, in the Caspian Sea, Offshore Azerbaijan, and was registered by the stations Turkmen01 – 09:15, Qum Island – 09:25, Siazan – 09:45, Neftchala – -11:15, 16 hours in advance of the earthquake.

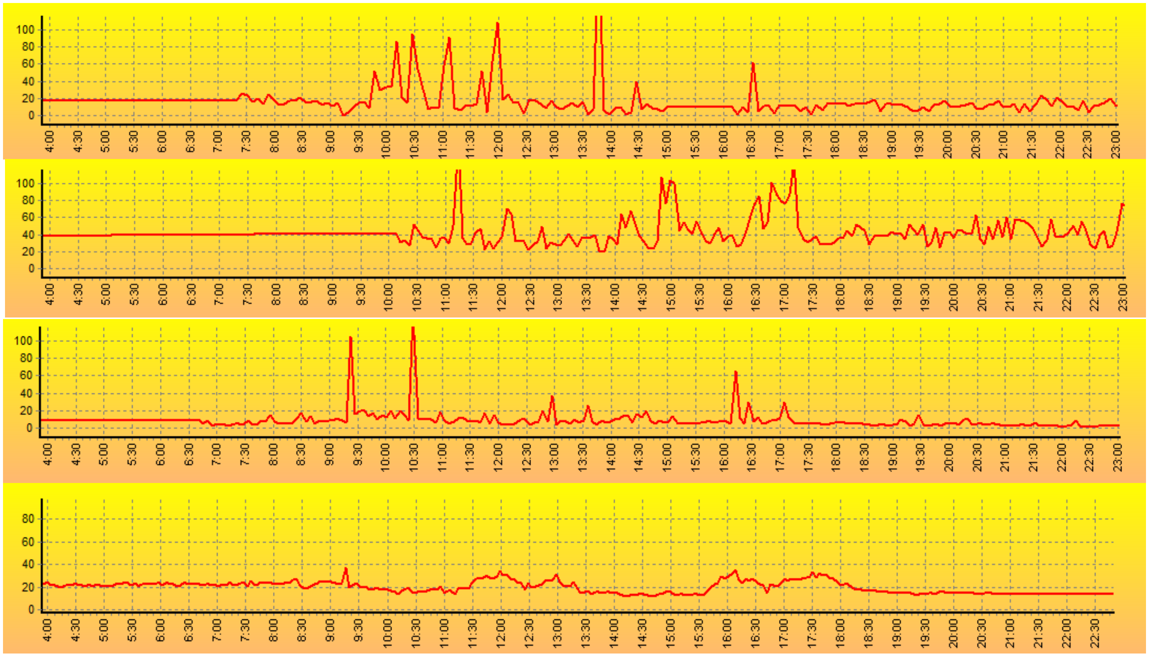
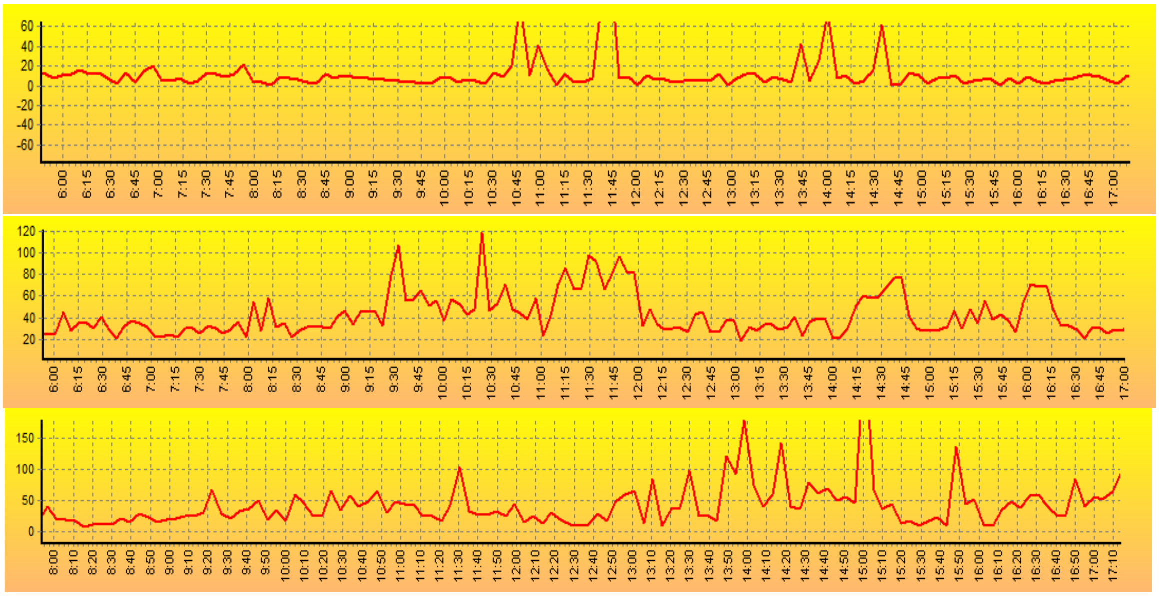


