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MODELING
IN PHYSICAL AND TECHNICAL RESEARCH

Prediction of Environmental Risks from Explosions Based on a Set of Coupled Geophysical Fields

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Abstract—This paper presents the results of experimental studies and numerical calculations of weather-dependent ecological risks to social infrastructure facilities from the effects of powerful infrasonic vibrations generated by man-made and natural explosions. The results were obtained by applying an original ecologically safe approach developed by the authors and involving the use of seismic vibrators as sources simulating explosions but having much less power compared to the explosions. Such sources generate both seismic and acoustic (seismoacoustic) vibrations with precision metrological power and frequency-time characteristics, which, in contrast to explosions, ensures high reproducibility of research results. Results comparable to explosions are achieved due to the energy accumulation of weak vibroseismoacoustic signals. The propagation of infralow-frequency wave fields is studied depending on weather conditions and taking into account the effect of heterogeneity of the atmosphere. The results of the experiments are compared with those of numerical calculations.

Keywords: quarry blasts, acoustoseismic fields, geo-environmental risk, seismic vibrator, weather conditions.

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INTRODUCTION

The problem of predicting the geo-ecological effect of technogenic explosions of different types: short-delay quarry blasts [1], test site explosions [2], impacts of falling rocket stages [3], and others on the environment and social infrastructure is of primary importance. Mass explosions associated with the destruction of recyclable munitions have recently become a great danger. The powerful natural explosion-like events include primarily earthquakes, magmatic and mud volcano eruptions [4], and the fall of heavenly bodies.

It is known that the major geo-ecological effects of explosions are the formation of air shock waves and underground seismic waves, the formation and propagation of a dust cloud and electrical impulses. Of great interest are the seismic and acoustic effects of mass explosions that affect the integrity of industrial and residential objects and their shock action on biological objects. These effects were considered in [1]. At the same time, little attention has been given to the influence exerted on them by external factors, such as wind force and direction, temperature inversion, atmospheric turbulence, and the surrounding landscape and topography. This is especially important because these factors can greatly enhance the destructive ecological action of explosions on the environment. This leads to the necessity of predicting the geo-ecological risks of powerful explosions, which requires additional studies of the physical effects of seismic and acoustic waves from mass explosions.

Fig. 1. TsV-40 vibration source.

The purpose of this paper is to present a methodological approach to such studies and the experimental and numerical results obtained. This approach is based on the use of seismic vibrators as sources simulating explosions but having a much lower power in comparison with them. This provides high ecological cleanness and repeatability of experiments, unlike explosions. The latter is due to the high metrological power and frequency-time characteristics of the vibration sources [5]. A rationale for the use of the proposed prediction method using seismic vibrators is its ability to generate seismic and acoustic oscillations simultaneously, which has already been proved theoretically and by numerous experiments [6–9].

ACOUSTOSEISMIC EFFECTS OF SEISMIC VIBRATORS AND EXPLOSIONS

Weather-Dependent Physical Effects in Experiments with Seismic Vibrators

The seismic and acoustic waves generated by powerful TsV-100 and TsV-40 vibrators can jointly propagate for tens kilometers from the source due to the acoustoseismic induction effect. The acoustic wave propagating in the near-surface waveguide generates a surface seismic wave in the earth, recorded by seismic sensors. This wave will be called acoustoseismic. The velocities of both types of waves are the same and equal to the infrasound propagation velocity [7]. A network of Baikal autonomous seismic stations was arranged on a circle of radius either 6 or 12 km at a vibroseismic test site (Bystrovka village, Novosibirsk region) to estimate the quantitative effect of wind on the propagation of acoustic waves. A TsV-40 vibrator was placed in the center of the circle (see Fig. 1). The source has a disturbing force 40 tf in the operating frequency band of 6–12 Hz.

