Possibilities of Enhancing the Safety of Rail Transport in Seismically Active Regions with the Application of Intelligent Seismic-Acoustic Technologies and Systems

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***Abstract*—The specific features of solving the problem of ensuring safety of railroads in seismically active regions necessitates taking into account seismic information across large territories. This, first of all, requires determining the area of the focus of the expected earthquake. It is also necessary here to take into account the information accumulated earlier by ground seismic services. The authors consider technologies for obtaining and analyzing seismic-acoustic signals from deep strata of the earth and versions of a network of seismic-acoustic stations for noise monitoring of the beginning of an earthquake preparation based on the analysis of seismic-acoustic signals. It has been established that the results of the analysis of seismograms obtained from deep strata of the earth by means of hydrophones allows detetcing the beginning of the earthquake preparation with sufficient reliability 10-25 hours in advance. Experiments have shown that the reliability and adequacy of these results can be increased by integrating the operation of seismic-acoustic stations of neighboring seismically active regions. The location of the earthquake focus area using the proposed decision-making system is determined as follows. Based on the results of the monitoring by the network of stations, the current combination of informative attributes is formed. They are saved and used in the learning process to form the corresponding reference sets, and in the process of further analysis of the current data, it is compared with all elements of the specified sets. Thus, during the training process of the system, new combinations of informative attributes of seismic-acoustic signals are constantly saved. When the system operates in the monitoring mode, if the current informative attributes match the elements in the reference set, the location of the expected earthquake area is identified by its number. Thus, the network of stations operates in combination with the monitoring center and the decision-making system as a whole. The stations are built on wells of different depths and make it possible to use an intelligent seismic-acoustic system in seismically active regions to warn about the area of the focus of an expected earthquake. In this case, saving, i.e., archiving of the relevant information from all stations is carried out using cloud technology. An integration of networks of stations of the countries in several seismically active regions can, in the long term, allow increasing the validity and reliability of determining the coordinates of an expected earthquake. Due to this, the railroad traffic safety service can get all necessary information on the seismic situation in the region, which will allow them to take appropriate measures in a timely manner.**

Keywords*—rail transport, seismically active regions, safety, seismic technologies, intelligent systems, early warning systems

I. INTRODUCTION

An analysis of the literature [1, 2] devoted to control technologies and control systems taking into account the specific characteristics of railroads has shown the importance of taking into account the specifics of seismic processes, which will allow improving the safety of this mode of transport in seismically active regions. To do this, it is reasonable to create warning systems that alert to the beginning of seismic processes, as well as appropriate technologies for the control of the latent period of the beginning of malfunctions in the railbed, bridges, tunnels and communications throughout the entire railroad track.

In this case, the traffic control service to receive additional information in advance, which allows taking appropriate actions to improve traffic safety in general

It is known that one of the main requirements for a railroad track is that all its elements, track superstructure, artificial structures, as well as the roadbed, must have adequate strength, stability and condition to ensure safe and smooth movement of trains at the speeds established for this particular section [1-6]. The control of the condition of the railroad track superstructure is mainly carried out under dynamic load [2-4].

In recent years, self-propelled flaw detectors [3-5] equipped with radio communications have been actively introduced to transmit information about detected violations to the duty officers at stations on both ends of a haul. In the end all the information is sent to the track maintenance department [2-5]. However, despite these efforts, wrecks of freight and passenger trains still occur frequently. This is due to the fact that it is currently impossible to carry out continuous control of the technical condition of the railway. As our studies have shown, by solving such problems as ensuring continuous control of the latent period of changes in the technical condition of railroad tracks, railroad bridges, tunnels, crossings, etc., it is possible to enhance the safety of rail transport. This is particularly important for rail transport in the countries located in seismically active regions. This is due to the fact that weak, 1–3-point earthquakes often occur in these regions, affecting the technical condition of the railroad tracks, bridges, tunnels and communications. As a rule, they do not result in great destruction. But each such earthquake is a potential factor contributing to the beginning of the latent period of changes in the facility's technical condition. In this regard, the new technologies and systems to ensure the safety of rail transport in seismically active regions is of undoubted practical interest [2-4].

II. Problem Statement

With the development of high-speed train traffic, the requirements for objects and devices of railroad infrastructure are becoming more stringent, both for the quality of determining the occupancy of the track and for the condition of the rail line, the track superstructure (ballast), on which the qualitative characteristics of performance, safety and uninterrupted operation of trains depend. To ensure the safety of the track, it is necessary to obtain sufficient information to monitor the technical condition of the track ballast, the subgrade, under the ballast and sloping areas of the roadbed during the movement of the rolling stock. Control of the technical condition of the railroad track is practically performed by geometry cars of each haul on schedule, i.e., "in turns", as it is believed that no significant changes occur between the checks, when no control is carried out. At the same time, in real life, due to the impact of various factors, such as seismic processes, certain changes take place even a day after control. Therefore, the issue of creating new alternative solutions in the field of improving the control of the technical condition of tracks is relevant. This is of particular importance for railroads in seismically active regions. It is advisable to take into account that one of the most effective methods of diagnostics of the technical condition of railroad tracks is based on the use of vibrations of the soil of embankments caused by the rolling stock [2-5]. The prerequisite for the application of the vibration method is that a certain condition of embankments corresponds to a group of diagnostic signs of a dynamic process that occur during the movement of trains.