Fig. 8. *III - Siazan, Neftchala, Qum Island, Turkmen01 2014-01-09 Caspian Sea, Offshore Azerbaijan*

Row 7 of the table shows that the system identified the focus of the expected earthquake in Turkmenistan. According to the chart in Fig. 9, based on its sequence of registrations by the stations Neftchala – 09:30, Siazan – 10:45, Qum Island – 11:30, the system demonstrated that the location of the expected earthquake was in Turkmenistan, i.e. in focus I east of Azerbaijan. The focus of the expected earthquake was identified more than 24 hours before the earthquake was registered.



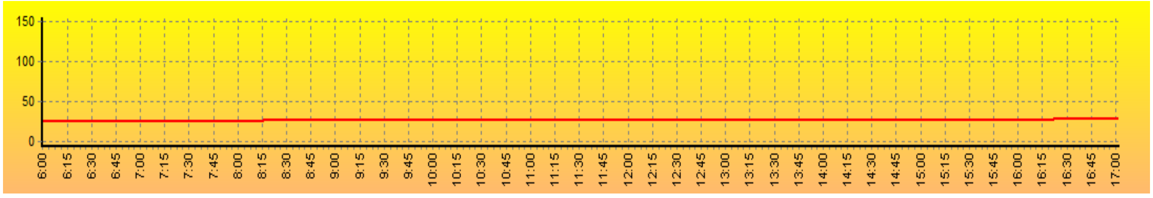


Fig. 9. *I - Siazan, Neftchala, Qum Island, Turkmen01 2014-01-13 Turkmenistan*

Row 8 of Table 1 shows the results of the identification of the focus of the earthquake that occurred in Western Iran. According to Fig. 10, the sequence of registrations by the stations Qum Island – 09:45, Shirvan – 07:30, Nakhchivan – 04:50 and Neftchala – 11:20 (TTTT), allowed the system to identify the location of the earthquake in focus IX – Western Iran.