One of the schematic diagrams of the arrangement of sensors at the points of a circle *1–8* is shown in Fig. 2. The sensors were SK1-P and SME-3011 three-component seismic sensors (developed at the Moscow Physical-Technical Institute), indicated in the figure by triangles. The figure illustrates the capabilities of simultaneous recording of acoustic and seismic waves from the seismic vibrator by means of sensors. The results of recording and processing are vibrational correlograms obtained by correlation convolution between the recorded and reference signals. The shapes of the reference signal follows the shape of the probing signal of the vibrator:

$$r(m) = \frac{1}{N-m}\sum_{n=1}^{N} x_n S_{n-m}, \qquad m = 0,\dots,M-1, \quad n = 1,\dots,N, \tag{1}$$

where M is the number of discrete samples of the vibration seismograms; N is the set of discrete samples of the recorded input $x_n = x(t_n)$; $S_n = S(t_n)$ is the reference signal with a linear frequency modulation of the form $S(t) = a(t)\cos(2\pi f_0 t + \beta t^2/2)$, where $a(t)$ is the envelope, f_0 is the initial sweep frequency, and β is the frequency sweep rate $\beta = (f_{\max} - f_0)/T$ is the maximum frequency ($f_{\max}$ and T is the sweep length).

In the experiment, the following values were used as the basis: $f_0 = 6.25$ Hz, $f_{\max} = 11.23$ Hz, and $T = 2850$ s. The obtained vibration correlograms are analogs of impulse seismograms and illustrate the

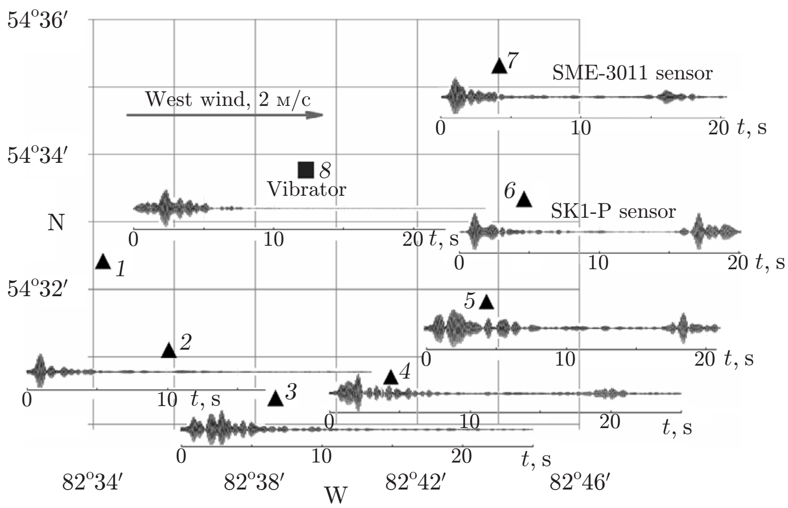

Fig. 2. Schematic diagram of the of arrangement of Baikal seismic stations with SK1-P and SME-3011 three-component sensors located on a circle of radius 6 km. Vibrational correlograms illustrating the arrival of seismic and acoustic waves are shown.

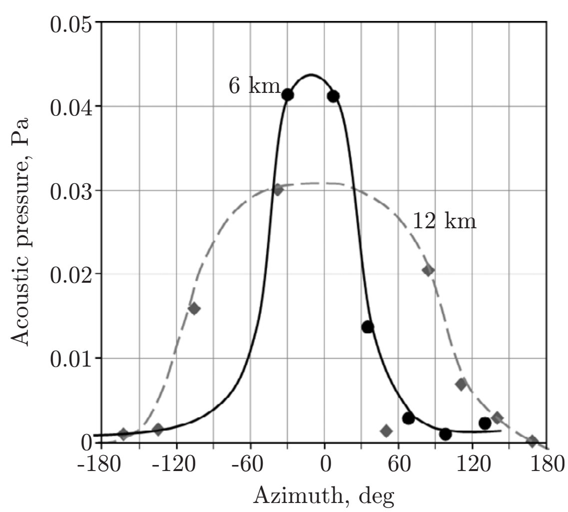

Fig. 3. Dependence of the acoustic pressure on the azimuth of the observation points taking into account the wind speed when recording from the TsV -40 vibrator. The solid curve corresponds to the case of a circular arrangement of sensors of radius 6 km at a wind speed of 2–4 m/s, and the dotted curve to 12 km and 4–6 m/s.

