UDK 550.370+550.379+550.34016

https://doi.org/10.30730/gtrz.2023.7.2.115-131
https://www.elibrary.ru/bogdqg

Observations of the inverse seismoelectric effect of the second kind during electrical sounding in the Central Sakhalin fault zone*

Leonid M. Bogomolov[*1], Dmitry V. Kostylev[1,2], Natalya V. Kostyleva[1], Sergey A. Gulyakov[1], Ilya P. Dudchenko[1], Pavel A. Kamenev[1], Nikolay S. Stovbun[1]*

**E-mail: bleom@mail.ru*

[1]*Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia*
[2]*Sakhalin Branch, Geophysical Survey, Russian Academy of Sciences, Yuzhno-Sakhalinsk, Russia*

Abstract. The results of experiments on electrical sounding of the near-surface layer of the Earth's crust in the fault zone, which have involved a recording of seismoacoustic and seismic noise in the close zone near the source (the primary dipole source), are represented. The experiments were carried out in 2021–2022 in the southern part of the Central Sakhalin fault with the use of the generator of electric pulses developed at IMGG FEB RAS, output electric power being up to 3 kW. The aim was to reveal seismoacoustic signatures of the medium reaction to the soundings with current pulses of 5–13 A. The generator provided significantly higher current in the dipole than its typical characteristics in the case of soundings for electrical exploration by resistance methods, as well as in the case of conventional seismic and electrical exploration. At the same time, the range of current amplitudes was much smaller in comparison with the case of a deep sounding based on application of geophysical MHD generators or other extra high-power electric pulses units. Up to now, the inverse seismoelectric effect has remained practically unexplored at currents in the "intermediate" range of ~10 A and scale lengths of the order of few hundreds of meters. The presence or absence of the medium reaction to electrical soundings was distinguished by the records of molecular-electronic sensors developed by R-sensors LLC: the CME-6111 broadband seismometer and the hydrophone, installed at a distance of about 50 m from one of the poles of the electric dipole source. An increase in the average level of seismoacoustic noise during electrical soundings was revealed, which is essentially a variety of the inverse seismoelectric effect of the second kind (excitation of elastic waves during an electric current run in a two-phase medium). Previously, no similar signature of medium reaction to the current pulses was noted in the close zone adjacent to one of the dipole electrodes. The noise level increase occurs almost without delay after the start of electrical soundings, and this is in accordance with the previously obtained results on the responses of seismic acoustic emission to powerful current pulses, which were used for a deep sounding in the Northern Tien Shan.

Keywords: electrical sounding, seismic noise, medium seismoacoustic reaction, seismoelectric effect

For citation: Bogomolov L.M., Kostylev D.V., Kostyleva N.V., Gulyakov S.A., Dudchenko I.P., Kamenev P.A., Stovbun N.S. Observations of the inverse seismoelectric effect of the second kind during electrical sounding in the Central Sakhalin fault zone. *Geosistemy perehodnykh zon = Geosystems of Transition Zones*, 2023, vol. 7, no. 2, 14 p. (In Engl.). https://doi.org/10.30730/gtrz.2023.7.2. 115-131; http://journal.imgg.ru/web/full/f-e2023-2-1.pdf

Acknowledgements

The authors are grateful to Yury V. Marapulets and Sergey B. Turuntayev for the opportunity to conduct experiments at the sites of the «Karymshyna» station and «Mikhnevo» GPO, and to Alexander S. Zakupin for discussing the results.

---

[*] A translation from Russian: Богомолов Л.М., Костылев Д.В., Костылева Н.В., Гуляков С.А., Дудченко И.П., Каменев П.А., Стовбун Н.С. Наблюдения обратного сейсмоэлектрического эффекта II рода при электрозондированиях в районе Центрально-Сахалинского разлома. *Геосистемы переходных зон*, 2023, т. 7, № 2, с. 115–131. https://doi.org/10.30730/gtrz.2023.7.2.115-131. *Translated by Galina S. Kachesova.*

Introduction

The interaction between seismic waves and electric fields has long been of practical interest, as it can become the basis for new methods for studying deep processes. Seismic and electrical fields are some of the most studied types of physical fields that exist in the geophysical medium, and they are widely used in practice and can be effectively created and measured. However, the complexity of geomechanical and physical processes in heterogeneous medium, their susceptibility to external influences of physical fields predetermine the urgency of further study of transformations of these fields [1].

There are two kinds of seismoelectric effects: the first is a change in the electric resistance of rocks affected by the elastic fields (passage of seismic waves), similar to the microphonic effect, and the second one is the appearance of an electric field, i.e. a potential gradient, in the medium with the same impact. Direct seismoelectric effect of the second kind was discovered by A.G. Ivanov during a field geophysical research in 1939–1940 [2, 3]. He has found the occurrence of electrification during the passage of elastic waves through wet rock and suggested the nature of the seismoelectric effect to be associated with the fact that at the interface between the liquid and solid phases (mineral solution and rock solids) there is a double electric layer, one part of which, facing to the liquid, is shifted due to the pressure difference. A model of seismoelectric effects was proposed in the works [4, 5] which explained the occurrence of the electric potential difference during elastic waves transfer. This model (named after the authors as the Frenkel–Biot model) was further developed in the works [6, 7] etc. Modern theoretical concepts of seismoelectric effects are described in detail in the monograph [8].

The presence of seismoelectric effect of the second kind is confirmed in recent studies [9, 10] with simultaneous recording of seismic oscillations and vertical component of electric field strength on the Earth's surface. The study in the Mikhnevo geophysical observatory of the Sadovsky Institute of Geosphere Dynamics of RAS showed the propagation of seismic waves in most cases to be accompanied by the variations of electric field strength on the Earth's surface. Exceptions are the periods of strong disturbances of the electric field in the form of atmospheric phenomena (cold fronts, strong wind, etc.), when seismoelectric effects cannot be distinguished [11].

The inverse seismoelectric effect of the second kind, that is the excitation of elastic waves during the flow of an electric current, has attracted the lesser attention of researchers (although it is worth mentioning the use of this effect to delineate hydrocarbon deposits and groundwater, as well as to clarify the interfaces between these liquids). This was the situation prior electrical soundings of the Earth's crust at the test sites in Central Asia in the 1980s using the most powerful current sources such as the geophysical MHD generators [12, 13]. The statistically significant results on the spatiotemporal change in the seismic regime after current pulsing to the Earth's crust through a grounded dipole were obtained in these and subsequent works devoted to electrical soundings, for example [14, 15]. Similar results were also obtained for the soundings, which were carried out in 2000–2005 at the Bishkek geodynamic test site in Kyrgyzstan [16], using a less powerful source – an electric prospecting generator unit. These results can be characterized as a manifestation of the inverse seismoelectric effect of the second kind, that is characterized by a time lag after the electrical impact beginning and the presence of inelastic deformation of the medium (the source of stimulated seismic signals). The reality of the electromagnetic trigger of inelastic deformation of geomaterials due to the inverse seismoelectric effect of the second kind was confirmed in laboratory experiments on loaded rock samples [17, 18].

However, the mechanism of current pulses impact on seismic sources has not been fully clarified. The complexity of the development of a model of seismoelectric interactions is due to the problem of involvement of a number of processes of various nature in heterogeneous media and two-phases media including a solid skeleton and interstitial fluid. The power fields of different physical-chemical origin are excited in such media, which are outside with respect to the applied electric field during its action. The effects of induced polarization [19] as well as electrokinetic and/or electrochemical effects contribute essentially [11, 20]. The acquisition of new data on seismoelectric effect of the second kind during electrical soundings, including different levels of amperage, duration of current impact and scale of a medium can take a step towards a model explaining this effect.