The result of the dynamic process reflecting the beginning of changes in the technical condition of the railroad track during the movement of the rolling stock affects the vibration signal $g(i\Delta t)$, which consists of the useful vibration signal $X(i\Delta t)$ and the sum noise $\varepsilon(i\Delta t)$ of the vibration signal, i.e.,

$$g(i\Delta t) = X(i\Delta t) + \varepsilon(i\Delta t).$$

It can be assumed that due to the impact of the technical condition of the track, due to the enormous weight of the car and rolling stock, low-frequency vibrations occur. At the same time, it can also be assumed that high-frequency components are mainly caused by other factors related to the technical condition of the rolling stock. Therefore, it can be assumed that in the sum noisy vibration signal $g(i\Delta t)$, the high-frequency components of the noise $\varepsilon(i\Delta t)$ are mostly indicative of the technical condition of the car of the rolling stock, and the useful signal consisting of low-frequency components of $X(i\Delta t)$ and the relationship coefficient between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ rather reflect the information about the technical condition of the track

The problem this paper aims to solve is obtaining information about the seismic state of the train's route and creating new intelligent technologies and means of monitoring the technical condition of railroad tracks, which allow, by analyzing vibration noisy signals, to identify its pre-failure states in real time without restrictions on the speed of train movement.

III. Main Components of Creating a Railroad Operation Safety System in Seismically Active Regions

It is known that a prerequisite for achieving highly competitive ability in the transportation market is the compliance of rail transport with the growing demands for speed, safety and comfort. The significant advantages of this mode of transport in comparison with other types offer great prospects in increasing the volume of traffic and at the same time require the improvement of this mode of transport [2-5]. There are great achievements in this area at present. However, seismic activity in the large territories of some regions can create problems. The most important and vulnerable element of rail transport is the railroad track, the insufficient monitoring of the condition of which does not ensure the proper safety of the rolling stock [1-5]. In view of the above, as the railroad passes through seismically active regions, additional requirements for traffic safety appear. This particularly applies to the problems of controlling the onset of the emergency condition of wheels and rails, their vulnerability, derailment conditions.

An analysis of the literature [3-7] devoted to control technologies and control systems taking into account the specific characteristics of railroads of seismically active regions has shown that the use of intelligent technologies and systems [1] can indeed improve the safety of this mode of transport. To do this, it is reasonable to create seismic hazard warming subsystems, as well as subsystems for control of the onset of the initiation and dynamics of development of changes in the technical condition of railroad tracks to incorporate in the existing railroad control systems. In view of the above, the issues of ensuring the safety of railroad tracks, taking into account the characteristics of seismically active regions along the route of the train, is an extremely relevant problem. Our studies have shown that in order to ensure an adequate level of safety of operation of rail transport in seismically active regions, it is necessary to create [1], [2]:

- ✓ a system of intelligent analysis of the level of seismic activity and prompt notification of seismic hazard along the main line;
- ✓ a system to control malfunctions of railroad tracks, bridges, tunnels and communication hubs of the entire route;
- ✓ a system to control the adequacy of the results of operation of the rolling stock diagnostic systems.

These subsystems will allow the driver and the traffic control service to receive additional information in advance and take appropriate measures to ensure traffic safety in general.

The first component includes the creation of a network of seismic-acoustic stations located along the route, as well as the development of software and equipment for transmitting, collecting, processing and analyzing seismic-acoustic information. Using a network of seismic-acoustic stations, the structural principle of which is given in [1], [2], this subsystem allows calculating in real time the probability of occurrence of dangerous earthquakes on the territory of the railroad route based on noise analysis of seismic-acoustic signals. The obtained information can be used to make appropriate decisions.

It is known that widely used seismic stations nowadays allow registering the moment of the beginning of an earthquake, determining the coordinates of its focus and magnitude. Various methods and technologies of spectral analysis are used to analyze seismic signals obtained from seismic sensors [1-4]. It is also known that many variants of short-term earthquake forecasting have been proposed over several decades [3-8].

In the considered version, solving the given problem first of all requires obtaining seismic-acoustic noise from the deep strata of earth, it being the primary immediate carrier of information on the incipient earthquake [3], [8], [9-15].

Thus, another important problem comes down to the development of a technology that takes into account the peculiarities of a heavily noisy seismic-acoustic signal in the period of the beginning of earthquake preparation (BEP). Here, the analysis of noise in the seismic-acoustic signal as a carrier of useful diagnostic information is of particular significance.

An experimental analysis of seismic processes occurring in deep strata of the earth during the preparation of earthquakes has shown that a systematic recording of seismological data in the territories of the entire region is necessary to monitor the beginning of an earthquake and to determine its focus area. In view of this, the appropriate technologies for obtaining and analyzing seismic-acoustic signals from deep strata of the earth were discussed.

Experimental versions of five seismic-acoustic stations were built on Gum Island in the Caspian Sea, in Shirvan District, in Neftchala District, in Siyazan District and in the resort town of Naftalan. A joint examination of the results of the analysis of seismograms of these stations allowed recording estimates of their characteristics related to the beginning of earthquake preparation with sufficient reliability 10-25 hours in advance. In this regard, a decision was made on the feasibility of creating an experimental version of the network of seismic-acoustic stations for noise monitoring of the beginning of earthquake preparation based on the analysis of seismic-acoustic signals received from deep strata of the earth by means of hydrophones.

These experiments have once again shown that to solve the problem of monitoring the earthquake preparation during its beginning, it is advisable to use noise technology for analyzing the noise of seismic-acoustic signals. It was also established that to determine the area of the focus of an expected earthquake, it is advisable to use modern intelligent technologies for analyzing the results of monitoring.

These experiments have also shown that the reliability and validity of the obtained results can be achieved by integration of seismic-acoustic stations of all seismic regions. Thus, the conducted experimental work made it obvious that it is necessary to create a system for Noise monitoring of the beginning of earthquake preparation and warning of its focus area.

Fig. 1 shows a seismic-acoustic system for noise monitoring of the beginning of earthquake preparation and warning of its focus area.

As can be seen from the block diagram in Fig. 1, the proposed system consists of the following components.