arrival of seismic waves (first-arrival waves) at arrival times of 0.96–1.05 s and acoustic wave (second wave) at the arrival times of 16–19.5 s. By the latter are meant the seismic waves recorded by seismic sensors as a result of the above-mentioned acoustoseismic induction process. Such waves were recorded in the experiments by SK1-P (*4–6*) and SME-3011 (*7*) seismic sensors (see Fig. 2) on the three components X, Y, Z. As can be seen from the figure, these waves are well defined in seismograms provided that the directions of the wind and the front of acoustic-wave propagation coincide. The wind direction and speed are shown by the arrow and are 2–4 m/s in this case. This feature of acoustic wave propagation is known in acoustics as the effect of increased effective speed of sound and decrease attenuation with a favorable wind [10]. This determines the role of weather conditions in the further propagation of acoustic waves. The recorded directional effect of the acoustic wave field is amenable to rigorous quantitative evaluation in experiments using a vibrator with a circular arrangement of sensors with respect to the source. Figure 3 shows graphs of the direction diagrams (DD) of the wave field corresponding to this effect for azimuths of $-180\ldots+180°$ and for the above variants of arrangement. Here the zero azimuth corresponds to the wind direction. The acoustic pressures corresponding to the given azimuth directions are shown on the ordinate. Quantitatively, the direction effect can be characterized by the width of the DP in degrees at a level of 0.7 of the maximum value. As follows from these graphs, the width of the DD in the first case (solid curve) is 60°, and in the second case (dashed curve), it is 160°. The obtained graphs characterize the pronounced dependence of the acoustic pressure on the wind. For example, in the first case, the ratio of the maximum and minimum acoustic pressures reaches 50. This spatial redistribution of the acoustic pressure leads to the important conclusion that even low-power explosions can become ecologically hazardous due to the manifold increase in the energy flow in a certain azimuthal direction.

Weather-Dependent Physical Effects in Test Site Explosions

By analogy with the experiments with vibrators, we studied the wind dependence of the acoustic pressure from another source that has a direct a destructive action on the environment — explosions of utilizable ammunition stocks. In recent years, such explosions have been performed regularly at different sites of Russia, including the Shilovo test site (Novosibirsk region). We have regularly recorded seismoacoustic vibrations of explosions at the Shilovo test site using the circular recording procedure described above. The corresponding diagram is presented in Fig. 4, which shows a combined picture of the arrangement of the sensors and their associated records of explosions, wind direction, and air temperature and humidity. In the records, one can identify the first-arrival (seismic) waves at times of 1.63–1.97 s and second-arrival (acoustic) at times of 27.0–32.4 s.

For the experimental conditions given in Fig. 4, we obtained a dependence (see Fig. 5) of the acoustic pressure on the azimuth within $-180\ldots+180°$ taking into account the wind speed of about 1 m/s. By analogy with vibroseismoacoustic waves, the graph in Fig. 5 also reflects the pronounced wind-dependent effect of the direction of propagation of the acoustic wave field. The obtained dependence corresponds to the DD width equal to 80°.

Base on the results of the experimental studies, the weather-dependent acoustic effects can be described using the direction function $f(\theta)$, which can be estimated from the increase in the amplitudes of the acoustic waves within a given angular sector. In this case, we can talk about the effect of focusing of acoustoseismic ascillations in space. The results of measurements of acoustic pressure by the sensors of circular arrangement

