Analysis of data on precursors of strong earthquakes

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Abstract. The work is devoted to the development of geomonitoring methods for predicting strong earthquakes and assessing the stress-strain state of the geological environment. The results of observations of precursors of various nature in geodynamic polygons in Siberia and the Far East in the period 2007-2018 are presented.

Keywords: geomonitoring, earthquake, precursors, forecast, stress-strain state of the geological environment.

1 Introduction

In addition to the monitoring networks of the Russian Academy of Sciences, in the territory of the Russian Federation there are geodynamic training grounds of various departments (the Ministry of Defense, the Ministry of Emergencies of the Russian Federation, the Ministry of Natural Resources, the Ministry of Energy, Minatom, etc.). Since 2000, regional observational geodynamic networks have also been developed in various subjects of the Federation (Krasnoyarsk Territory, Kemerovo Region, Tuva Republic, etc.). At the same time, both seismological networks and integrated networks are used that record various geological and geophysical parameters.

In the Ministry of Natural Resources monitoring of endogenous processes is based on the hydrogeo-deformation field of the Earth (HGD) monitoring). In various seismically active regions of Russia (the Caucasus, Altai-Sayan area, Kamchatka, Sakhalin), geophysical testing grounds have been developed to control the stress-strain state (SSS) of the geological environment in industrial zones including large cities to predict seismic hazard. At the same time the ideology of the development of geodynamic testing ranges of the Ministry of Natural Resources is based on a combination of various geological and geophysical methods (seismology, electromagnetic measurements, HGD monitoring, gas monitoring, etc.). Due to the variety of energy processes in the geological environment, registration (monitoring) of methods of various physical nature is objectively necessary. Thus, an integrated approach to the organization of geodynamic monitoring is a kind of "standard" of the Ministry of Natural Resources in contrast to the "mono-networks" of geodynamic monitoring of various departments.

At the same time, despite the long-term use of the complex of geological and geophysical methods used in geodynamic monitoring the regulatory and methodological basis of the complex has not been developed. Basically, such types of geodynamic monitoring are regulated as: HGD monitoring [1]; normative documents have been developed for the organization and operation of seismological networks in the RAS system; electromagnetic monitoring, in particular, on the basis of registration of the Earth's natural pulsed electromagnetic field (NPEMFE), carried out on the basis of author's developments [2]; monitoring of radon and other gases also carried out on the basis of the development of various researchers [3].

Over the past 10 years significant experimental material has been accumulated in the geological and geophysical methods used at the geodynamic test sites of the Ministry of Natural Resources. This work summarizes the data of a complex of geological and geophysical methods (seismology, NPEMFE, radon emission) at geodynamic test sites in Siberia and the Far East in 2007-2018. to assess changes in the geological environment SSS and forecast seismic events. In our opinion, despite the dilatability of a number of conclusions this generalization can be used to develop normative and methodological recommendations for combining geological and geophysical methods at geodynamic test sites in order to control the geological environment SSS. The discharge of stress fields can provoke man-made disasters and thus affects the safety of people and structures.

During 2007-2018 at geodynamic test sites in the Altai-Sayan seismically active region (ASSAR) of Central Siberia, on the Kamchatka Peninsula and Sakhalin carried out monitoring of the geological environment SSS by a complex of geological and geophysical methods – seismic monitoring, registration of the Earth's natural pulsed electromagnetic field (NPEMFE), gas-geochemical monitoring based on radon emission. The scientific and methodological foundations and technological solutions used in monitoring the SSS of the geological environment at geodynamic test sites have been tested for many years. The following is an assessment of the capabilities of the complex of geological, geophysical, and gas hydrogeochemical methods for predicting the stress-strain state of the geological environment based on the results of geodynamic monitoring in Kamchatka, Sakhalin and the Altai-Sayan seismically active region in 2007-2018.

2 Seismic monitoring

Seismic monitoring is the basis for predicting the SSS of the geological environment. Consider the results of the use of seismological monitoring at geodynamic ranges in Siberia and the Far East, provide recommendations for its improvement. The stress-strain state of the geological environment determines the state of seismic activity of the territory. Endogenous factors such as block movements of lithospheric plates (from millimeters to tens of centimeters per year), have the greatest impact on the seismic process; thermodynamic processes in the core and mantle of the Earth including the development of mantle plumes. Volcanism has a significant effect on the seismic processes of Kamchatka. Geophysical monitoring at Petropavlovsk-Shipunsky, Yuzhno-Sakhalinsky and Altai-Sayan geodynamic ranges of the Ministry of Natural Resources of the Russian Federation in 2007-2018 made it possible to identify and evaluate the effect of gravitational lunar-solar tides and their resonances in the earth's crust on cyclic changes in SSS within various blocks of the earth's crust.