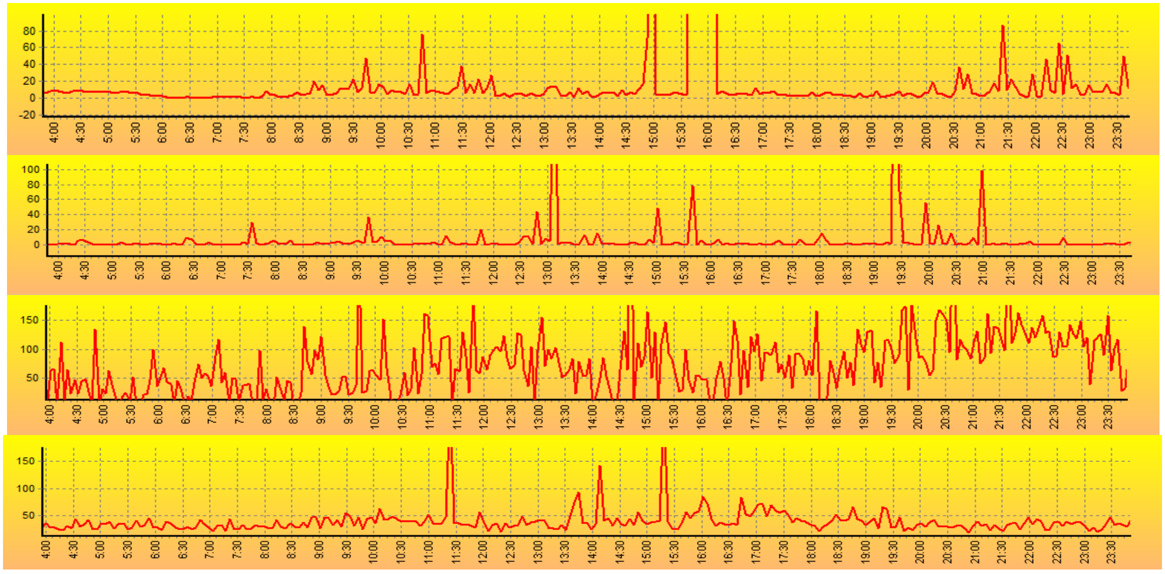
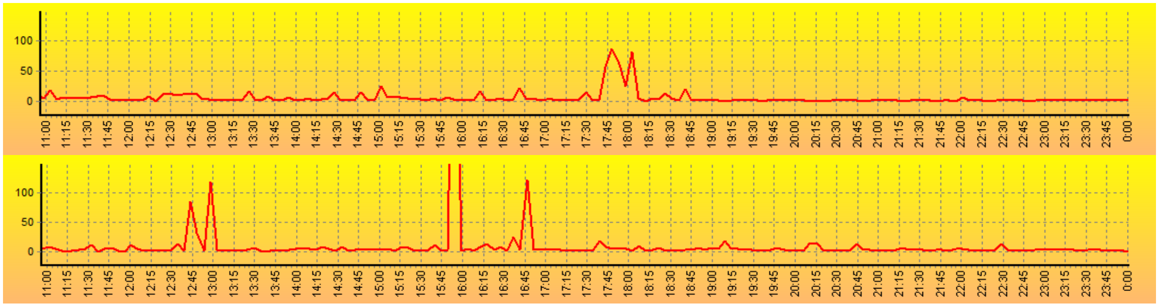


Fig. 10. *IX - Qum Island, Shirvan, Nakhchivan, Neftchala 2014-01-28*
2014-01-28 23:47:38.0 UTC ML 5.1 WESTERN IRAN

Row 9 of Table 1 shows the results of the identification of the focus of the earthquake that occurred in Azerbaijan. According to the charts in Fig. 11, the stations registered the corresponding ASP in the following order: Qum Island – 17:45, Shirvan – 12:45, Qazakh – 19:00 and Nakhchivan – 18:30, which allowed the system to identify the number (IV) of the focus of the expected earthquake with a lead time of 19 hours.