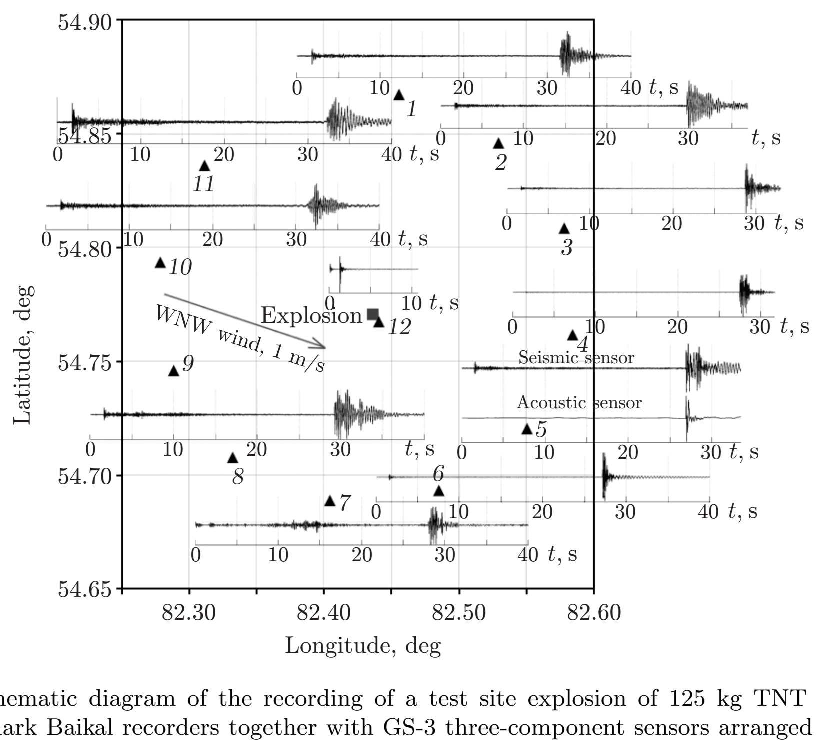

Fig. 4. Schematic diagram of the recording of a test site explosion of 125 kg TNT equivalent. Triangles mark Baikal recorders together with GS-3 three-component sensors arranged on a circle of radius 10 km under numbers *1–11*. Point *12* is the reference one. The seismograms show the first arrivals of seismic waves and the second arrivals of acoustic waves.

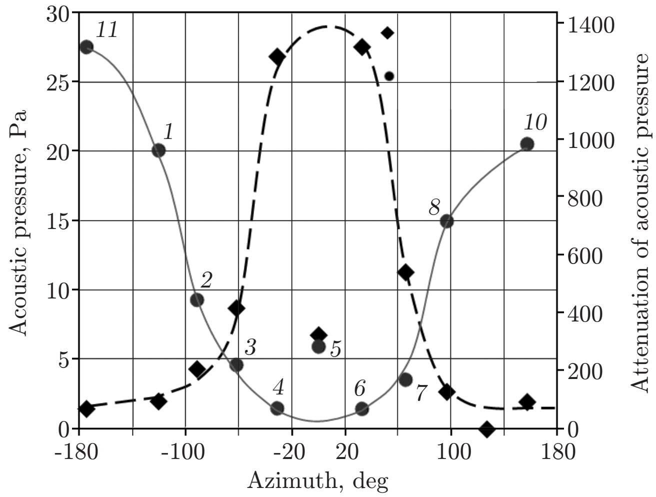

Fig. 5. Acoustic pressure versus azimuth for a test site explosion of 125 kg power at a wind force of 1 m/s and arrangement of sensors on a circle of radius 10 km (dashed curve). The graph of acoustic pressure attenuation relative to its level at the reference point (0.457 km from the explosion site) is shown by a solid curve. The attenuation coefficients are given on the right.

and the acoustic pressure at the reference point (the point *12* in Fig. 4) at a distance of 0.457 km from the epicenter of the explosions were used to estimate the pressure attenuation with distance and direction (solid curve in Fig. 5). As can be seen in the figure, the minimum coefficient corresponds to the wind direction and is within 70–72. The maximum value of the attenuation coefficient for the given experimental conditions is about 1300. Thus, at a distance of 10 km from the source of the explosion, the acoustic pressure of the air wave decreases by more than three orders of magnitude, and the ratio of the maximum and minimum attenuation coefficients of the acoustic pressure, determined by the contribution of the wind, is about 20.

Let us compare the acoustic pressure levels from the vibrator and the test site explosion. The maximum acoustic pressure from the TsV-40 vibrator at a distance of 12 km (see Fig. 3) was $p = 0.03$ Pa, whereas that from the explosion at a distance of 10 km (see Fig. 4) was about 30 Pa. Thus, at comparable distances, the acoustic pressure from the vibrator is the three orders of magnitude lower than that from the explosion. This proves the ecological cleanness of the vibrators as a tool for experimental studies.

It is of interest to compare the levels of waves (of the first and second arrivals) for both types of sources used. Figure 6 shows seismograms from both sources, obtained at points corresponding to the maxima of seismoacoustic waves: at point *5* in Fig. 2 (from the vibrator), at points *5* and *6* in Fig. 4 (from the explosion).