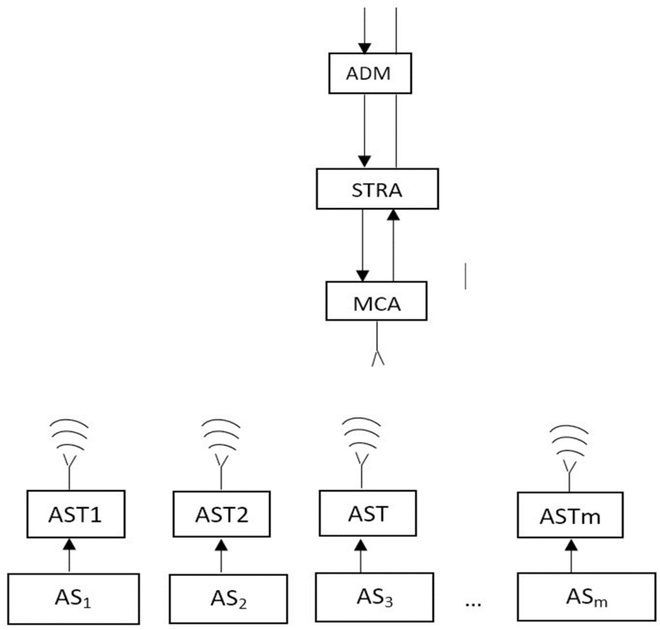

Fig. 1. Block diagram of the intelligent seismic-acoustic system

1. AS_1-AS_m – seismic-acoustic stations for Noise monitoring of the beginning of earthquake preparation;

2. AST1- ASTm – systems for transmitting the seismic-acoustic information from seismic-acoustic stations to respective monitoring centers;

3. MCA – centers of Noise monitoring of the beginning of earthquake preparation;

4. STRA – systems for transmitting and receiving information on the results of Noise monitoring of the beginning of earthquake preparation;

5. U'AS (sam) – unit of archiving samples of seismic-acoustic signals during earthquake preparation by means of cloud technology.

6. ADM – decision-making systems about the beginning of the earthquake preparation time, its focus area and possible intensity.

Let us now consider the main functions performed by these components (1-5).

AST1 and ASTm transmit recorded information about the start of earthquake preparation as a result of Noise monitoring of the noise of the seismic process. The information is transmitted in the form of an estimate of noise characteristics to the monitoring center in two versions. In the first version, the information is transmitted via the "Internet channel". In the second version, information is transmitted via satellite communication.

The monitoring centers form the sets of corresponding reference informative attributes only in the periods of the beginning and preparation of the earthquake on the basis of the results obtained from the respective Noise monitoring stations. Subsequently, knowledge bases are formed on their basis, by means of which the the process of registration of the beginning of earthquake preparation is studied. Ultimately, in the future they are used to determine possible focus areas and the beginning of the time of the expected earthquake.

The system for transmitting and receiving information STRA, when registering the start of earthquake preparation by the respective stations, transmits and receives information between monitoring centers. This information is also transmitted to ADM decision-making systems.

Studies devoted to this problem in recent years have shown that with the advent of a new, more efficient technology for the analysis of noisy signals, more accurate methods for their identification and more advanced methods for determining the location of the earthquake focus, their application it requires the availability of experimental data obtained at seismic-acoustic stations and recorded during earthquake preparation. Unfortunately, in the monitoring centers of the above-described seismic stations, only estimates of the noise characteristics obtained as a result of Noise analysis of seismic-acoustic noise are saved. This was due to the fact that storing all data consisting of samples of seismic-acoustic signals, even with one earthquake, requires an enormous amount of memory. Storing it for several years even for one station requires even a much larger amount of memory. At the same time, storing, i.e. archiving relevant data from all stations is very important. Our analysis of achievements and opportunities related to this problem has shown that using cloud technology it is possible to create a unit for archiving samples of seismic-acoustic signals received by Noise monitoring stations during earthquake preparation periods. For this reason, the system includes a unit of archiving seismic-acoustic signals by means of cloud technology.

Decision-making systems operate as follows.

At the beginning of earthquake preparation, estimates of Noise characteristics obtained as a result of analysis of seismic-acoustic noise by respective stations via the communication channel are synchronously transmitted to the server of the respective monitoring center MC. Based on the obtained monitoring results, the combinations of the sequence of indication times T_{1i}, T_{1j} and the combinations of their difference $\Delta\tau_{ij}$ are formed, which can be used as source data to determine the location of the expected earthquake.

The experiments have demonstrated that the combinations of the sequence of the times of indication by the stations practically repeat themselves for each earthquake focus area. Our analysis of the recorded charts has demonstrated that each sequence combination of time of indication of current BEP corresponds to one of the concrete earthquake areas. Employees of the laboratories studying the problem of interpretation of the experimental materials for over 2 years have learned to identify the location of the area of an expected earthquake intuitively and practically error-free, using these time combinations. It then became obvious that the problem of identifying the location of an expected earthquake should be solved by using expert systems (ES). This, in its turn, demonstrated the possibility of creating an ES which in the future will allow seismologists to use the network of the proposed stations as a toolkit to determine the location of the area of an expected earthquake.

The proposed experimental version of the expert system for identifying the location of the focus area will be based on a knowledge base (KB) formed from the totality of corresponding sets consisting of the combination of sequence of times of BEP indication by the stations T_{1i}, T_{1j}, the combination of the differences in times of their indication $\Delta\tau_{ij}$, and the combination of the estimates of the noise characteristics of the noise of the seismic-acoustic signal. The value of magnitude M_i determined during the corresponding earthquakes by ground seismic stations can also be entered in the KB.

Thus, the identification of the location of earthquake areas by the decision-making system after training is carried out as follows. The current combination is formed on the basis of the results of monitoring carried out by the network of stations. After that, the current element is compared with all elements of the indicated sets. If it matches any element of any set, the location of the area of an expected earthquake is identified based on the number of that set. At the same time, the current combination is entered into that set of the KB. New combinations of informative attributes of seismic-acoustic signals are continuously written into the KB during the operation of the system. Thus, the network of stations, the monitoring center and the decision-making system operate as a single whole.