According to the results of many years of geodynamic monitoring, resonances of gravitational tides in the earth's crust have been experimentally revealed [4-5]. Below are the conditions and examples of manifestations of resonances of gravitational tides in the Earth's crust. In 2009 the need was substantiated for taking into account the fluctuations of the barycenter when assessing tidal effects on the geological environment [6]. To estimate the coordinates of the barycenter, the California Institute of Technology (USA) software package was used to calculate the ephemeris. In order to link external geodynamic factors into a single reference frame, we normalized the values of these parameters in the range from zero to unity. In this case the maximum value of the parameter during the year is taken as the unit and the minimum annual value is taken as 0.

As a result we have obtained graphs of the time variation normalized to the unit of parameters of the studied factors (Earth-Moon distance, Moon phases, distance of the barycenter from the Earth's surface and from the observer). In this case the maximum influence on the SSS of the geological environment of the Earth is exerted by fluctuations of the barycenter in the range of ± 28-30° relative to the ecliptic plane. Tidal waves can resonate with each other under certain conditions of proximity of frequency and phase. Long-period (14-15 days) gravitational tides satisfy these conditions therefore the graphs of these factors form the intersection points, which we consider as an indicator of resonances of gravitational tides.

The validity of this assumption is confirmed by long-term experimental data. In particular, the authors studied the correlation between the resonances of gravitational tides, seismic, electromagnetic emission and radon emission in groundwater. It was shown that the structure of the NPEMFE, radon emissions, and the structure of seismic emissions are clearly correlated with the intersection of the graphs of the studied factors, i.e. with resonances of gravitational tides. In all regions of Siberia and the Far East this pattern of manifestation of tidal resonances in the structure of geophysical data during monitoring is stably recorded.

A comparison of the time of catastrophic (M≥6.0) earthquakes on the globe for the 20th and 21st centuries with the calculated resonances of gravitational tides for each seismic event suggests that more than 80% of the catastrophic earthquakes in time with an accuracy of ± 12 hours coincide with the calculated resonances. A close correlation (more than 80%) between the calculated resonance time and the seismic source response was recorded in the Altai-Sayan seismically active region, Kamchatka and Sakhalin for earthquakes with M≥5.0. Thus, the resonances of gravitational tides are the triggers of the vast majority of strong and catastrophic earthquakes on the globe.

Not every resonance (and there are at least 10 of them during the lunar-solar month anywhere in the world) will cause an earthquake in a particular focus. This requires the fulfillment of additional conditions. The natural oscillations of a particular seismic source must be close in frequency and phase to the forced oscillation of the geological environment resulting from the passage of tidal deformation waves through the medium. The accumulated (potential) energy in the seismic source has reached or exceeds the limit of the mechanical (energy) strength of the rocks composing the seismic source. Under these conditions, the resonance of gravitational tides can cause an earthquake, i.e. discharge of accumulated stresses.

Various researchers experimentally recorded slow deformation waves in the geological environment with velocities of the order of 0.1-10.0 m/s, including during geodynamic monitoring in Siberia and the Far East. If a single deformation wave of the soliton type occurs negative consequences are possible.

An analysis of the occurrence of a deformation wave during the resonance of gravitational tides in August 2009 in the Altai-Sayan region allows us to consider as a cause of the well-known accident at the Sayano-Shushenskaya hydroelectric station on August 17, 2009 not only a violation of safety measures by the station personnel, but also the negative impact of low-speed (1.5 km/h) of the deformation wave formed 5–6 days before the accident at the hydroelectric power station.

Thus, the resonances of gravitational tides in the Earth's crust are not only the main trigger for discharging stresses in seismic centers, but also the source of the emergence of low-speed (cm/sec, m/sec) deformation waves in the geological environment.