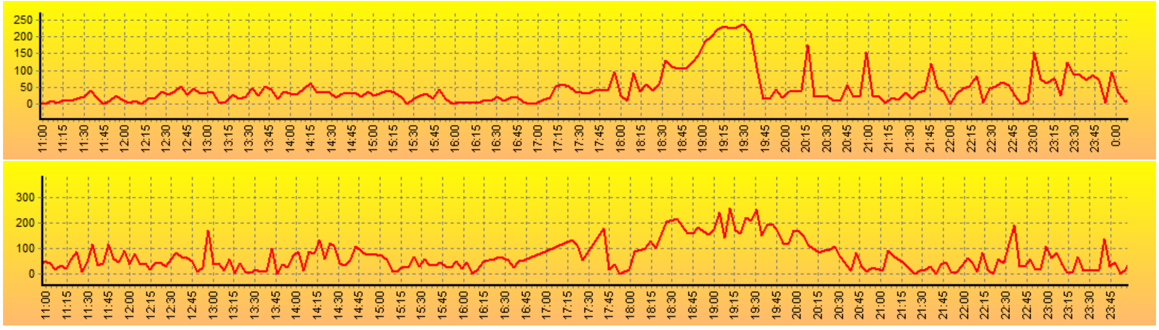
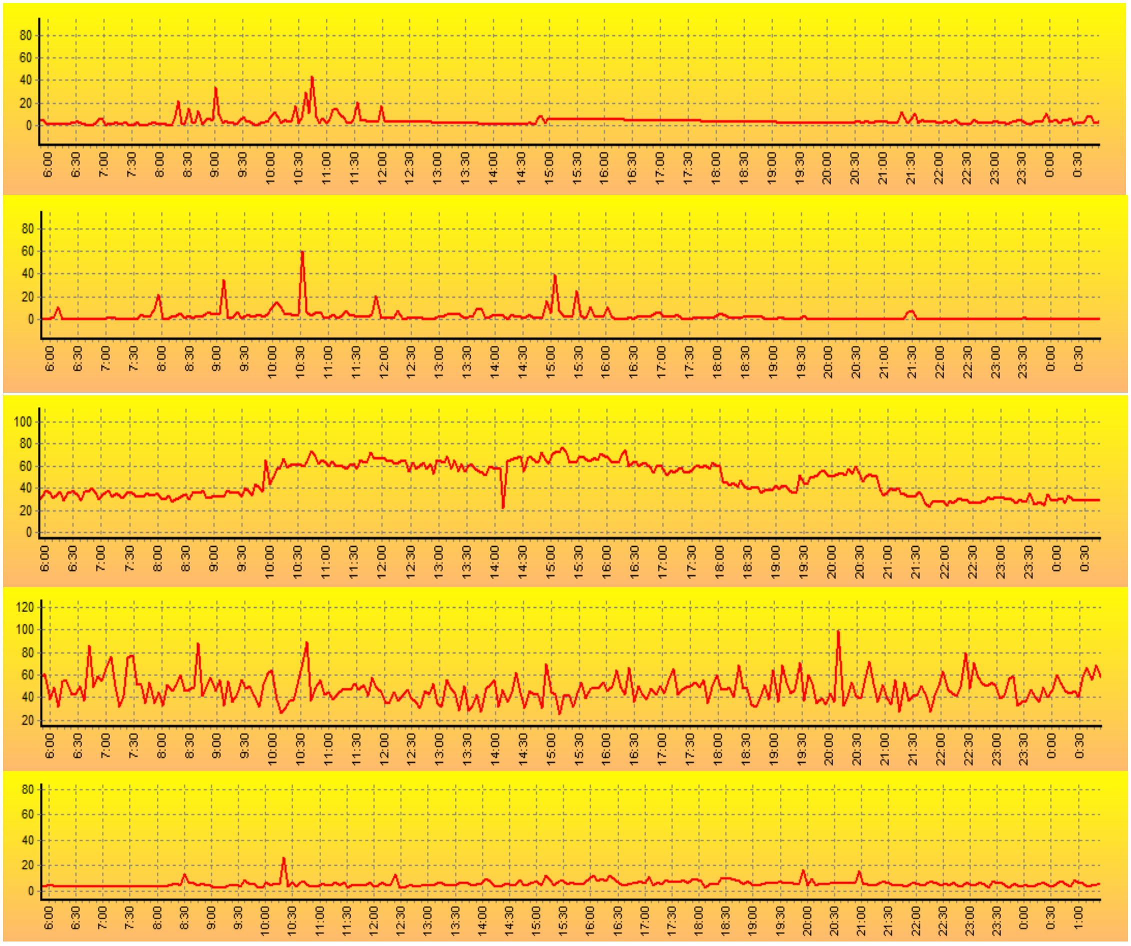


Fig. 11. *IV - Qum Island, Shirvan, Qazakh, Nakhchivan 2014-02-09*
2014-02-10 12:06:48.0 UTC Mw 5.4 AZERBAIJAN

Row 10 of Table 1 shows the results of identification of the focus of the earthquake that occurred in Offshore Turkmenistan. According to the charts in Fig. 12, this event was registered by the stations Neftchala – 06:45, Qum Island – 07:55, Siazan – 08:15, Cybernetic – 09:55, Shirvan – 10:20.