To check the validity and reliability of the identification of the location of the earthquake focus area, the experimental version was tested during all several earthquakes. The obtained results have demonstrated the real possibility of practical application of this version of the system to identify the location of the earthquake focus area, which creates prerequisites for using it as a toolkit for determining the location of the area of an expected earthquake. Taking this prospect into account, a function of forming and providing the following information to railroad personnel can be included in the list of key functions of the decision-making block:

1. Date of the beginning of preparation and the number of the area of the expected earthquake.
2. Results of the current monitoring performed by the stations.
3. Estimated lead time at the beginning of BEP monitoring compared with the time of registration of the expected earthquake by ground seismic stations.
4. Magnitudes of previous earthquakes.
5. Minimum magnitude of the expected earthquake.

If the knowledge base contains no elements matching at least some of the elements in the sets, information on the impossibility of identifying the earthquake area is formed.

Our analysis of the results of experiments to determine the location of the BEP area has shown that, knowing the current values of the estimate of the noise of the seismic-acoustic signal and the distance from the area to the stations, the approximate minimum magnitude of the expected earthquake can be calculated.

IV. The Structural Principle of a Seismic Acoustic Noise Monitoring Station

The diagram of the seismic station for noise monitoring of BEP is given in Fig. 2.

The station includes the following equipment:

1. System unit;
2. Fastwell Micro PC type station controller;
3. GURALP LTD CMG 5T seismic accelerometer;
4. BC 321 hydrophone made in Zelenograd;
5. Amplifying and normalizing elements;
6. Siemens MC35i terminal forming an Internet channel via GPRS;
7. Antenna;
8. Voltage regulator;
9. UPS;
10. Monitor;
11. Connector

An experimental version of the station was installed at the head of a 3 500 m deep suspended oil well No 5 on 01.07.2010. The well is filled with water, and for this reason a BC 312 hydrophone is used as the sensor.

Experimental research has demonstrated that in the analysis of the noise $\varepsilon(i\Delta t)$ of the seismic-acoustic signal $g(i\Delta t)$, clear identification of the time of the beginning of earthquake preparation by means of traditional technologies is impossible. At the same time, using the robust technologies for noise analysis of the estimates of the noise characteristics of the cross-correlation function between the useful signal, the noise $R_{X\varepsilon}(\Delta t)$ and the noise variance D_ε, the system detects the beginning of earthquake preparation reliably and adequately.

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

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

The first results of experiments show that it is possible to register the beginning of an earthquake within a radius of over 300-500 km 10-25 hours before the earthquake by means of these stations. These results have shown that the time of earthquake preparation changes depending on the location of the earthquake focus.

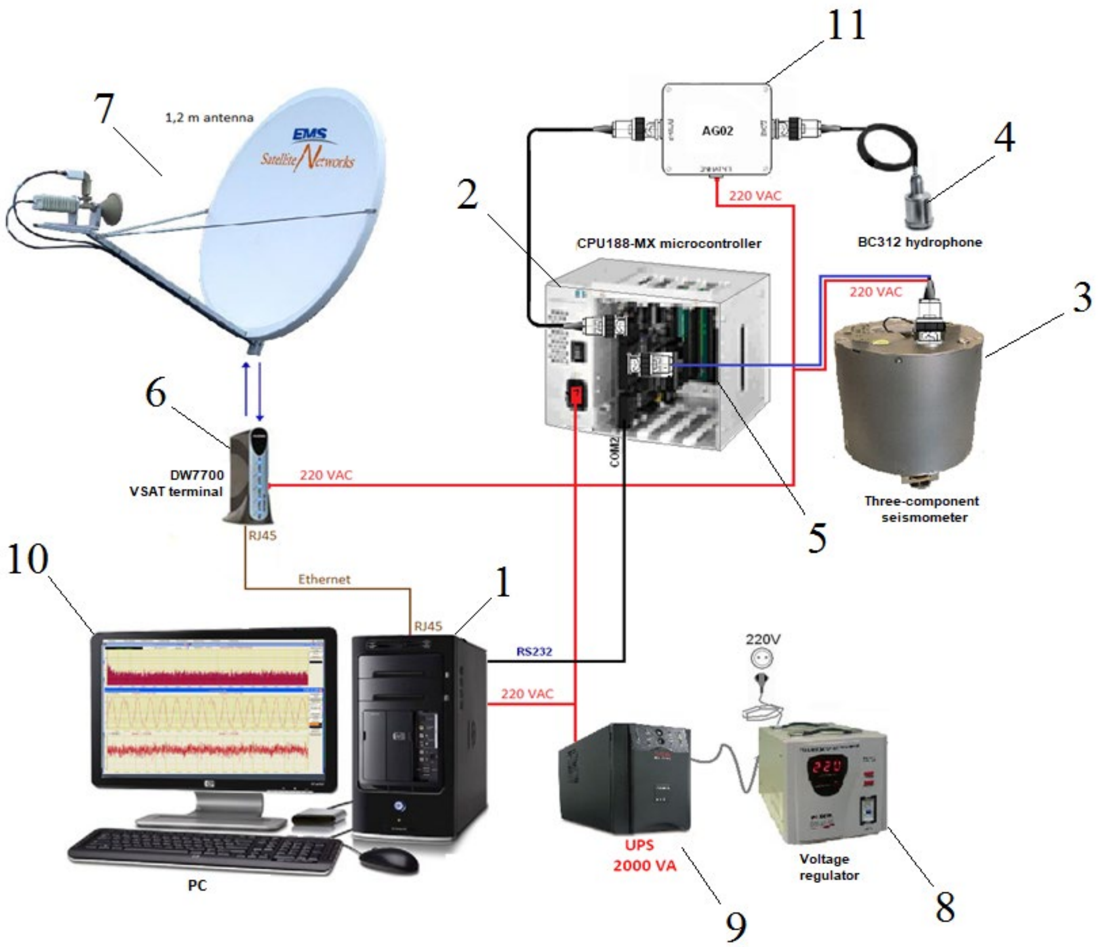

Fig. 2. Diagram of the station

Based on the obtained results, one can also assume that, when spreading from the earthquake focus, seismic-acoustic waves are reflected due to the resistance of certain upper strata of the earth, and for this reason they propagate horizontally. One can also assume that sufficient intensity of those waves allows them to travel to long distances (300-500 km).