In 2020, the Institute of Marine Geology and Geophysics of the Far Eastern Branch of the Russian Academy of Sciences began to conduct shallow electrical soundings of the Earth's crust at the Petropavlovskoye geophysical test site located in the southern part of the Central Sakhalin fault [22]. A pulse voltage generator (designed at the IMGG FEB RAS, its description can be found in [22]) was used as a current source. It was loaded on a dipole source with an electrode spacing of 408 m. The records of seismic and seismoacoustic noise were obtained, which can be used to reveal the medium reaction to the impact of series of current pulses. For further studies of the manifestations of the inverse seismoelectric effect of the second kind and the identification of its features in fault zones, it is necessary to accumulate data on the medium reaction to the electrical soundings, i.e., on an increase in the amplitude of seismoacoustic and seismic noise. In this regard, the experiment at the Petropavlovskoye test site was continued in 2021 and 2022, and three series of electrical soundings were carried out. The results obtained are analyzed in this work. The possibilities and problems of seismoelectric monitoring of an active fault segment based on the developed source of electrical soundings and portable seismic or seismoacoustic stations are also discussed here.

Sounding and recording equipment

Experimental shallow soundings were carried out at the complex geophysical test site of the IMGG FEB RAS near the Petropavlovskoye village, Anivsky district, Sakhalin Island, in the southern part of the Central Sakhalin fault (CSF) [23]. The assessment of the medium reaction to the electrical sounding was determined from the records of molecular-electronic sensors (manu-

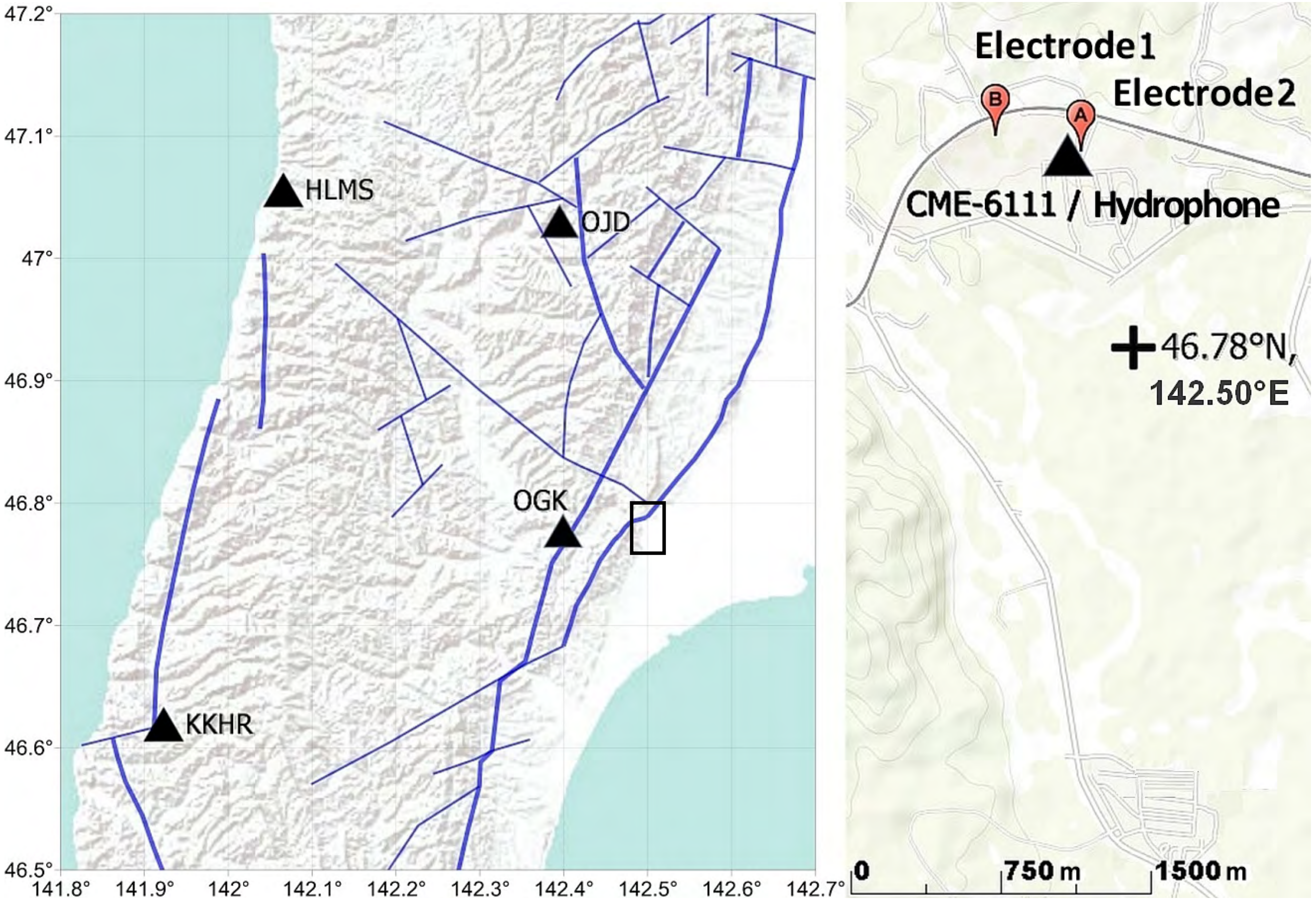

Fig. 1. The location of the Petropavlovskoye geophysical test site (rectangle) and seismic stations of the network of the SB UGS RAS (black triangles) on the map of southern Sakhalin. The blue lines are tectonic faults, according to [25]. Inset (right): Positions of earthing electrodes 1 (pole B) and 2 (pole A) and seismic instruments in the test site.

factured by R-sensors LLC, Russia): the CME-6111 broadband seismometer and the hydrophone [23, 24] installed at this test site at a distance of about 50 m from one of the poles of an electric dipole source.

The use of the above equipment allowed detection of the medium reaction to the electrical sounding by signals in a wide frequency range. In this case, the hydrophone can record high-frequency signals, the sources of which are located at a distance of no more than several hundred meters (due to spherical divergence and wave attenuation). The CME-6111 seismometer is designed to record seismic waves at frequencies of 1–50 Hz, which sources are at depths of at least several kilometers. There are no sources of seismic signals in the close zone near the equipment location. Thus, the combination of a seismometer and a hydrophone provides a way to compare the medium reaction to the electrical soundings at different distances from the electric dipole source. The general layout of the Petropavlovskoye complex test site, seismic stations, and fault structures of southern Sakhalin [25] are represented in Fig. 1. The same figure (see inset) shows the position of the electric dipole source AB formed by two ground electrodes. The reference point coordinates are also indicated for terrain association.

It should be noted that at the final stage of the experiment in November 2022, the CME-6111 seismometer was moved from the seismic chamber [1] to a concrete pedestal out of necessity. Due to this fact, the degree of the device protection from the effects of external interference has decreased, despite equipping the device with a protective cover.

Patterns of the electrical soundings routine

The experiment was carried out in four stages during 2020–2022. Information on the sounding time and current pulse parameters at each stage is given in the table. The sounding technique is described in the article [23], that is devoted to the first stage of the experiment. At all stages, the same dipole AB of 408 m long was used to inject current pulses in the ground. The load resistance resulting from the current spreading in the medium was specified by means of the MS5209 Insulation Resistance Meter, it was 38 Ohms. The resistance value was controlled before each stage of the experiment. It was found that prolonged exposure to moist soil of electrodes made of stainless steel pipes had practically no effect on the so-called “apparent resistance”, which consists of the resistance at the contacts of the electrodes with the ground and the actual resistance of the distributed load.

Table. Sounding parameters at the geophysical test site near the Petropavlovskoye village, Sakhalin Island

Stage no.	Date of sounding	Starting time (UTC)	Current source	Average voltage, B	Average current amplitude, A
1	29.10.2020 29.10.2020	00:15 01:45	PF1000A-360 module	360	4.9
2	15.11.2021 16.11.2021 17.11.2021 18.11.2021	00:50 02:45 09:29 00:33	Generator 230 V AC with the CSP–3000–400 unit	300	5.1
3	25.04.2022 26.04.2022 27.04.2022 28.04.2022	02:20 00:30 07:36 23:39	Generator 230 V AC with the CSP–3000–400 unit in current source mode	200-400	5.9
4	07.11.2022 08.11.2022 09.11.2022 10.11.2022	01:39 07:18 01:47 01:05	IIN-25-540 source: three-phase AC generator with a rectifier	540	13

Note. The sounding time and current pulse parameters are the same at each stage: a series of 200 pulses with a duration of 20 s and pauses of 20 s.