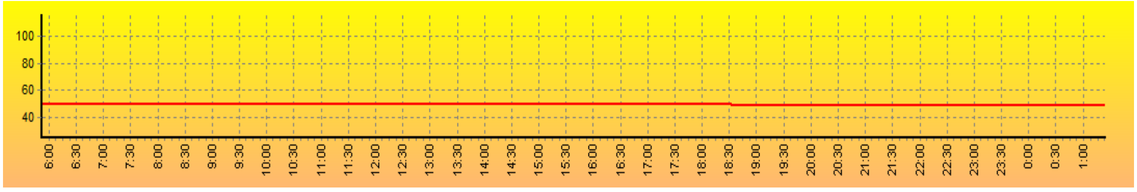


Fig. 12. *I - Siazan, Qum Island, Cybernetic, Neftchala, Shirvan, Turkmen01 2014-06-06*
2014-06-07 06:05:32.1 UTC mb 5.6 CASPIAN SEA, OFFSHR TURKMENISTAN

Row 11 of Table 1 contains the information on the identification of the location of the expected earthquake that occurred in focus I in Azerbaijan. It follows from Fig. 13 that the anomaly was indicated by the stations in the following order: Siazan – 00:50, Qum Island – 02:15, Shirvan – 07:20, Qazakh – 07:30, which allowed the system to identify the location of the focus of the expected earthquake (Azerbaijan).