The research conducted on these stations has demonstrated that to determine coordinates and magnitudes of expected earthquakes, we need to build networks consisting of at least 18-20 stations located across large areas along the entire route of the railroad. It was also obvious that they should be integrated with networks of similar seismic stations.

During the operation of all these seismic stations, as was indicated earlier, the results of noise analysis of seismic-acoustic signals at the moment of the beginning of earthquake preparation are transmitted from each station to the server at the Monitoring Center. As a result, sets of corresponding informative attributes form there.

Similarly, using the corresponding formulas for other Noise characteristics of the noisy signal $g(i\Delta t)$ given below [1, 9-12], it is possible to increase the reliability of the analysis results, which will allow controlling seismic processes across the entire region along the route of rail transport.

$$R^*_{1X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} g'(i\Delta t)g'(i\Delta t)-2g'(i\Delta t)g'\big((i+1)\Delta t\big) + g'(i\Delta t)\, g'\big((i+2)\Delta t\big)$$

$$R^*_{2X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} g'(i\Delta t)g(i\Delta t)-2g'(i\Delta t)g\big((i+1)\Delta t\big) + g'(i\Delta t)g\big((i+2)\Delta t\big)$$

$$R^*_{3X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t)g(i\Delta t)-2g^2(i\Delta t)g\big((i+1)\Delta t\big) + g^2(i\Delta t)g\big((i+2)\Delta t\big)$$

$$R^*_{4X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} {g'}^2(i\Delta t)g'(i\Delta t) - 2{g'}^2(i\Delta t)g'\big((i+1)\Delta t\big) + {g'}^2(i\Delta t)\, g'\big((i+2)\Delta t\big)$$

$$R^*_{5X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} sgn\ g(i\Delta t)g(i\Delta t) - 2sgn\ g(i\Delta t)g\big((i+1)\Delta t\big) + sgn\ g(i\Delta t)g\big((i+2)\Delta t\big)$$

$$R^*_{6X\varepsilon}(0)=\frac{1}{N}\sum_{i=1}^{N} sgn\ g'(i\Delta t)g'(i\Delta t) - 2sgn\ g'(i\Delta t)g'\big((i+1)\Delta t\big) + sgn\ g'(i\Delta t)\, g'\big((i+2)\Delta t\big)$$

where $g(i\Delta t)$ is the centered noisy seismic-acoustic signal, $g'(i\Delta t)$ is the non-centered noisy signal, $R_{X\varepsilon}(\mu\Delta t)$ is the cross-correlation function between the useful signal $X(i\Delta t)$

and the noise $\varepsilon(i\Delta t)$; $\mu\Delta t$ is the time shift between the samples of the useful signal $X((i+\mu)\Delta t)$ and the noise $\varepsilon(i\Delta t)$; $g((i+\mu)\Delta t)$ is the $(i+\mu)$-th sample of the centered noisy signal; $g'(i\Delta t)$ is the sample of the non-centered noisy signal; N us the number of samples.

As a result of experiments conducted at these stations, it has been established that during the initiation of ASP there is indeed a cross-correlation between the useful signal and the noise of the seismic-acoustic information.

The results of the experimental operation of these stations has shown that based on changes in the estimate of the cross-correlation function between the useful signal and the noise, each of them individually reliably indicates the start of earthquake preparation processes within a radius of 300-500 km with sufficient reliability. Using intelligent technologies, by means of a network of these stations located across large areas, it is possible to identify the location of the earthquake focus area.

Analyzing the seismic data obtained by means of acoustic sensors installed at well heads, we find that during ASP initiation, seismic-acoustic noise traveling in the earth's deep layers anticipates expected earthquakes by dozens of hours T_1. Experiments have established that seismic-acoustic stations can quite reliably monitor the beginning of the time T_1 by the above-described technology.

In the following paragraphs, we consider the results of the development of the intelligent technology for locating the ASP area, using the data from the stations installed in seismically active regions of the Caspian Sea (Fig. 3). The geographical coordinates and well depths of the stations are as follows:

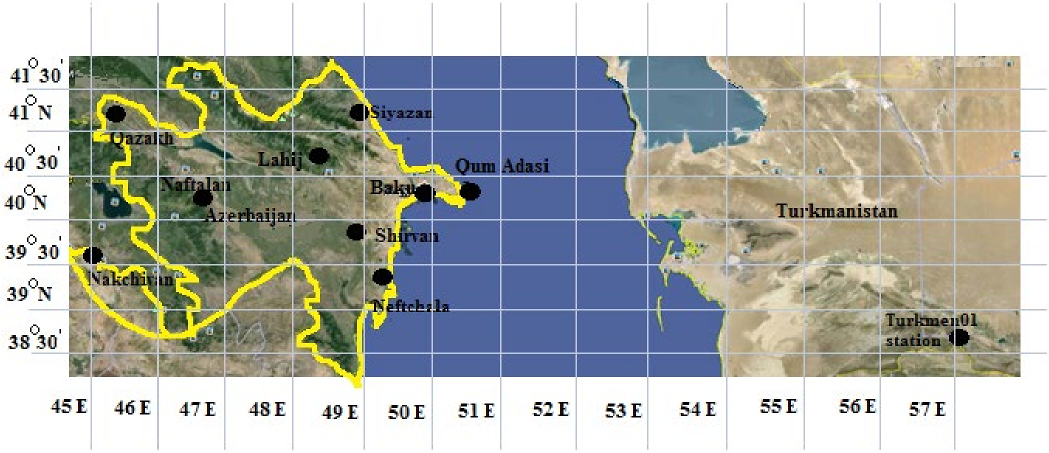

Fig. 3 Map of the locations of RNM ASP stations in the seismically active Caspian region