The generator for the electrical soundings was improved when preparing the experiments in 2021–2022 in order to eliminate the disadvantages revealed at the first stage in 2020. The operability of the apparatus was tested in a series of tests at the site in the IMGG FEB RAS using a dummy load with a resistance of 38 Ohms, as in the case of a dipole at the Petropavlovskoye test site. The generator unit designed and improved in the IMGG FEB RAS was named IEIG-7-400 (the geophysical source of electric pulses with a nominal current of 7 A and maximum voltage of 400 V). The blocking diagramm of the IEIG used at the second and third stages of the experiments is shown in Fig. 2. The alternating current generator with an output voltage of 230 V and a frequency of 50 Hz is used in the unit as a primary power supply. AC voltage from the output of a primary generator is supplied to the CSP-3000-400[1] power supply, which converts the voltage into DC with an amplitude of 400 V, that provides a current of up to 7.5 A. The voltage from the power supply is then fed through a current automatic switch to an electric dipole in accordance with the programmed control. A specific feature of the current switch in the IEIG is the use of a powerful electronic IGBT switch [23] capable of switching current up to 40 A and withstanding voltage up to 1200 V. The voltage reserve is necessary to prevent failure of the semiconductor switch of the automatic switch due to the negative switching overvoltage that occurs when the circuit is switched off because of the spreading of current from the poles of the dipole (the presence of an equivalent inductance). The switch is shielded with a special protective coating in order to protect against electromagnetic interference in the field conditions, that violate the programmed control.

The voltage from the power supply through the current switch is supplied to the electric dipole according to the control program. The IEIG-7-400 modulus was placed near electrode 2 (pole A) at all stages of the experiment, starting from the second (see Table).

At the second and third stages of the experiment, the equipment operated in an intermittent mode, with alternating current pulses and currentless pauses. During electrical sounding on November 15–18, pulses were generated in single series of 200 pulses with an equal duration of current pulse and currentless pause of 20 s. Thus, the electrical sounding session took about 2.2 h. On November 15, 16, and 18, the session was conducted during daylight hours, and the beginning was timed for the noon, which occurs in this area at about 13:40 local time (2:40 UTC), and on November 17, the soundings were carried out shortly before astronomical midnight. During soundings, the current and voltage were continuously monitored directly at the electrodes, for which a separate line was laid to electrode 2. In each separate pulse, the current decreased from a maximum value of ~7 A at the beginning to ~5 A at the end. A smooth decrease in the maximum current amplitude occurred during the session, but it was compensated by manually adjusting the voltage of the CSP-3000-400 module during currentless pauses. During the period of a currentless pause, a residual voltage on the load (dipole AB) was noted, the value of which was ~10 V at the beginning of the pause, gradually decreasing until the next current pulse. The voltage on the electrodes was maintained after the last pulse in the session.

The essential difference between the third stage of the experiment and the two previous ones is the use of the CSP-3000-400 power supply in

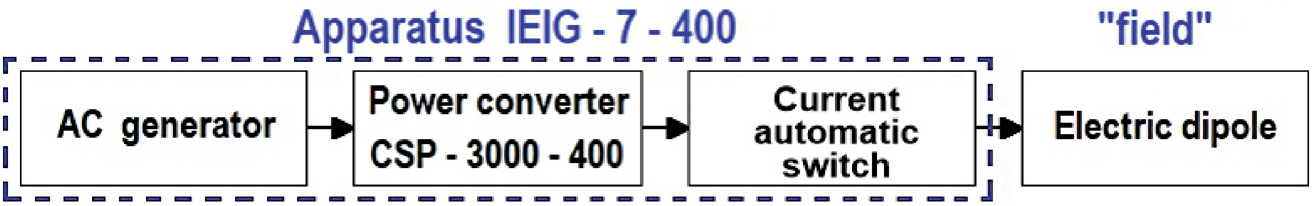

Fig. 2. The block diagram of the IEIG-7-400 source of electric pulses, used for electrical sounding in the periods of November 15–18, 2021 and April 25–28, 2022.

---

[1] MW, 3000W Power Supply with Single Output. CSP-3000 series. URL: http://www.mean-well.ru/uploads/files/datasheets/CSP-3000-400.pdf (accessed 10.03.2023).

the mode of a current source, rather than a voltage source. This solution eliminated the instability of the current intensity (decrease from 7 to 5 A) during a single pulse. The method of pulse-width modulation was used to keep a constant value of the current. However, this method leads to some decrease in the voltage amplitude. To follow the changes in the amplitude of current and voltage during electrical sounding, photo and video recording of the readings of measuring instruments was used. In the future, it is planned to automate the measurements of electrical parameters.

Figure 3 shows the IEIG-7-400 modulus for electrical sounding placed near electrode 2, and electrode 1 with a geophysical cable connected to it.

At the fourth and final stage of the experiment, it was necessary to increase the current and voltage in the pulses applied to the dipole source in order to prevent the negative bias on the overall statistics of the results (for all four stages) due to possible degradation of the medium reaction to repeated exposures, similar to the Kaiser effect. The experience of the multistage electrical sounding at the Bishkek geodynamic test site using a powerful electric pulse installation was taken into account [16].

The characteristics of the CSP-3000-400 power supply did not allow increasing the power of output pulses, that is why the following changes were made in the sounding source. A three-phase alternating current generator was used as the pri-

Рис. 3. The source of electric pulses and measuring equipment used in the second and third stages of the experiment (left). The arrow points to the electrode 1. November 15, 2021. *Photo by I.P. Dudchenko*

Fig. 4. The exterior of three-phase rectifier – a current source in electrical soundings of 7–10 November 2022 (left). Recording of 13 A current on the voltammeter at the moment of a separate pulse (right).

mary voltage source at this stage of the experiment (November 2022). The generator voltage is fed to a three-phase rectifier with a voltage amplitude of 540 V. The three-phase rectifier was designed as a separate device in a case with a built-in circuit switch and smoothing filter. From the rectifier output, the voltage is fed to the current switch unit, as in the previously used IEIG-7-400 modulus. Figure 4 shows the exterior of the three-phase rectifier – a new unit relative to the IEIG-7-400 modulus (Fig. 2, 3). Using a new source of pulse voltage, which is called IIN-25-540 (rated current 12 A, maximum voltage 540 V), allowed actually to increase the current in the dipole. During electrical soundings in the period of 7–10 November 2022, the average current amplitude over a series of 200 pulses was 13 A (Fig. 5, on the right), which is almost two times higher than its values at the second and third stages.

It should be noted that the resource of the current switch allows generating more powerful pulses for electrical sounding. But currently their maximum power is limited by the primary voltage source (mobile AC generator).

Manifestations of the medium reaction in seismic and seismoacoustic noise

Initially, the analysis of seismic noise records was carried out according to the data of the molecular-electron hydrophone during the days of electrical sounding. The SpectrumSeism program was used for this purpose, which is designed for analyzing the spectra of seismic data [26]. The records of waveforms of seismoacoustic signals built by means of this program during the days of electrical soundings in November 2021 are shown in Fig. 5. Time of the start and end of the intervals with increasing seismoacoustic noise in Fig. 5 corresponds to the start and end of the sounding session according to the experiment log. Thus, the molecular-electron hydrophone steady registered all sessions with the supply of current pulses to the dipole. Recordings of waveforms can be used for tracking the duration of the sounding sessions and even the number of pulses in a session.