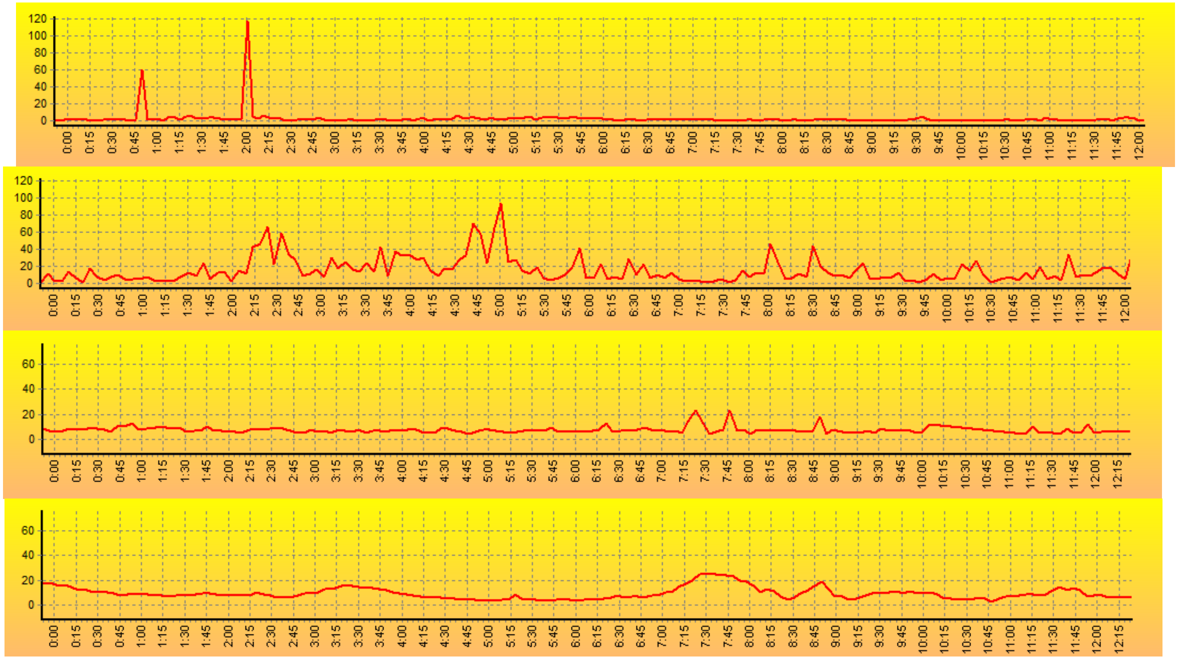


Fig. 13. *Siazan, Qum Island, Shirvan, Qazakh 2014-06-29*
2014-06-29 17:26:10.4 UTC mb 5.1 AZERBAIJAN

7. Conclusions.

1. The intelligent system based on the network of the RNM ASP stations and an ES combined with a neural network system can be used as a tool for identifying the location of the focus of an expected earthquake. The seismologist is supplied with the information containing the direction and the number of the focus of the expected earthquake, current combinations of the ASP, and amount, list, date and magnitude of similar combinations registered in the given focus during previous earthquakes. This information will allow the seismologist to evaluate the degree of authenticity of the obtained information on the location of the focus of the expected earthquake. Having enough time before the earthquake occurs, the seismologist can involve other specialists in the decision-making process if there is any doubt, ruling out an accidental error.

2. The RNM ASP stations in the network of the proposed system are built on wells with different depths and, consequently, different characteristics. These characteristics are difficult to take into account in identifying the location of the focus of an expected earthquake and in determining its magnitude.

Moreover, as the depth of a well increases, its cost increases sharply, too. For instance, to drill a 4000–

5000 m deep well costs 20–30 million dollars; this makes the building of the RNM ASP stations in the countries that have no suspended oil wells quite challenging.

Considering the above-mentioned arguments, we recommend forming a network of stations built in 50–100-m deep water wells in the future, with hydrophones placed in the water column at a depth of 10–20 m. To improve the authenticity and reliability of the identification of the location of the focus of the expected earthquake, we found it appropriate to build a network consisting of a large number of stations (over 10–15) in wells of equal depth located at an equal distance from one another. Integration of the network of the RNM ASP stations of the countries in several seismically active regions via satellite communication can, in the long term, allow for increasing the authenticity and reliability of determining the coordinates of the location of an expected earthquake.

3. Our experiments have demonstrated that the reliability of the ASP monitoring results and the validity of the results of identification of the location of the focus of an expected earthquake grow with the growth in earthquake strength. With the strength exceeding 5 points, the results of the identification of the earthquake location proved to be valid in almost all cases. The value of the estimate of the cross-correlation function $R_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ decreases as the distance from the earthquake focus grows. The value of the estimate of noise variance D_ε increases as the distance from the focus grows; the correlation $R_{X\varepsilon}(\mu)/R_{X\varepsilon\varepsilon}(\mu)$ decreases with distance and $D_\varepsilon/R_{X\varepsilon\varepsilon}$ increases. The propagation velocity of the seismic-acoustic noise in different types of medium, e.g. water, sand or clay, significantly varies. There is a correlation between the well depth and the radius of the ASP monitoring.

4. The experiments at the Qum Island station in the Caspian Sea have demonstrated that the monitoring range of that station is much wider than that of the stations located far from the Caspian Sea. Other stations in Siazan and Neftchala located near the Caspian Sea also have a wide monitoring range compared with other stations. Practically all seismic processes reaching the Caspian Sea are clearly registered by those stations. Therefore, in building networks of new stations, one should consider the fact that the sea is a “perfect conductor” for seismic-acoustic noises emerging during ASP origin in the region.

5. The results obtained from the experimental data allow for the assumption that the lead time of the registration of the ASP origin by a seismic-acoustic RNM ASP station over standard seismic equipment is due to two factors.