TABLE 1 GEOGRAPHIC COORDINATES AND DEPTHS OF STATIONS

1	Qum Island	40.310425°	50.008392°	3500 m	July	2010
2	Siazan	41.046217°	49.172058°	3145 m	November	2011
3	Naftalan	40.609521°	46.791458°	4000 m	May	2012
4	Shirvan	39.933170°	48.920745°	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°	45.100278°	200 m	August	2013
8	Turkmenistan	38.530089°	56.654472°	300 m	August	2013
9	Baku (Cybernetics)	40.375700°	49.810833°	10 m	February	2014

Our experiments on these stations (Fig. 2) have shown that the seismic-acoustic noises received by hydrophones installed at the head of wells from the earth's deep layers are immediate precursors of the earthquake preparation process.

The results of the measurement and analysis of those noises are transmitted from every station to the server of the Center for Seismic-acoustic Monitoring (CM) via the Internet or satellite communication. The system also has the feature of forwarding the obtained results to the serves of CMs in neighboring countries in seismically active regions.

Starting from 01.07.2010, Qum Island (Caspian Sea), Shirvan, Siazan, Naftalan, Neftchala, Nakhchivan (on the borders with Iran and Turkey), Qazakh (on the border with Georgia), and Cybernetic (Baku) stations were put into operation one by one to conduct large-scale experiments in the monitoring of anomalous seismic processes. The last three stations were built on 300 m, 200 m, and 10 m deep water wells, respectively. Those wells are filled with water by gravity flow. Hydrophones are placed in the water at the depth of 10-20 m from the water level. Our analysis of the seismic-acoustic signals received by these stations shows that during ASP initiation seismic-acoustic noises emerge spreading tens of hours earlier than seismic waves that are registered by the ground stations during an earthquake.

A synchronous robust noise analysis of the seismic-acoustic signals received from all stations via radio communication channels is performed during the operation of the network. The estimates of the noise characteristics $R_{X\varepsilon}(1\Delta t)$, $R_{X\varepsilon\varepsilon}(2\Delta t)$ and D_{ε} are sent to the server of the CM from the stations every 5 seconds. Based on the changes in those estimates, the identification of the starting points T_{1i} and T_{1j} of ASP initiation for the i -th and j -th stations, respectively, is carried out.

The result of the operation of these stations has shown that each of them individually makes it possible to reliably perform the indication of the process of initiation of ASP preceding an earthquake. It also became clear that we can use the results obtained by means of the network of these stations to create an intelligent technology for identifying the location of the area of an anticipated earthquake. For this purpose, by means of the network, we first determine the combinations of indication moments T_{1i} and T_{1j}, which together with the location coordinates of the stations represent the initial data for the solution of the problem of locating the ASP area. For the results to be more adequate and trustworthy, it is appropriate to use, in addition to the combinations of indication moments, time differences T_{1i}-T_{1j} for each chosen pair of stations. In other words, to solve the problem at hand, we should determine not only the combination T_{1i}, T_{1j} but also the difference in time of ASP indication between the stations, i.e. the differences $\Delta\tau_{ij} = (T_{1i} - T_{1j})$.

According to the results of our experiments, it is not easy to determine the start of the time of indication T_{1i} with sufficient accuracy by means of the estimates of noise characteristics. For this reason, taking into account the importance and necessity of improving its accuracy, the proposed system duplicates the process of determining $\Delta\tau_{ij}$. To this end, it was found expedient to also determine the time difference $\Delta\tau_{ij} = (T_{1i} - T_{1j})$ using 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 from different combinations of RNM ASP stations, using the following expressions:

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

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

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

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

1. finding the time of registration of the start of the period T_{1i} of ASP initiation by the first station (Qum Island);
2. finding the time of registration for the second (Shirvan), third (Siazan), fourth (Naftalan) station, etc.;
3. calculating the sets of estimates of the cross-correlation functions $R_{g_i g_j}(i\Delta t)$, $R^{*}_{g_i g_j}(i\Delta t)$ and $R^{**}_{g_i g_j}(i\Delta t)$ from the corresponding expressions, choosing from the results the time shifts $\mu\Delta t$, at which the curve of the cross-correlation function has the peak (extreme) value and using those time shifts to calculate $\Delta\tau_{ij} = (T_{1i} - T_{1j})$, i.e., the difference in ASP registration time by the i-the and the j-the station, respectively
4. using the found time differences $\Delta\tau_{1i} = (T_{1i} - T_{1j})$ as the source data to identify the location of ASP area.

Thus, in the proposed system, the estimates of the noise characteristics $R_{X\varepsilon}(1\Delta t)$, $R_{X\varepsilon\varepsilon}(2\Delta t)$ and D_{ε} obtained as a result of ASP monitoring by RNM ASP stations Qum Island, Shirvan, Siazan, Naftalan, Neftchala and Nakhichevan, Qazakh and Cybernetic (Baku) are synchronously transmitted via the communication channel to the server of the CM. On the basis of the obtained monitoring results, combinations of sequences of indication times T_{1i} T_{1j} and combinations of time differences $\Delta\tau_{ij}$ are formed and used as the source data for identifying the location of the area of an expected earthquake.