In order to reveal the regional features of the medium reaction to the current pulses dur-

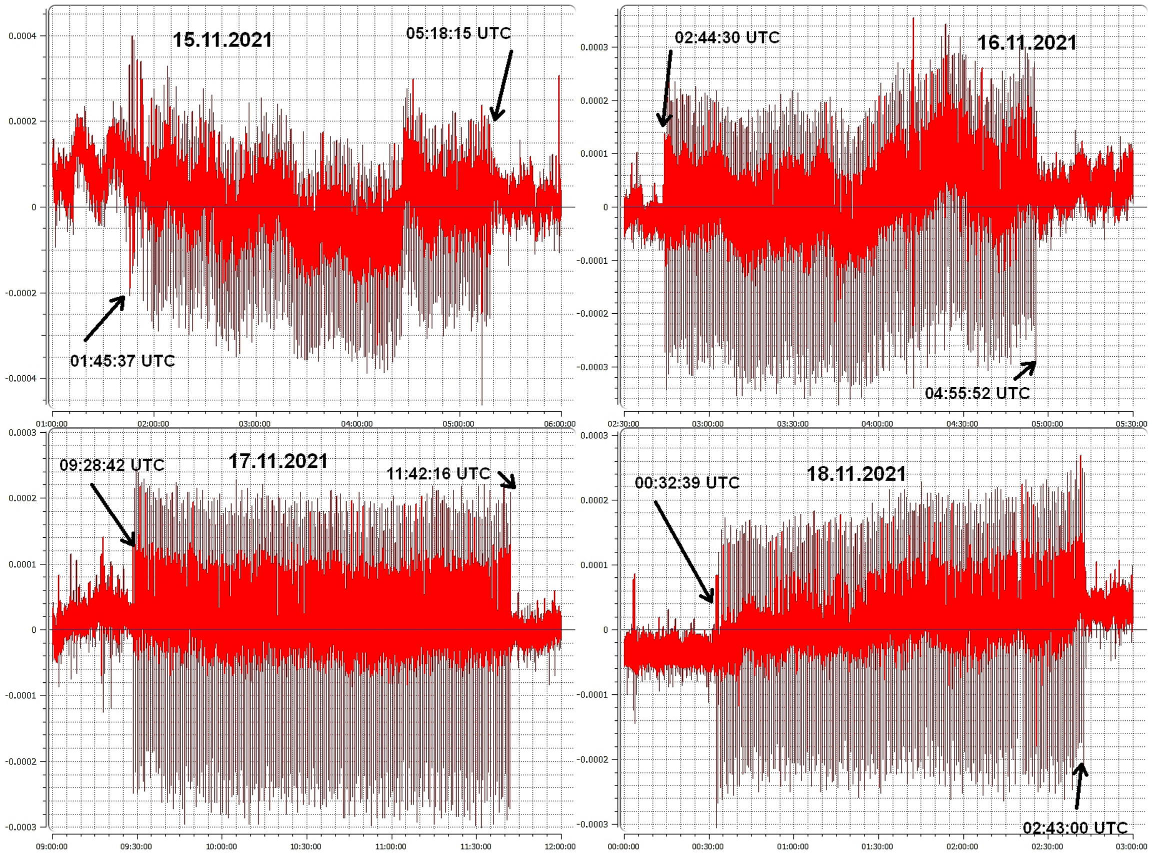

Fig. 5. The waveforms given by the molecular-electronic hydrophone on the days of electrical sounding in November 2021.

ing sounding in the zone of the Central Sakhalin fault, a spectrum of seismoacoustic signals from a molecular-electron hydrophone was constructed. The recording of seismoacoustic noise in the period from 00:00:00 on November 15, 2021, to 06:00:00 on November 18, 2021 (UTC), was used. Individual harmonics with the frequencies of 4.27 and 12.5 Hz were identified (Fig. 6, top panel) by the spectral-temporal analysis during the sounding sessions. The dependence of the spectral density on time was analyzed for these harmonics (Fig. 6, bottom panel). The choice of harmonics was determined by the fact that in the earlier experiment at the Bishkek geodynamic test site [27], seismoacoustic responses to the electrical impact were found at these frequencies over the borehole geophone records.

The reaction of hydrophone signals to electrical soundings in the frequency range of 3–25 Hz is visible on the spectrum in Fig. 6 (top). The analysis at higher frequencies is difficult due to the presence of various continuous noises, apparently of man-made origin. It is important to note that the characteristic response to the internal impact at the frequency of 4.27 Hz described earlier in [27] is also present in our experiment, while the response amplitude at the frequency of 12.5 Hz is of an order of magnitude smaller, although it does occur.

The frequency dependences of the signal spectral amplitude recorded by the hydrophone at the start of the electrical sounding sessions on November 15 and 18, 2021, were plotted (Fig. 7) for identifying the frequencies at which the maximum impact of elastic vibrations on the near-pipe space and fluid inside the casing pipe, where the molecular-electron hydrophone is installed.

Figure 7 shows that in both cases the maximum density of the spectrum falls at the frequencies of 4.7–4.9 Hz, that can be considered as confirmation of the sensitivity of the seismoacoustic signals recorded by the hydrophone by the start of the session with a series of current pulses. The source of signals with such a frequency could be located at a distance of no more than tens or several hundred meters from the hydrophone, otherwise the signals could not be recorded due to the divergence and absorption of elastic waves. No significant difference in the records of seismoacoustic noise in comparison with the above results was revealed during electrical soundings in 2022 (the third and fourth stages of the experiment).

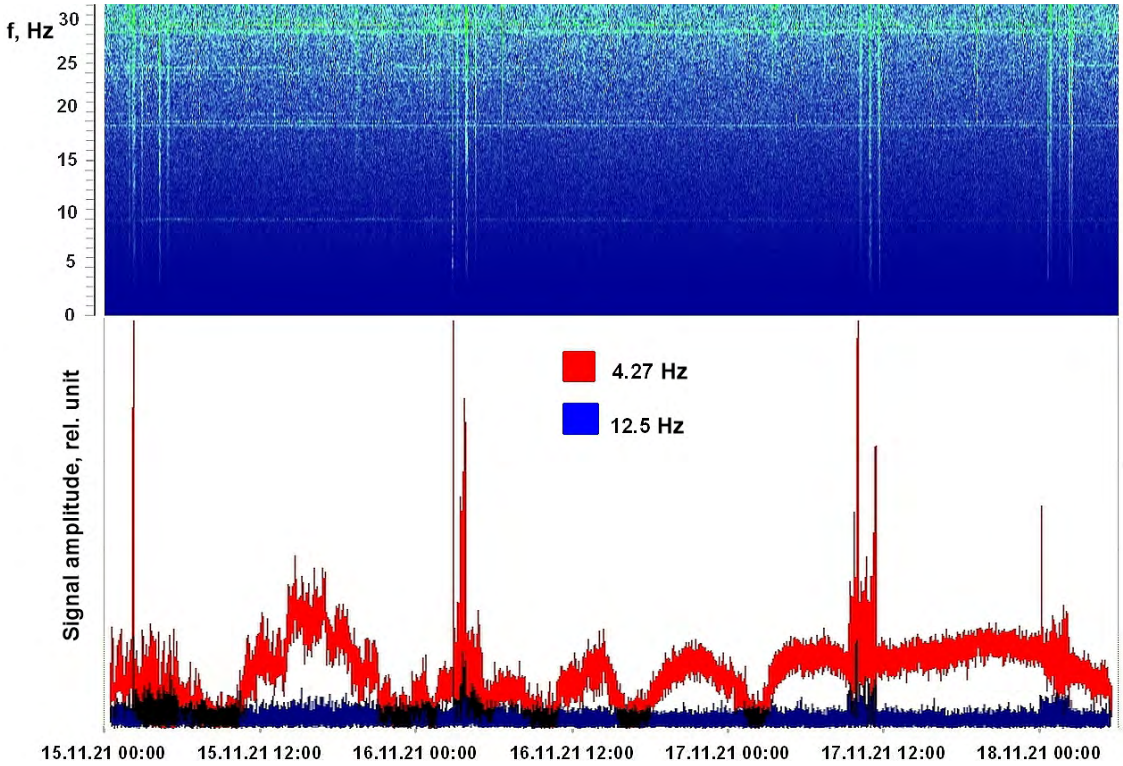

Fig. 6. The spectrogram of seismoacoustic noise recorded by the molecular-electronic hydrophone (top panel) and the spectral density at frequencies 4.27 and 12.5 Hz (bottom panel) at the second stage of the experiment.