In the second case, the pressure levels of both types of waves are comparable, whereas in the first case, the level of the second wave exceeds the level of the first wave by an order of magnitude or more. This indicates that surface explosions cannot be used as effective seismic sources. At the same time, they generate destructive infrasonic oscillations in the frequency range of 1–10 Hz. Figure 7 shows spectra of these oscillations, which were recorded at the reference point at a distance of 0.5 and 10 km. It is seen in the figure that with increasing distance from the source, there is a sharp attenuation of high frequencies and a shift of the dominant spectrum to the region of infralow frequency of 1–10 Hz.

EVALUATION OF THE GEO-ECOLOGICAL EFFECTS OF SEISMOACOUSTIC WAVES FROM EXPLOSIONS ON THE ENVIRONMENT

The environmental impact of explosions is estimated by the specific energy density

$$E = \frac{1}{\rho c} \int_0^T p^2(t)\, dt. \qquad (2)$$

Here ρc is the specific acoustic impedance of air 42 g/(cm^2 · s); $p(t)$ is the acoustic pressure recorded at the exit of the acoustic sensor; T is the duration of the acoustic wave. The wave pulse energy is calculated

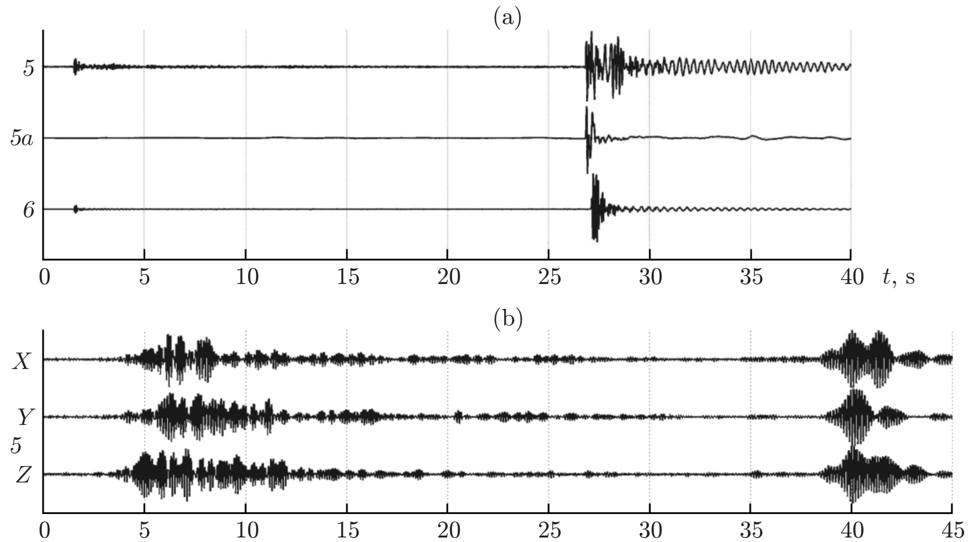

Fig. 6. Records of seismic and acoustic waves: (a) from a test site explosion at a distance of 10 km from seismic sensors *5* and *6* and acoustic sensor *5a*; (b) from a TsV-40 vibrator at a distance of 12 km over the components X, Y, Z.