Existing systems of geodynamic monitoring are currently used mainly to determine the parameters of earthquakes (coordinates, time and magnitude) based on the registration of fast (5-7 km/s) seismic waves. At the same time, seismic monitoring networks with additional spectral processing of the source data can also provide monitoring of slow deformation waves (1.0 ÷ 5.0 km/h). This will allow warning in advance the control systems of technogenic objects with resonant properties close to the deformation waves about the geodynamic hazard.

This leads to practically important conclusions:

1. Existing systems of geodynamic monitoring (a network of seismic stations) in addition to recording seismic events can be used to evaluate dangerous resonances and identify the low-speed (1.5÷2 km/h) deformation waves generated by them. Deformation waves are constantly recorded during HGD monitoring.

For this in addition to using the records of seismic stations to determine the parameters of earthquakes it is necessary to conduct a spectral analysis of the noise of the source records. This will reveal the formation of slow deformation waves and determine their main modes. Due to the low propagation speed of deformation waves there is always time (from hours to days) to take measures to exclude resonance phenomena on controlled technical systems.

2. To ensure the geodynamic safety of critical facilities it is necessary to supplement the existing monitoring networks with a system for controlling the resonances of gravitational tides. Regional systems for predicting the geodynamic hazard should be created which will allow timely measures to be taken to protect highly dangerous objects from the influence of deformation waves in the geological environment.

Seismic monitoring provides a medium-term (1-2 months) forecast of changes in the SSS of the geological environment. In predicting specific seismic events the authors used an “entropy” model for the development of energy processes in a seismic source at the stage of earthquake preparation [4].

The experience of using the "entropy model" allows us to provide a forecast of seismic events (M≥5.0 with time errors Δt ± 3-15 days, magnitude ± 0.5. As for the forecast of the position of the epicenter the following feature is revealed – the more accurately the forecast is made magnitude (ΔM ± 0.5) and time (Δt ± 1-3 s-current) of the seismic event the more unreliable the position of the epicenter (ΔS ± 100-500 km) is predicted. When using only seismic catalogs in principle it is impossible to reliably determine (predict) three parameters at once – magnitude, time and place (epicenter coordinates) of the earthquake.

Earthquake prediction practice in Kamchatka, Sakhalin and the Altai-Sayan region in 2007-2018 suggests that a short-term (with an accuracy of ± 1-3 days, M ± 0.5) forecast is possible, but the error in the position of the epicenter increases to ± 200-500 km. And, on the contrary with a successful forecast of the position of the epicenter (with an accuracy of ± 50-100 km), the error in time can reach ± 10-15 days and in magnitude ± 1.0-1.5.

In relation to the practice of forecasting seismic events it is necessary in addition to seismic catalogs to use a complex of various methods (having a physical nature different from the seismic wave process). In particular, to predict the position of the epicenter of the earthquake it is advisable to use infrared, infrasound radiation, gas emission in the zones of seismic centers based on remote sensing of the Earth.

3 Electromagnetic monitoring

Consider the basic requirements for electromagnetic monitoring based on the registration of the natural pulsed electromagnetic field of the Earth (NPEMFE). The nature of the NPEMFE is still debatable. The founders of the method (Vorobyov and others – Tomsk Polytechnic Institute, 70-80 years of the twentieth century) studying the NPEMFE in the frequency range of 10-20 kHz came to the conclusion that in the spectrum of the NPEMFE signal there are two main components: ionosphere (associated with thunderstorm activity and other atmospheric-ionosphere processes) and lithospheric (having a mechanic-electromagnetic nature) [7-8].

The results of geodynamic monitoring (seismic, electromagnetic, gas hydrogeochemical) in 2007-2018 at the ranges of Petropavlovsk-Shipunsky, Yuzhno-Sakhalinsky, Altai-Sayansky (Krasnoyarsk and Tyvinsky) training grounds revealed the main mechanism for the formation of the diurnal course of the EEMPZ – compression-extension waves associated with gravitational tides in the earth's crust and lithosphere.

The shape and amplitude of the diurnal variations of the NPEMFE are stably (r > 0.8) correlated with the resonances of gravitational tides (diurnal, monthly, and annual). The effects of changes in the structure of the NPEMFE at the stage of earthquake preparation are manifested both in the short-term (1-10 days) and in the medium-term (up to two months) plan were confirmed in the results of geodynamic monitoring in 2007-2018 in Kamchatka, Sakhalin and ASSAA.