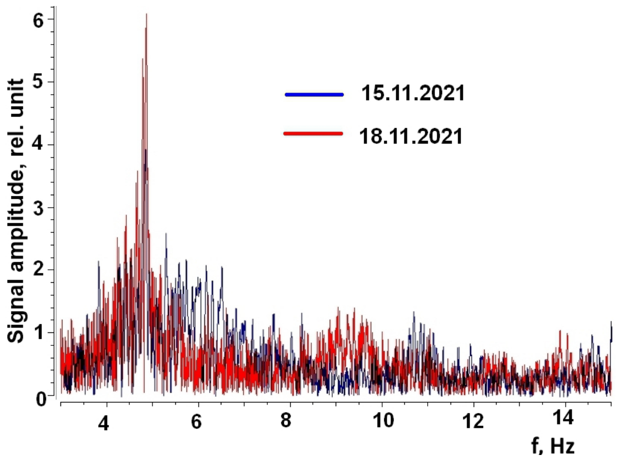

Fig. 7. Spectral density of seismoacoustic signals during electrical sounding according to the records of the molecular-electronic hydrophone.

12 electrical sounding sessions were totally carried out in 2021–2022 (see Table). For each session, the seismic records with a duration of 4 h each, obtained by the CME-6111 molecular-electronic seismometer, were analyzed. The recording period covers the time of the session itself (2.2 h), as well as the intervals of about 1 h before and after the end of electrical sounding. Seismic records were analyzed using the SpectrumSeism program [26]. The records are almost identical for all 12 cases of electrical sounding, little differences involve the presence or absence of other noises not associated with current pulses excitation in the medium. Figure 8 shows the spectrogram of seismic signals during one of the sessions at the second stage of the experiment. It can be clearly seen from the figure that during the session, the CME-6111 seismometer registers an increase in the signal amplitude at the frequencies of about 25 Hz, and at two close harmonics.

The graphs of the spectral density of seismic signals were plotted at an arbitrary time after the start of the electric impact sessions in order to refine the values of these frequencies by means of the same program for all 12 cases. Figure 9 shows the examples of such graphs, the dates of electrical soundings are 18.11.2021 and 09.11.2022.

Two harmonics are also traced well in Fig. 9 and in all other obtained graphs, and the amplitude of the first harmonic is higher than the second one. The graphs of the change in the amplitude of harmonic, at which the maximum signal amplitude is fixed, are plotted versus time for 4 hours (as well as for all 12 cases). Two examples of such graphs are shown in Fig. 10, one for the third stage of electrical soundings (see Table), and the other for the fourth one.

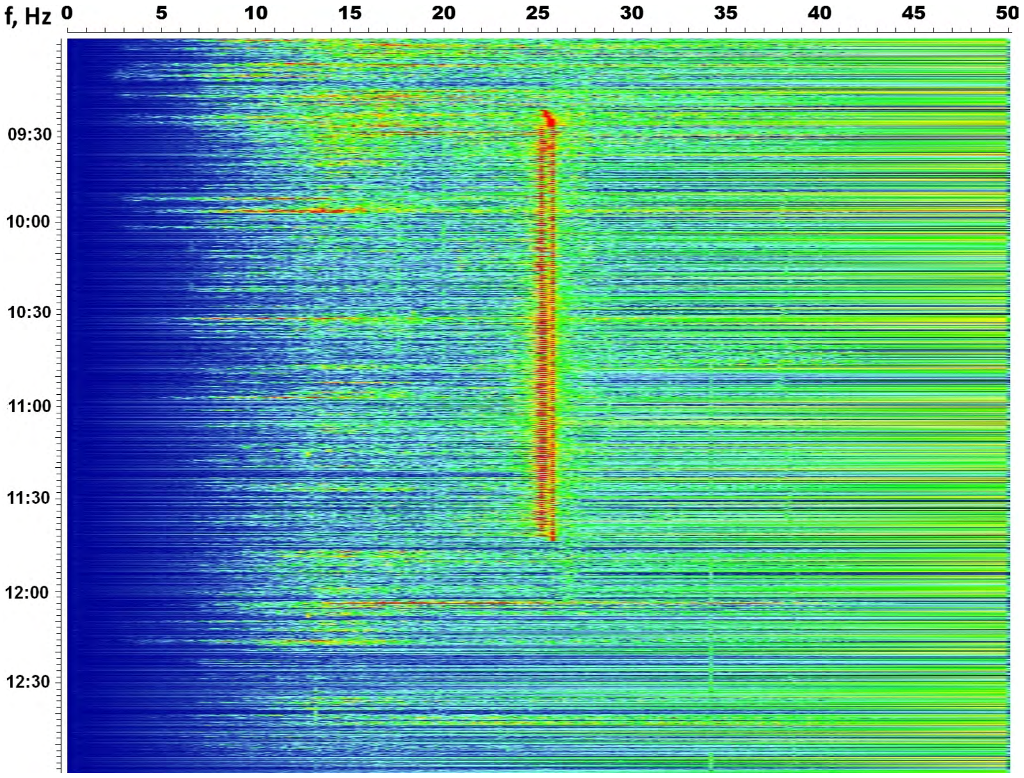

Fig. 8. Spectrogram of the seismic signal record of 17.11.2021, which was recorded on the vertical channel of the CME-6111 seismometer.

The start and end times of these sessions (coinciding with the records from an experimental log), as well as all cases when breaks or failures occurred during the sessions (as, for example, a 7-minute break in Fig. 10, a frame on the left), are clearly visible on the graphs, presented in Fig. 10. The similar patterns on graphs are for other electrical sounding sessions. The influence of electrical impact is noted in the range of seismic frequencies up to 25 Hz, and it manifests itself most contrastingly for individual harmonics. The parameters of the current pulses at different stages of the experiment and on different days of sounding at each stage slightly differed from each other in terms of current amplitude, polarity, and also the start time of electrical sounding sessions in order to uphold the principle of randomization of the experiment. According to this principle, new physical effects can be considered completely reliable if they are stable when some changes in the parameters of the experiment occur [28]. An element of randomness is introduced into the experiment design in the cases, when the mathematical model is still unknown or insufficiently developed. These cases include our study of the inverse seismoelectric effect of the second kind in the fault zone.

Summarizing the above results, we can conclude that current pulses in the near-surface layer of the crust during electrical sounding in the Central Sakhalin fault zone affect the sources of seismic and seismoacoustic waves, due to which the noise amplitude increases.

Discussion of the results

Before discussing how the obtained results fit into the concept of seismic and seismoacoustic responses of the medium to the impact of current