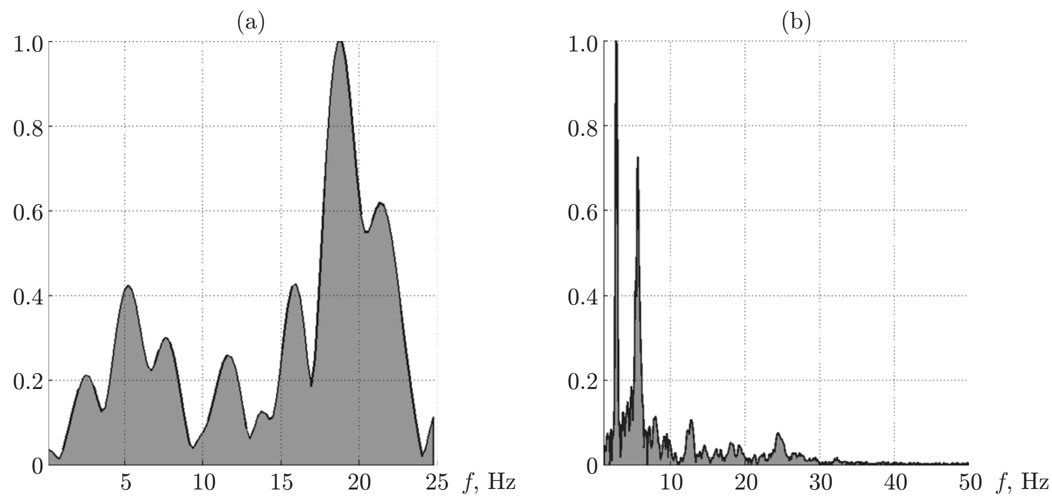

Fig. 7. Spectra of the acoustic wave from a test site explosion: (a) at a distance of 0.5 km ($m = 0.007093$, $f = 18.411$) and (b) at a distance of 10 km ($m = 1.477 \cdot 10^5$, $f = 2.724$) (f is the frequency corresponding to the maximum value of the spectrum m).

from the experimentally obtained records (see Fig. 6). Admissible acoustic impacts on social infrastructure facilities are determined by the tabulated values of the specific energy density ε given in table.

As can be seen from the table, the safe specific energy density for humans is up to 3 J/m^2. For test site explosions of about 125 kg TNT equivalent, the specific acoustic energy density was estimated, according to (2), at points *1–11* of the circular arrangement (see Fig. 4) and at the reference point *12*. As an example, Fig. 8 shows a graph of the azimuthal energy distribution in space within $-180\ldots+180°$. Its feature is that it defines the pronounced phenomenon of focusing of acoustic energy in space, in this case, within an azimuthal angle of about 50°. The correlations between the specific energy density of explosions and the critical values for various objects are shown in Fig. 9. Column numbers *1–4* correspond to the types of objects, and column numbers *5* and *6* to the specific energy density of explosions at distances 0.5 and 10 km. Critical (*1–4*) and measured (*5*, *6*) specific energy densities are indicated on top of each column. The figure illustrates the level of danger of explosion of such power for different types of objects. In particular, it is

Protected object	Critical value of ε, J/m^2	
	destructive	safe
Seismic wave		
Residential building, single explosion	2600	1000
Industrial building, single explosion	—	1500
Air wave		
Window glass 2–3 cm thick	80	15
Explosive noise (irritating action)		
Human	—	3

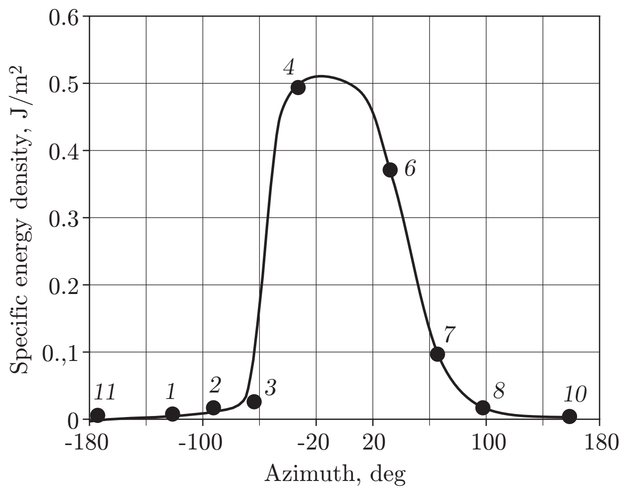

Fig. 8. Energy of explosion versus azimuth at a wind speed of 1 m/s, at a temperature of 4 °C, and an air humidity of 44%.

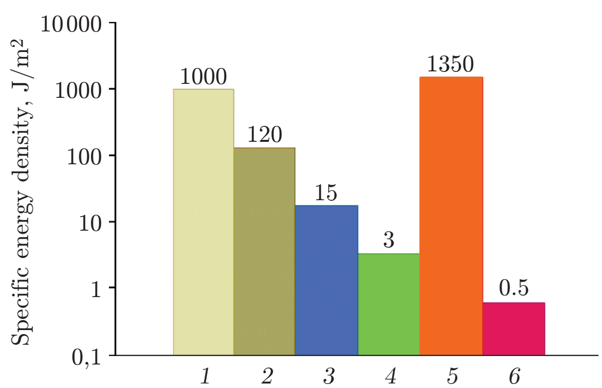

Fig. 9. Critical specific energy density: (*1*) for a residential building in a single explosion, (*2*) for a residential building in multiple explosions, (*3*) for window glass 2–3 mm thick, (*4*) for humans. Specific energy density from an explosion: (*5*) at a distance of 0.5 km from the explosion, (*6*) at a distance of 10 km.

clear that a 125 kg TNT equivalent explosion at a distance of 0.5 km is destructive to buildings and is very dangerous for humans, since the excess over the admissible limit is approximately 400 times.