After the above results were obtained, three more stations were built to increase the reliability and accuracy of determining the coordinates of the focus area of the expected earthquake:

- ✓ in the village of Lagich, Ismayilli District (seismically active zone – the southern border of the Republic of Dagestan, Russian Federation) in 2015;
- ✓ in Lerik District (the northern border with the Islamic Republic of Iran) in 2016;
- ✓ in Sheki District (seismically active zone bordering with the Mingachevir reservoir) in 2017.

All these stations are built on 40-100 m deep wells. Our experiments after the inclusion of additional seismic-acoustic stations in the network confirmed the advisability of using the intelligent seismic-acoustic system in the warning mode to inform about the area of the focus of the expected earthquake [1, 16, 17].

V. Correlation Technology for Noise Control of the Beginning and Dynamics of Development of the Latent Period of Accidents in Rail Transport

It is shown in [1] that at the beginning of the latent period of the initiation of accidents as a result of the appearance of the noise $\varepsilon_2(i\Delta t)$, the estimate of the cross-correlation function between the sum noise $\varepsilon_2(i\Delta t)$ and the useful signal $X(i\Delta t)$ differs from zero. At the same time, in a stable emergency state, this estimate does not change. However, as the defect develops, this estimate increases. This makes it possible to control the dynamics of the development of accidents. However, by increasing or decreasing the value of the estimates of the noise variance, it is impossible to control the dynamics of the development of accidents. As numerous experiments show, the dynamics of the development of accidents leads both to an increase in the variance of the noise $\varepsilon_2(i\Delta t)$, which leads to an increase in the correlation between the useful signal and the noise. As a result, in the presence of the dynamics of the development of a malfunction, a correlation first arises between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. Then the further development of dynamics leads to the appearance of a correlation between $X(i\Delta t)$ and $\varepsilon(i+2)\Delta t$, then between

$X(i\Delta t)$ and $\varepsilon(i+3)\Delta t$, etc. Therefore, to control the dynamics of the development of accidents, it is necessary to calculate the estimates corresponding to the cross-correlation function between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$. In [1], the possibility of calculating the estimate of $R_{X\varepsilon}(\Delta t)$ is considered and it is shown that if there is a correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ at m different time shifts $\mu = m\Delta t$, $m = 1, 2, 3, \dots$, it is advisable to use a generalized expression in the form

$$R_{X\varepsilon}(m\Delta t) \approx \frac{1}{2N}\sum_{i=1}^{N}[\ g(i\Delta t)g\left(\left(i+(\mathrm{m}+1)\right)\Delta t\right) -2g(i\Delta t)g\left(\left(i+(\mathrm{m}+1)\right)\Delta t\right)+g(i\Delta t)g\left(\left(i+(\mathrm{m}+2)\right)\Delta t\right)].$$

An experimental analysis of noisy signals received at various technical facilities [1-12] showed that, depending on the degree of dynamics of the development of accidents at these facilities, a correlation appears between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ first at $\mu = 1\Delta t$, then at $\mu = 2\Delta t$, $\mu = 3\Delta t$, then at $\mu = 4\Delta t, 5\Delta t, 6\Delta t$, etc. Moreover, the values of these estimates reflect the dynamics of the development of accidents over time. Due to this, the generalized expression for calculating the estimates $R_{X\varepsilon}(\mu = 1\Delta t), R_{X\varepsilon}(\mu = 2\Delta t), R_{X\varepsilon}(\mu = 3\Delta t), \dots, R_{X\varepsilon}(\mu = m\Delta t)$ makes it possible to control and diagnose not only the beginning, but also the dynamics of the development of rolling stock malfunctions.

As shown above, at the beginning of the latent period of malfunctions, the error $\varepsilon_2(i\Delta t)$ appeares as a result of the initiation of various defects. At the same time, in essence, the dynamics of the development of accidents, despite the indirect influence on the value of the estimate of the noise variance, uniquely manifests itself only in the estimates of the cross-correlation functions between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ at different time shifts. Therefore, as indicated above, to control the dynamics of the development of accidents, it is advisable to use the estimate of $R_{X\varepsilon}(m)$. However, quite often, to control the onset and dynamics of the latent period of accidents, it is possible to use easily implementable algorithms that make it possible to significantly simplify the solution of this problem. From this point of view, it is advisable to use estimates of relay correlation functions, which can be calculated from the formula

$$R^*_{X\varepsilon}(\mu) = \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} g(i\Delta t)\varepsilon^2(i\Delta t) = \frac{1}{N}\sum_{i=1}^{N} \operatorname{sgn} X(i\Delta t)\varepsilon^2(i\Delta t).$$

However, to use this formula, it is necessary to determine the samples of the noise $\varepsilon(i\Delta t)$, which cannot be measured directly.

The following estimate can be used as informative attributes:

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

$$\varepsilon^2(i\Delta t) = g(i\Delta t)\left[g(i\Delta t)g(i\Delta t) - 2g(i\Delta t)g\left((i+1)\Delta t\right) + g(i\Delta t)g\left((i+2)\Delta t\right)\right]$$

It is also advisable to use for these purposes simple options for the approximate calculation of estimates of the relay cross-correlation function $R^*_{X\varepsilon}(\mu)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ at various time shifts $m\Delta t$:

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

When this formula is used, in the case of the presence of dynamics of the malfunction development, the obtained estimate will change at different time shifts [1]. At the same time, by determining the estimate of the relay cross-correlation function $R^*_{X\varepsilon}(\mu\Delta t)$ between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$ at different $\mu\Delta t$, it is possible to control the dynamics of the development of the malfunction.