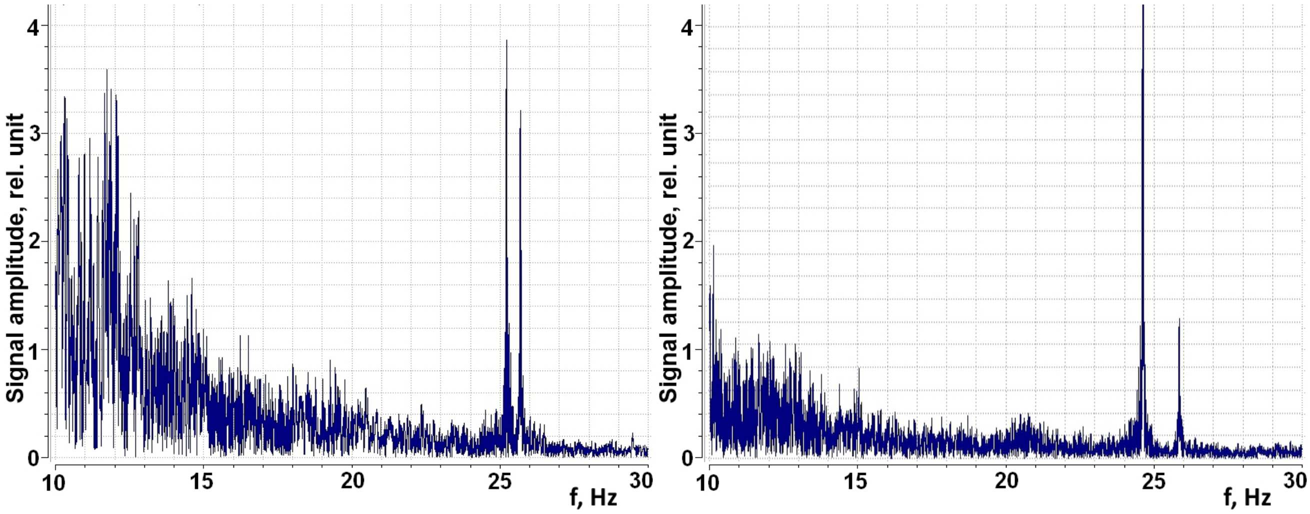

Fig. 9. The spectral density of the signal during the periods of electrical sounding 18.11.2021 (left) and 09.11.2022 (right)

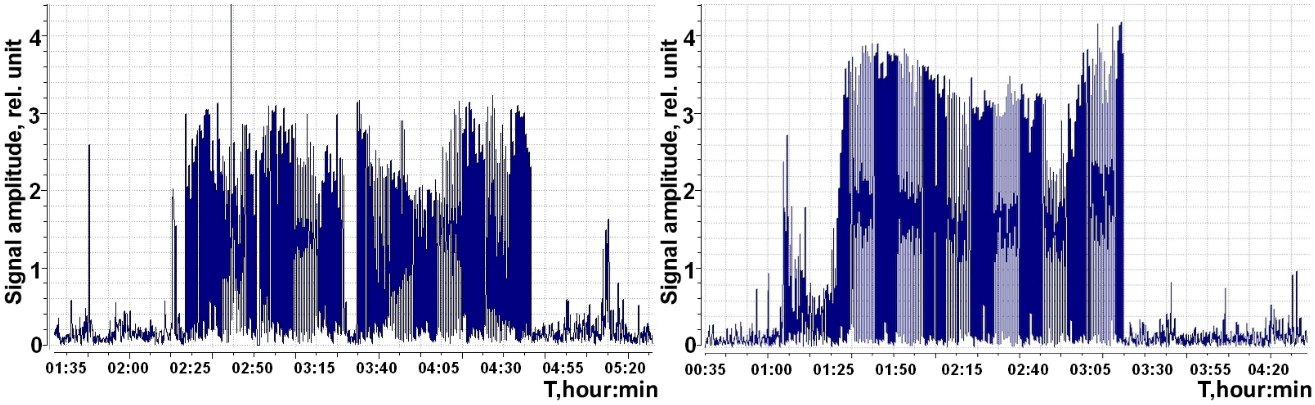

Fig. 10. Changes in the amplitude of the seismic signal spectrum during the period of the electrical sounding at a frequency of 25.06 Hz on 25.04.2022 (left) and at a frequency of 24.51 Hz on 10.11.2022 (right).

pulses, we would estimate the density of the current excited by an electric dipole. It is convenient to use the formula from [29] for current density j at a sufficient distance from the dipole center:

$$j(r) = I\,L/(2\pi r^3), \tag{1}$$

where I – current intensity, determined by a source and load resistance, L – distance between the electrodes (dipole length), r – distance from the dipole center to a point in the medium, $r >> L$. Formula (1) gives an approximate result for the distances $r \geq L$, which is confirmed by the coincidence of $j(r)$ when $r = L$ with the expression for the current density at the symmetric spreading from the pole to the hemispheric zone. The conductivity distribution of the medium is considered to be quasi-homogeneous.

During electrical soundings carried out at the Petropavlovskoye test site, the values of the parameters were as follows: I = 5–13 A, L = 408 m. The sources of seismoacoustic noise that the hydrophone can record are at a distance of no more than a few hundred meters from the receiver and, consequently, from the electrode 2 (see Fig. 1). Due to this fact, in order to estimate the current density at the location of the sources, we can set $r = L$ in (1), and then this expression yields $j \sim (0.5–1)\cdot10^{-5}$ A/m^2. The current density decreases rapidly with r increasing. So, at a kilometer distance at a maximum sounding current of 13 A, $j(r_{1000}) \sim 10^{-6}$ A/m^2, while at a distance of 5 km from the dipole (for example, down to the layer where earthquake hypocenters can fall) $j(r_{5000}) \sim 10^{-}$ A/m^2. The estimates obtained show that, during electrical soundings, the current density in the medium at distances up to 1 km from the center of the electric dipole source was higher than the characteristic values of $j(r)$ in practical applications of the seismoelectric effect of the second kind for hydrocarbon deposit delineation [30, 31]. Indeed, in such applications, the length of the dipole is usually about 100 m, the voltage of the source (car battery) is 12 or 24 V, and the apparent load resistance is ≥100 Ohms. The $j \sim 10^{-6}$ A/m^2 values for the above electrical soundings (at the distance of $r \sim 1$ km from the source) correspond to the calculated estimates of the current density, which can be excited in the conductive layer of the lithosphere at global ionospheric disturbances – the effects of X-class solar flares [32, 33]. A number of works (bibliography in [34]) have noted seismic noise to increase after geoeffective solar flares causing strong magnetic storms. The possible mechanism of this effect is associated with micropulsations in the Earth's magnetic field and induced telluric currents. In view of these circumstances, we can say that our results are somewhat similar to the general picture of the geological medium reaction to the excitation of electric current in it.

It is possible to estimate the current density values for other experiments using expression (1) to compare them with our case of electrical soundings ($j \sim 10^{-6} – 10^{-5}$ A/m^2). Take the distance $r = 400$ m as a reference value for numerical estimates and consider a few examples.

1. In the period of October 22–26, 2018, we together with the staff of IKIR FEB RAS conducted electrical soundings similar to the above ones. The place for experiments was the site of the Karymshyna station of IKIR DVO RAS, Kamchatka region, which is located in the zone of faults of different ranks. The current in the pulses was I = 0.9 A when conducting electrical soundings, and the length of the dipole was L = 18 m. It follows that at a reference distance of 400 m the current density $j \sim 0.4\cdot10^{-7}$ A/m^2, and only at distances up to 140 m the current density can reach values of 10^{-6} A/m^2. Seismoacoustic signals were recorded by hydrophones of different types installed in a small artificial pond, as well as by a high-frequency seismic receiver (A1638 geophone, made by ZAO Geoacoustics[2]). The distance from the hydrophones (the center of the pond) to the nearest pole of the dipole (casing pipe buried at 5 m) was about 20 m. The geophone was rigidly mounted on a metal beam welded to the construction of another pole (identical casing pipe). No changes in seismoacoustic noise were detected during the electrical sounding sessions.

2. On August 29 and 30, 2019, electrical soundings using our methodology were also conducted on the territory of the Mikhnevo geophysical observatory of the Sadovsky Institute of Geosphere Dynamics of RAS, Moscow region. In this

---

[2] Geoacoustics. **2009.** URL: http://geophone.narod.ru/TTX/ttx.html (accessed 23.04.2023)

case, the current in the pulses was $I = 3.1$ A, and the length of the dipole was $L = 180$ m. Therefore, the current density at the reference distance of 400 m was $j \sim 1.4 \cdot 10^{-6}$ A/m^2. The Mikhnevo geophysical observatory has a small aperture seismic antenna, SSA, including a central seismometer, which is located in an adit at a depth of 20 m, and 11 peripheral instruments. As a result, SSA (in other words, a local seismic network) is highly sensitive to seismic waves and is able to record regional seismic events with small magnitudes (M < 2). In our experiment, the center of the dipole source was located about 350 m from an adit with a central seismometer. It was not possible to use hydrophones or geophones due to technical reasons.