RESULTS OF NUMERICAL SIMULATION

Numerical calculations were performed to estimate the effects of the direction of the acoustic wave field of infralow-frequency sources occurring in a moving medium, i.e., in the presence of a wind characterized by direction and speed. The calculations were made in accordance with [11]. The model is a point source of infrasound located at height h above the Earth's surface, which is considered to be flat and the atmosphere is assumed to be layered-inhomogeneous. The speeds of sound and wind depend only on the vertical coordinate, and the wind speed has only horizontal components. At infralow frequencies, the ray approximation of sound propagation is valid, and the change in its intensity obeys the assumption of the geometric divergence of rays. In the Cartesian coordinate system, the z axis is directed upward from the Earth's surface, and the x direction at the height h coincides with the direction of the wind. The initial direction of the ray is given by the spherical angles θ (zenith angle), and φ (azimuth). The latter is measured with respect to the x direction.

The effect of the direction of the acoustic field is determined by the focusing factor, which is equal to the ratio of the infrasound intensity in an inhomogeneous moving medium to its intensity in an infinite stationary medium: $f = I[z,\theta,\varphi]/I_0$. Here

$$I(z,\theta,\varphi) = \frac{Qc_0^2\xi}{4\pi c^4 t^2 \cos\theta}\left(1 + 2\,\frac{w_0}{c_0}\,\sin\theta\cdot\cos\varphi - 2\eta\right); \quad I_0 = \frac{Q}{4\pi}\,[x^2 + y^2 + (z-h)^2];$$

Q is the power of the source.

The calculated equation for the focusing factor can be written as

$$f = \frac{c_0^2\xi[x^2 + y^2 + (z-h)^2]}{c^4 t^2 \cos\theta}\left(1 + 2\,\frac{w_0}{c_0}\,\sin\theta\cdot\cos\varphi - 2\eta\right),$$

where $c_0 = c(h)$ is the modulus of the ray velocity; w_0 is the wind speed along the x axis; t is the time of sound propagation along the ray. The expressions for ξ and η are of the form [11]:

$$\xi = \left[1 - \left(\frac{c}{c_0}\right)^2 \sin^2\theta - 2\eta + 2\,\frac{w_0}{c_0}\left(\frac{c}{c_0}\right)^2 \sin\theta\cdot\cos\varphi\right]^{1/2}, \quad \eta = \frac{1}{c_0}\sin\theta\,(w_x\cos\varphi + w_y\sin\varphi).$$

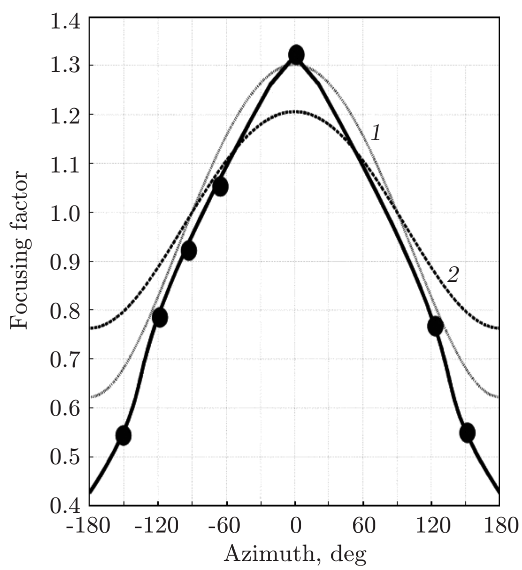

Fig. 10. Focusing factor versus the azimuth of the observation point. Calculated graphs for a circular arrangement of the sensors with a radius of 12 km and a wind speed of 6 m/s (curve *1*) and 4 m/s (curve *2*). The height of the source is 5 m. The solid curve shows the experimental results obtained at a radius of circular arrangement of 12 km and a wind speed of 4–6 m/s.