It should be borne in mind that at various registration points depending on the geological and tectonic structure and geodynamic regimes of different blocks of the earth's crust a different manifestation of short-term signs of earthquake preparation in the structure of diurnal NPEMFE diurnal passages (up to antiphase) can be observed. So, during an earthquake of February 10, 2011 with a magnitude of 5.8 in the Ermakovsky district in the south of the Krasnoyarsk Territory the closest station of Ergaki NPEMFE (100 km from the epicenter) two days before the earthquake recorded a decrease in the level of NPEMFE. While the EARP “Narva” station (Preserve “Pillars”) at a distance of about 400 km from the epicenter of the earthquake recorded a clear maximum NPEMFE within two days before the event.

In summer the signs of earthquake preparation manifest themselves against the background of an increased level of intensity of the NPEMFE as a whole, and therefore it is more difficult to identify them as signs of earthquake preparation. The anomalous structure of the NPEMFE in ASSAA correlates with the nature of the change in radon concentration at various points (Krasnoyarsk – Tumanny – Askiz – Kyzyl). Registration of radon in combination with geophysical methods has proven its effectiveness in the ASSAA for assessing the SSS of the geological environment. The preparation of weak earthquakes (M about 3.0) also manifests itself in the structure of the diurnal course of the NPEMFE.

The preparation of strong catastrophic earthquakes (M≥8) even at a considerable distance from the registration point (up to 1000-3000 km) has a significant influence on the structure of the NPEMFE. An analysis of the records of the NPEMFE on Sakhalin during the preparation of the Japanese catastrophic earthquake (M = 9.0, March 11, 2011) was performed. The structure of the NPEMFE on Sakhalin (1000 km from the epicenter) changed 6 months before the Japanese catastrophe. In Kamchatka (3,000 km from the epicenter of the Japan earthquake) the structure of the NPEMFE 3 months before the disaster also clearly changed.

A similar picture in the structure of the NPEMFE at the Kamchatka training ground was recorded in May 2013 in preparation for the well-known Okhotsk deep (hypocenter depth ≈ 600 km) earthquake which was manifested by macro effects throughout Asia (from Kamchatka to India, Siberia, the Urals).

The change in the structure of the NPEMFE during the preparation of strong earthquakes can be used for the medium-term (several months) forecast of catastrophic earthquakes in the Kuril-Kamchatka region. For this it is necessary to install the MGR-01 equipment not only at local geodynamic test sites, but also along the Kuril-Kamchatka seismically active belt from the Aleutian Islands to Japan including the Kuril Islands with an interval between stations of about 500 km.

Thus, the results of geodynamic monitoring in 2007-2018 in Kamchatka, Sakhalin, in the Altai-Sayan region the in formativeness of the NPEMFE for the forecast of changes in the SSS of the geological environment and in some cases for the forecast of earthquakes was confirmed. It should be recognized that the use of the method of registering NPEMFE without complex with other (above mentioned) methods does not allow us to unambiguously assess the change in the SSS of the geological environment and the forecast of earthquakes.

The theory and hardware and technology base of the NPEMFE method needs additional development. In particular, the fact of considerable depth of the EEEMP method (tens of km) was experimentally established while the mechanic-electromagnetic model the most common idea of the nature of the NPEMFE at present does not allow the emission of electromagnetic pulses with a frequency of 10-20 Hz from a depth of more than 1 km. It is necessary to increase the dynamic range of the NPEMFE registration from 96 dB to a minimum of 128 dB. The width of the pulse counter must be increased from 16 bits to 24 bits of the minimum and extend the frequency range of the registration in the range of 1–25 kHz.

When using the existing MGR-01 equipment, it is advisable at each point to simultaneously register the NPEMFE at one "reference" frequency (about 14 kHz) with different gain factors. This will make it possible to more reliably identify signals of lithospheric origin against the background of the influence of other types of sources (ionosphere, atmospheric, temperature and noise).

4 Radon monitoring

Radon monitoring in 2007-2018 it was carried out in the Altai-Sayan region where it confirmed its effectiveness in conjunction with other geophysical methods for controlling the SSS of the geological environment. The nature of the change in radon concentration within the Altai-Sayan geodynamic range is also associated with long-period (3-6 months) cycles of gravitational tides.