According to the data of the Mikhnevo local seismic network, no significant changes in seismic noise were found in the days of the sounding (presumably due to insufficient data accumulation at a small number and duration of electrical sounding sessions).

3. According to [28], seismic acoustic emission (SAE) responses were recorded when sounding the Earth's crust in Northern Tien Shan with the alternating current pulses with an amplitude of 600 A and a duration of 5 s (source – ERGU-600-2 electric prospecting generator unit) at a distance of about 8 km from the center of the dipole source. The signals were recorded using the A1638 geophone located in the borehole at a depth of about 80 m. Based on the data [28] on the dipole length ($L = 4.2$ km) and distances to the receiver, it is possible to estimate the current density in the area where the SAE signals were recorded, with a value of $j \sim 0.8 \cdot 10^{-6}$ A/m^2.

Comparing these examples with the results of electrical soundings at the Petropavlovskoye test site, it is possible to summarize that the medium reaction occur, which manifests in seismoacoustics in seismically active regions (where there are excess stresses in the Earth's crust), when exciting an electric current in the medium with a density of 10^{-6} A/m^2 or higher. In this case, different forms of the medium reactions (so-called responses) can be registered by means of different methods of primary data processing. Examples of responses include both an increase in seismoacoustic noise level (see above) and an increase in the number of SAE events determined by exceeding the level of discrimination in noise records [27]. There may be other forms of responses.

Other factors may affect seismoacoustic and seismic noise levels in addition to electrical soundings. It is known that baric variations in the atmosphere caused by cyclones [35] can have the strongest influence on seismic noise. At the same time, short-period baric variations lasting from 5 to 30 minutes lead to an increase in seismic noise in the range of 4–8 Hz [35]. But it is most unlikely that in all cases, the sessions of electrical soundings were superimposed on such short-period baric variations. Furthermore, pressure drops, as well as wind loads, do not increase at cyclones as sharply as the current supply to the dipole. So, baric variations associated with cyclones cannot explain the sharp (as in Fig. 5) increase in seismoacoustic noise. Nevertheless, we will provide information on the passage of cyclones over the southern part of Sakhalin Island during the experiment days (according to the hydrometeorological bulletins of the Far Eastern Regional Hydrometeorological Research Institute). According to these bulletins[3], on the days of electrical sounding in 2021–2022, cyclones were recorded on 18.11.2021 (the last day of the second stage of the experiment) and 26–27.04.2022 (the second stage). Even if we assume that in the statistics of cases of increase in seismoacoustic noise under the influence of electrical soundings only 9 days without cyclones make a positive contribution, and for 3 days the experiment result is not determined, then the "success rate" will be 75 %, that the hypothesis about the medium reaction to current pulses is confirmed.

Concluding the discussion of the results, we will dwell on the requirements for the source of electrical sounding for seismoelectric monitoring of fault zones. To do this, it is necessary to expand the boundaries of the zone near the source, where, during sounding, a current with a density above 10^{-6} A/m^2 is excited to at least 5 km (the characteristic width of the zone of the fault influence).

---

[3] Mezentseva L.I., Kaptyug V.A. **2021** [Mezentseva L.I., Kaptyug V.A. **2021.** Monthly hydrometeorological bulletin of the FERHMI. Vladivostok: FERHMI, 11: 21 p.]. URL: http://www.ferhri.ru/images/stories/FERHRI/Bulletins/Bul_2021/11/2021.11_ch1_meteo.pdf ; The same. **2022**, 4: 20 p. URL: http://www.ferhri.ru/images/stories/FERHRI/Bulletins/Bul_2022/4/2022.04_ch1_meteo.pdf ; The same. **2022**, 11: 21 p. URL: http://www.ferhri.ru/images/stories/FERHRI/Bulletins/Bul_2022/11/2022.11_ch1_meteo.pdf (accessed 16.02.2023).

By means of expression (1) it is easy to obtain that this is ensured by the product of current in the dipole on its length $I{\cdot}L = 8{\cdot}10^5$ A·m. Such values can be achieved with the most powerful but very expensive current pulse sources.

The purpose of further experiments may be studying the inverse seismoelectric effect of the second kind at a lower current density, $j \sim 10^{-7}$ A/m^2 (i.e. in the remote zones outside the source).

Conclusion

On the basis of the results of a four-stage experiment on electrical sounding, which was conducted in the influence zone of the Central Sakhalin fault, the effect of increase in the seismoacoustic noise level in the surface layers near the source – an exciting electric dipole source – was found.

As a source, the IEIG-7-400 generator unit developed at the Institute of Marine Geology and Geophysics of the Far Eastern Branch of the Russian Academy of Sciences with a power of 3 kW, higher than that of ordinary sources for electrical prospecting by the resistance methods. Registration of seismic and seismoacoustic noises in the background and during soundings was carried out by means of molecular-electronic sensors: a borehole hydrophone and a CME-6111 seismometer. The correlations between the periods of current pulses supply to the medium through the dipole and the increase in seismoacoustic noise were found on the base of the records of these sensors. The revealed medium reaction to the transfer of current pulses is a form of the inverse seismoelectric effect of the second kind, which is realized at sufficiently high current densities. The results obtained are consistent with the results of seismoacoustic emission variations, which were recorded by borehole sensors during electrical sounding in the Northern Tien Shan. The difference between seismoacoustic manifestations of the medium reaction and the responses of seismicity (changes in the parameters of the flow of seismic events after soundings by means geophysical MHD generators and apparatus for electric pulse supply) lies in the practical absence of a delay after the start of the impact. The development and application of more powerful, but economically acceptable generating units can provide additional information on this issue.

References

1. Cherdyncev S.N. **2022.** The seismoelectric effect is the basis of a new geophysical method of oil well research – seismoelectric logging. *Advances in Current Natural Sciences*, 11: 143–150. (In Russ.). https://doi.org/10.17513/use.37942
2. Ivanov A.G. **1940.** Seismoelectric effect of the 1st kind in near-electrode regions. *Transactions (Doklady) of the USSR Academy of Sciences*, 68: 53–56. (In Russ.).
3. Ivanov A.G. **1940.** Seismoelectric effect of the 2nd kind. *Izvestiya AN SSSR. Seriya geograficheskaya i geofizicheskaya*, 5: 699–727. (In Russ.).
4. Frenkel‘ Ya.I. **1944.** On the theory of seismic and seismoelectric phenomena in moist soil. *Izvestiya AN SSSR. Seriya geograficheskaya i geofizicheskaya*, 8(4): 134–149. (In Russ.).
5. Biot M.A. **1956.** Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range. *Journal of the Acoustical Society of America*, 28(2): 168–178. https://doi.org/10.1121/1.1908239
6. Pride S.R. **1994.** Governing equations for the coupled electromagnetics and acoustics of porous media. *Physical Review B*, 50(21): 15678–15696. https://doi.org/10.1103/physrevb.50.15678
7. Haartsen M.W., Pride S.R. **1996.** Electroseismic waves from point sources in layered media. *J. of Geophysical Research: Solid Earth*, 102(B11): 24745–24769. https://doi.org/10.1029/97jb02936
8. Svetov B.S. **2008.** *Fundamentals of geoelectrics*. Leningrad: Izdatel'stvo LKI, 656 p. (In Russ.).
9. Adushkin V.V., Spivak A.A. **2014.** *Physical fields in near-surface geophysics*. Moscow: GEOS, 360 p. (In Russ.).
10. Adushkin V.V., Ovchinnikov V.M., Sanina I.A., Riznichenko O.Yu. **2016.** Mikhnevo: from seismic station no. 1 to a modern geophysical observatory. *Izv., Physics of the Solid Earth*, 52(1): 105–116. https://doi.org/10.1134/s1069351315060014
11. Spivak A.A., Kishkina S.B. **2004.** The use of microseismic background for the identification of active geotectonic structures and determination of geodynamic characteristics. *Izv., Physics of the Solid Earth*, 40(7): 573–586.
12. Tarasov N.T. **1997.** Variation of seismicity of the Earth crust by electric impact. *Doklady Rossiiskoi akademii nauk* [*Transactions (Doklady) of the Russian Academy of Sciences. Earth Science Sections*], 353(4): 542–545. (In Russ.).
13. Tarasov N.T., Tarasova N.V., Avagimov A.A., Zeigarnik V.A. **2000.**The effect of high energy electromagnetic pulses on seismicity in Central Asia and Kazakhstan. *Volcanology and Seismology*, 21(4-5): 627–639.
14. Avagimov A.A., Zejgarnik V.A., Fajnberg E.B. **2005.** Electromagnetically induced spatial-temporal structure of seismicity. *Izv., Physics of the Solid Earth*, 41(6): 475–484.
15. Smirnov V.B., Zavyalov A.D. **2012.** Seismic response to electromagnetic sounding of the Earth's lithosphere. *Izv., Physics Solid Earth*, 48: 615–639. https://doi.org/10.1134/S1069351312070075