Figure 10 shows the calculated and experimental dependences of the focusing factor on the azimuth of the observation point. A comparison of these dependences shows that experimentally estimated focusing factor is more sensitive to the wind than the theoretical one. This may be due to the specification of a flat air–ground interface in the initial conditions in the calculations, instead of the real curvilinear interface.

CONCLUSIONS

In this paper, we proposed and experimentally implemented a technique for evaluating the environmental risks determined by the admissible (critical) acoustic energy densities from technogenic and natural explosions in relation to social infrastructure facilities. The technique is based on the use of seismic vibrators that meet the requirements of geo-ecological safety and are sources of seismic and acoustic oscillations. These sources have high metrological power and time-frequency characteristics, which ensures reproducibility of the results of evaluation of the effect of weather conditions, inhomogeneities of the soil surface, and atmospheric conditions on the propagation of the pair of seismic and acoustic vibrations.

An extensive series of experiments using a TsV-40 and test site explosions in conjunction with compact self-contained Baikal seismic stations was performed to study the propagation of acoustic and seismic waves in a wide range of frequencies and at different azimuthal directions, taking into account weather conditions and the parameters of both sources. In the experiments, we identified and qualitatively evaluated the focusing effects of acoustic oscillations in space, which greatly enhance the geo-ecological action of mass explosions on the environment in a direction determined by weather factors. It is proved that even at a low wind speed of 2–4 m/s, the ratios of the maximum and minimum levels of acoustic waves, depending on the azimuthal direction, reach a factor of 50.

Comparative analysis of the levels of seismic and acoustic waves leads to the conclusion that the main ecologically hazardous effect of test site explosions is determined by acoustic waves, whose energy exceeds the energy of seismic waves by an order of magnitude.

Calculated dependences of the focusing effect of acoustic waves in the infralow frequency range on the azimuth of the observation points were obtained at different wind speeds and source–receiver distances. Comparison of the calculated and experimental dependences shows that the focusing effect is more pronounced in the latter case.

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REFERENCES

1. V. V. Adushkin, A. A. Spivak, and S. P. Solovev, "Geoenvironmental Consequences of Bulk Chemical Explosions in Quarries," Geoekologiya. Inzhenernaya Geologiya. Gidrogeologiya. Geokriologiya, No. 6, 554–563 (2000).
2. M. S. Khairetdinov and S. A. Avrorov, "Detection and Identification of Explosive Sources," Vestn. NYTs RK, No. 2, 17–24 (2012).
3. V. M. Krasnov, Ya. V. Drobzheva, and A. N. Maslov, "Acoustic Field on the Qround from an Explosion of a Launcher," Vestn. NYaTs RK, No. 2, 79–85 (2006).
4. *Newest and Modern Volcanism in Russia,* Ed. by N. P. Laverov (Nauka, Moscow, 2005) [in Russian].
5. A. S. Alekseev, B. M. Glinskii, V. V. Kovalevskii, et al., *Active Seismology with Powerful Vibrating Sources* (Izd. SB RAS, Novosibirsk, 2004) [in Russian].
6. A. S. Alekseev, B. M. Glinskii, S. I. Dryakhlov, et al., "Effect of Acoustoseismic Induction in Vibroseismic Sounding," DAN **346** (5), 664–667 (1996).
7. B. M. Glinskii, V. V. Kovalevskii, and M. S. Khairetdinov, "Relationship between the Wave Fields of Powerful Vibrators and Atmospheric and Geodynamic Processes," Geologia i Geofizika **40** (3), 431–441 (1999).
8. V. V. Kovalevskii, "Acoustoseismic Wave Fields Generated by Surface Seismic Vibrators," Akust. Zh. **51** (5), 92–102 (2005).
9. Yu. M. Zaslavskii, *Generation of Seismic Waves by Vibrating Sources* (Institute Applied Physics, Nizhny Novgorod, 2007) [in Russian]..
10. A. M. Isakovich, *General Acoustics* (Nauka, Moscow, 1973) [in Russian].
11. A. V. Razin, "On the Propagation of Sound in an Inhomogeneous Moving Atmosphere," Izv. Akad. Nauk SSSR, Ser. Fiz. Atmos. Okeana **18** (6), 674–676 (1982).