For instance, at $\mu = 1\Delta t$, the formula for calculating the estimate $R^*_{X\varepsilon}(\mu = 1\Delta t)$ will have the form

$$R^*_{X\varepsilon}(\mu = 1\Delta t) \approx \frac{1}{N}\sum_{i=1}^{N}[\operatorname{sgn} g(i\Delta t)g(i+1)\Delta t -2 \operatorname{sgn} g(i\Delta t)g(i+2)\Delta t + \operatorname{sgn} g(i\Delta t)g(i+3)\Delta t].$$

At $\mu = 2\Delta t$, the formula for calculating the estimate $R^*_{X\varepsilon}(\mu = 2\Delta t)$ will have the form

$$R^*_{X\varepsilon}(\mu = 2\Delta) \approx \frac{1}{N}\sum_{i=1}^{N}[\operatorname{sgn} g(i\Delta t)g(i+2)\Delta t -\operatorname{sgn} g(i\Delta t)g(i+3)\Delta t + \operatorname{sgn} g(i\Delta t)g(i+4)\Delta t].$$

It is obvious that the estimates $R^*_{X\varepsilon}(\mu = 3\Delta t), R^*_{X\varepsilon}(\mu = 4\Delta t)$, ..., can be calculated in a similar manner.

It is clear that in the absence of a correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the estimate of the cross-correlation function $R_{X\varepsilon}(\mu = 0)$ between the useful signal and the noise will be close to zero. It is also obvious that at the initiation of various defects preceding accidents at the facility, as a result of the appearance of the noise $\varepsilon_2(i\Delta t)$ $(\varepsilon(i\Delta t) = \varepsilon_1(i\Delta t) + \varepsilon_2(i\Delta t))$, the value of the estimate of the relay cross-correlation correlation function due to the presence of a correlation between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$ will increase sharply. A distinctive feature of this algorithm is that at the initiation of various malfunctions, when a correlation occurs between $X(i\Delta t)$ and $\varepsilon(i\Delta t)$, the differences in the estimates $R^*_{X\varepsilon}(1\Delta t)$, $R^*_{X\varepsilon}(2\Delta t)$, $R^*_{X\varepsilon}(3\Delta t)$ unambiguously reflect the dynamics of the development of accidents, which makes it possible to provide reliable information on the dynamics of the malfunction development.

Similarly, using the corresponding formulas for other Noise characteristics of the noisy signals $g(i\Delta t)$, [1, 9-12], it is possible to increase the reliability and adequacy of control of the beginning of the latent period and the dynamics of the development of malfunctions preceding accidents in rail transport.

$$R^*_{1X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N} g'(i\Delta t)g'(i\Delta t) - 2g'(i\Delta t)g'\left((i+1)\Delta t\right) + g'(i\Delta t)\, g'\left((i+2)\Delta t\right)$$

$$R^*_{2X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N} g'(i\Delta t)g(i\Delta t) - 2g'(i\Delta t)g\left((i+1)\Delta t\right) + g'(i\Delta t)g\left((i+2)\Delta t\right)$$

$$R^*_{3X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N} g^2(i\Delta t)g(i\Delta t) - 2g^2(i\Delta t)g\left((i+1)\Delta t\right) + g^2(i\Delta t)g\left((i+2)\Delta t\right)$$

$$R^*_{4X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N} g'^2(i\Delta t)g'(i\Delta t) - 2g'^2(i\Delta t)g'((i+1)\Delta t) + g'^2(i\Delta t)\, g'((i+2)\Delta t)$$

$$R^*_{5X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N} sgn\, g(i\Delta t)g(i\Delta t) - 2sgn\, g(i\Delta t)g((i+1)\Delta t) + sgn\, g(i\Delta t)g((i+2)\Delta t)$$

$$R^*_{6X\varepsilon}(0) = \frac{1}{N}\sum_{i=1}^{N} sgn\, g'(i\Delta t)g'(i\Delta t) - 2sgn\, g'(i\Delta t)g'((i+1)\Delta t) + sgn\, g'(i\Delta t)\, g'((i+2)\Delta t)$$

where $g(i\Delta t)$ is the centered noisy signal, $g'(i\Delta t)$ is the non-centered noisy signal, $R_{X\varepsilon}(\mu\Delta t)$ is the cross-correlation function between the useful signal $X(i\Delta t)$ and the noise $\varepsilon(i\Delta t)$; $\mu\Delta t$ is the time shift between the samples of the useful signal $X((i+\mu)\Delta t)$ and the noise $\varepsilon(i\Delta t)$; $g((i+\mu)\Delta t)$ is the $(i+\mu)$-th sample of the centered noisy signal; $g'(i\Delta t)$ is the sample of the non-centered noisy signal; N us the number of samples.

VI. Conclusion

On the basis of the experimental studies on the development and use of networks of seismic-acoustic stations for the warning of the focus area of expected earthquakes, the following can be pointed out:

1. The intelligent system consisting of the network of seismic-acoustic stations and an expert system combined with a neural network can be used in a rail transport safety system as a toolkit for identifying the location of the area of an expected earthquake in advance. The obtained information will allow railroad workers, after a certain amount of experience, to take necessary measures to ensure safety due to having enough time before the expected earthquake. If there is any doubt, they can consult professional seismologists, ruling out possible mistakes in taking rolling stock safety measures.

2. The seismic-acoustic stations in the proposed network are built on wells with different depths. Based on the results of the experiments, 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 validity and reliability of the identification of the location of the area 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. An integration of networks of stations of the countries in several seismically active regions via satellite communication can, in the long term, allow increasing the validity and reliability of determining the coordinates of the location of the focus 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 area 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 area grows. In contrast, the value of the estimate of noise variance D_ε, increases as the distance from the area grows. 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 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 the initiation of BEP in the region.

5. The results obtained from the experimental data give us reason to assume that the lead time of the registration of the initiation of BEP by a seismic-acoustic station over standard seismic equipment is due to two factors.

First, seismic-acoustic waves that arise at the onset of BEP 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 analyzing seismic-acoustic noise allows, when a correlation appears between the useful signal and the noise, registering BEP at its onset.

These two factors make it possible for seismic-acoustic stations to indicate the time of the onset of BEP much earlier than is done by standard ground stations.

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