16. Sychev V.N., Bogomolov L.M., Rybin A.K., Sycheva N.A. **2010.** Influence of electromagnetic sounding of the Earth‘s crust on the seismic regime of the territory of the Bishkek geodynamic test site. In: Adushkin V.V., Kocharyan G.G. (eds) *Trigger effects in geosystems*: Proceedings of the All-Russian seminar-meeting. Moscow: GEOS, p. 316–325. (In Russ.).
17. Sobolev G.A., Ponomarev A.V. **2003.** *Earthquake physics and precursors*. Moscow: Nauka, 270 p. (In Russ.).
18. Bogomolov L.M., Il’ichev P.V., Sychev V.N., Zakupin A.S., Novikov V.A., Okunev V.I. **2004.** Acoustic emission response of rocks to electric power action as seismic-electric effect manifestation. *Annals of Geophysics*, 47(1): 65–72. https://doi.org/10.4401/ag-3259
19. Svetov B.S. **2000.** On the theoretical substantiation of the seismoelectric method of geophysical exploration. *Geofizika*, 1: 28–39. (In Russ.).
20. Kormil‘cev V.V. **1980.** *Transients under induced polarization*. Moscow: Nauka, 112 p. (In Russ.).
21. Svetov B.S., Ageev V.V., Karinskij S.D., Ageeva O.A. **2013.** Self-consistent problem of induced polarization of electrokinetic origin. *Izv., Physics Solid Earth*, 49(6): 836–843. https://doi.org/10.1134/s1069351313060141
22. Dudchenko I.P., Kostylev D.V., Gulyakov S.A., Stovbun N.S. **2021.** A geophysical pulse voltage generator for seismic and electric exploration of the subsurface. *Geosystems of Transition Zones*, 5(1): 46–54. DOI 10.30730/gtrz.2021.5.1.046-054 (In Russ.).
23. Kostylev D.V., Bogomolov L.M., Boginskaya N.V. **2019.** About seismic observations on Sakhalin with the use of molecular-electronic seismic sensors of new type. *IOP Conference Series: Earth and Environmental Science*, 012009. doi:10.1088/1755-1315/324/1/012009
24. Kostylev D.V., Boginskaya N.V. **2020.** Seismoacoustic observations using molecular-electronic hydrophones on Sakhalin and the South Kuril Islands (Kunashir Island). *Geosystems of Transition Zones*, 4(4): 486–499. doi:10.30730/gtrz.2020.4.4.486-499 (In Russ.).
25. Rozhdestvenskij V.S., Saprygin S.M. **1999.** Structural relationships between Neogene and Quaternary deposits, active faults and seismicity in South Sakhalin. *Geology of the Pacific Ocean*, 6: 59–70. (In Russ.).
26. *RU 2021666241*. **2021.** *SpectrumSeism*: Certificate of state registration of the computer program. Authors: Seleznev V.S., Lisejkin A.V., Sevost’yanov D.B., Bryksin A.A. No. 2021665611, application 11.10.2021; publ. 11.10.2021. (In Russ.).
27. Zakupin A.S., Bogomolov L.M., Mubassarova V.A., Il’ichev P.V. **2014.** Seismoacoustic responses to high-power electric pulses from well logging data at the Bishkek geodynamical test area. *Izv., Physics Solid Earth*, 50(5): 692–706. https://doi.org/10.1134/s1069351314040193
28. Krasovskii G.I., Filaretov G.F. **1982.** Experimental design. Minsk: Izd-vo BSU. 302 p. (In Russ.).
29. Kolesnikov V.P. **1984.** Fundamentals of interpretation of electrical soundings. Moscow: Nauka, 400 p. (In Russ.).
30. Russell R.D., Butler K.E., Kepic A.W., Maxwell M. **1997.** Seismoelectric exploration. *The Leading Edge*, 16(11): 1611–1615. https://doi.org/10.1190/1.1437536
31. Potylitsyn V., Kudinov D., Alekseev D., Kokhonkova E., Kurkov S., Egorov I., Pliss A. **2021.** Study of the seismoelectric effect of the second kind using molecular sensors. *Sensors*, 21: 2301–2316. https://doi.org/10.3390/s21072301
32. Sorokin V., Yaschenko A., Mushkarev G., Novikov V. **2023.** Telluric currents generated by solar flare radiation: Physical model and numerical estimations. *Atmosphere*, 14: 458–477. https://doi.org/10.3390/atmos14030458
33. Novikov V.A., Sorokin V.M., Yashchenko A.K., Pushkarev G.Yu. **2023.** Physical model and numerical estimates of telluric currents generated by X-ray radiation of a solar flare. *Dynamic Processes in Geospheres*, 15(1): 23–44. (In Russ.). doi:10.26006/29490995_2023_15_1_23
34. Sycheva N.A. **2022.** Solar flares, strong magnetic storms and variations in the level of seismic noise in the Northern Tien Shan. *Geophysical Processes and the Biosphere*, 21(4): 93–109. (In Russ.). doi:10.21455/GPB2022.4-7
35. Adushkin V.V., Loktev D.N., Spivak A.A. **2008.** The effect of baric disturbances in the atmosphere on microseismic processes in the crust. *Izv., Physics Solid Earth*, 44(6): 510–517. https://doi.org/10.1134/s1069351308060086

About the Authors

Bogomolov, Leonid M. (https://orcid.org/0000-0002-9124-9797), Doctor of Physics and Mathematics, Director, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, bleom@mail.ru

Kostylev, Dmitry V. (https://orcid.org/0000-0002-8150-9575), Director, Sakhalin Branch of the Federal Research Center of Geophysical Survey of the Russian Academy of Sciences, Yuzhno-Sakhalinsk; Researcher, Laboratory of Seismology, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, d.kostylev@imgg.ru

Kostyleva, Natalya V. (https://orcid.org/0000-0002-3126-5138), Researcher, Laboratory of Seismology, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, n.kostyleva@imgg.ru

Gulyakov, Sergey A. (https://orcid.org/0009-0001-7924-6972), Junior Researcher, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, gulyakov_97@mail.ru

Dudchenko, Ilya P. (https://orcid.org/0000-0002-4967-7405), Cand. of Sci. (Engineering), Senior Researcher, Center for Collective Use, Head of the Department of research of geophysical fields and physical properties of geomaterials, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, ilpadu@mail.ru

Kamenev, Pavel A. (https://orcid.org/0000-0002-9934-5855), Cand. of Sci. (Engineering), Senior Researcher, Laboratory of geochemistry and regional geology, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, kamepav@mail.ru

Stovbun, Nikolai S. (https://orcid.org/0009-0004-1927-798X), Junior Researcher, Institute of Marine Geology and Geophysics, Far Eastern Branch of the Russian Academy of Sciences, Yuzhno-Sakhalinsk, nikolay19972016@gmail.com

Поступила 27.04.2023
Принята к публикации 21.05.2023

Received 27 April 2023
Accepted 21 May 2023