Radon precursors of the preparation of a strong earthquake are manifested in positive or negative anomalies in the level of radon in groundwater [3]. Monitoring of the radon content in groundwater is carried out in order to identify medium-short-term (month, 2-10 days) precursors of strong earthquakes M> 5.0-6.0 and assess changes in the stress-strain state of the geological environment based on an analysis of the relationship between the dynamics of fluctuations in radon concentration due to seismic activity of the region.

The analysis is carried out and radon precursors of strong earthquakes in the Republic of Tuva in 2011 and 2012 are demonstrated. Estimates of the harbinger of the preparation of the December 27, 2011 earthquake of magnitude 6.5 are obtained. Radon emission changed 5-10 days before the earthquake in all four observation points of the Altai-Sayan region.

Most clearly the forerunner appeared on Kyzyl 100 km from the epicenter of the earthquake. 4 days before the main event an anomaly was observed in the level of radon concentration expressed by a sharp increase in the level of radon concentration. Based on the article [6] a numerical analysis of changes in the concentration of radon in groundwater was performed. Estimates are determined in three ways: by the magnitude of the absolute maximum deviation – positive or negative – from the average background concentration; the value of the relative maximum deviation; by the number of standard deviations for background concentrations.

Based on this approach the analysis of earthquake precursors in the Kaa-Khem district of the Republic of Tuva on December 27, 2011 with a magnitude of 6.5 and February 26, 2012 with a magnitude of 6.7 was performed. During the preparation of the first earthquake the average background concentration of radon was at a level of 69.6 while the average value of radon concentration in the anomalous period was 88.2. The time of the precursor radon anomaly was estimated from the beginning of a steady increase in the radon concentration of $2*S_{fon}$ (standard deviation of the background concentrations) until the earthquake and amounted to 5 days.

During the preparation of the second earthquake the average background concentration of radon was at 69.6, while the average concentration of radon in the anomalous period was 86.0. The time of the precursor radon anomaly was estimated from the beginning of a steady increase in the radon concentration of $2*S_{fon}$ (standard deviation of the background concentrations) until the earthquake and amounted to 3 days. These calculations were carried out according to the Kyzyl measurement point the distance to the sources of earthquakes is about 100 km. Changes in the concentration of radon in natural water sources make it possible in conjunction with the NPEMFE and seismic emission data to predict not only the change in the geological environment SSS, but also provide a medium-term (1-3 months) forecast of strong seismic events M≥6.0.

A short-term (1-3 days) forecast is also possible, but without integration with other methods (seismic, NPEMFE) the reliability of the interpretation of local radon anomalies with a rare network of observations does not allow reliable prediction of even strong earthquakes (M≥5.0). To solve the problem of short-term earthquake forecasting using radon monitoring data it is necessary to increase the network of observations by bringing the number of radon level observation points to a minimum to the number of NPEMFE observation points within the geodynamic range.

5 Conclusion

Geodynamic monitoring by a complex of geological and geophysical methods (seismology, NPEMFE, radon) provides not only an estimate of the change in the SSS of the geological environment, but also a medium-term (1-3 months) and short-term (1-10 days) forecast of strong earthquakes with M≥5.0. The achieved accuracy of forecasts is in magnitude $\Delta M \pm 0.5$; by time $\Delta t \pm$ 1-15 days; at the location of the epicenter ΔS from 100 to 500 km. The low accuracy of determining the position of the epicenters of seismic events is associated with the fundamental impossibility of identically determining the conjugate quantities: magnitude and position of the epicenter.

On the other hand, the level of integration (low density of the NPEMFE recording networks and measuring the level of radon concentration in groundwater) does not provide a reliable forecast of the location of the epicenter ($\Delta S \pm$ 50-100 km). To increase the reliability of determining the position of earthquake epicenters, it is necessary to increase the density of the NPEMFE and radon registration networks and supplement the geological and geophysical complex used with satellite infrared and geochemical (CO_2, methane) surveys.

In connection with the propagation in the geological environment along with high-speed waves of the seismic range (speed of 5-7 km/s) slow deformation waves (1-2 km/h or less) it is necessary to design geodynamic polygons for monitoring and slow deformation waves. When organizing geodynamic testing ranges along with existing seismic networks with a large aperture (hundreds of km) use highly sensitive low-aperture (10-20 km) local groups.

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