First, seismic-acoustic waves that arise in the beginning of the ASP origin do not reach the Earth’s surface due to the frequency characteristics of certain upper strata, which furthers their horizontal spread in deep strata as noise. Reaching the steel pipes of the well, seismic-acoustic waves transform into acoustic signals and go to the ground surface at the velocity of sound, where they are detected by a hydrophone. At the same time, low frequency seismic waves from seismic processes are perceived at the surface after a certain amount of time, when the earthquake is already in progress, and are registered by seismic receivers of standard ground equipment much later.

Second, the use of noise technologies by analysing seismic-acoustic noise allows one, with the emergence of correlation between the useful signal and the noise, to register the ASPs in the beginning of their origin. These two factors make it possible for RNM ASP stations to indicate the time of the beginning of the ASP origin much earlier than is done by stations of the seismic survey service.

6. Seismic-acoustic stations of ASP monitoring can also be used for monitoring the latent period of volcano formation well before the eruption. Their use will also allow the monitoring, on a regional basis, of the testing of minor and major nuclear bombs and other experiments related to the manufacture of military equipment.

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A.M. Paşayev, A.A. Əlizadə, T.A. Əliyev, A.M. Abbasov, Q.A. Quluyev, F.H. Paşayev, Ü.E. Səttarova. **Gözlənilən zəlzələ ocağının təyin edilməsi üçün İntellektual Seysmoakustik Sistem.**

Anomal seysmik proseslərin 10, 200, 300, 1400-5000 m dərinliyində quyular üzərində qurulmuş doqquz seysmoakustik stansiyada 01.07.2010 tarixindən 01.06.2014 tarixinə qədər aparılan monitorinqinin nəticələri analiz edilmişdir. Üç ildən çox müddətdə əldə edilmiş eksperimental məlumatlar əsasında faydalı siqnalla $X(i\Delta t)$ *küy* $\varepsilon(i\Delta t)$ *arasında qarşılıqlı korrelyasiya* $R_{X\varepsilon}(\mu)$ *funksiyasının qiymətlərinin dəyişmə vaxtlarının kombinasiyalarına görə ASP ocağının koordinatlarını zəlzələdən 10-20 saat əvvəl müəyyən etməyə imkan verən intellektual sistem yaradılmışdır. Sistem gələcəkdə seysmoloqlar tərəfindən gözlənilən zəlzələnin ocağının yerinin təyin edilməsində instrumental vasitə kimi istifadə edilə bilər.*

Açar sözlər: seysmoakustik siqnal, zəlzələ ocağı, küy dispersiyası, qarşılıqlı korrelyasiya funksiyası, biliklər bazası, ekspert sistemi, intellektual sistem, neyron şəbəkə

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А.М. Пашаев, А.А. Ализада, Т.А. Алиев, А.М. Аббасов, Г.А.Гулуев, Ф.Г. Пашаев, У.Э. Саттарова. **Интеллектуальная сейсмоакустическая система выявления местонахождения очага ожидаемого землетрясения.**

Анализируются результаты noise мониторинга аномальных сейсмических процессов (АСП), проводимых с 01.07.2010 по 01.06.2014 на девяти сейсмоакустических станциях, построенных на устье скважины глубиной 10, 200, 300, 1400-5000 м. По результатам экспериментальных данных, полученных в течение более трех лет, создана интеллектуальная система, позволяющая по комбинациям времени изменения оценки взаимнокорреляционной функции $R_{X\varepsilon}(\mu)$ *между полезным сигналом* $X(i\Delta t)$ *и помехой* $\varepsilon(i\Delta t)$ *сейсмоакустической информации, полученной от различных станций за 10-20 часов до землетрясения, выявить местонахождение его очага. Система, в перспективе, может быть использована сейсмологами, как инструментарий при определении местонахождения очага ожидаемого землетрясения.*

Ключевые слова: сейсмоакустический сигнал, очаг землетрясений, дисперсия шума, взаимнокорреляционная функция, база знаний, экспертная система, интеллектуальная система, нейронная сеть

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