Bull. Nov. Comp. Center, Math. Model. in Geoph., 17 (2014), 13–20

A geoinformation technology for assessment of the ecological risk of powerful technogenic and natural explosions*

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Abstract. This paper presents the results of experimental investigations of the original ecologically safe approach as related to the assessment of the geoecological risk from powerful mass explosions for the social and natural environment. In this approach, seismic vibrators are used as sources imitating explosions but having, in contrast to them, a much smaller power. Such sources can simultaneously excite in a medium seismic and acoustic (vibro-seismo-acoustic) oscillations with precision power and frequency-temporal characteristics.

1. Introduction

The problem of predicting the geoecological effect of various technogenic explosions, namely, short-delay quarry blasts [1], test site ones [2], falling rocket stages, etc., on the natural environment and social infrastructure is of primary importance. Mass explosions that have been made recently for the purpose of eliminating the utilizable ammunition stock are a serious hazard. Powerful natural explosions include, first of all, eruptions of magmatic and mud volcanoes [3] and falls of celestial bodies. It is well-known that the major geoecological effects of explosions are due to the formation of air-shock and underground seismic waves, formation and propagation of dust clouds and electric pulses. Studying the seismic and acoustic effects of mass explosions damaging industrial and residential objects and the shock action on bio-objects is of greatest interest. Such effects were considered earlier [1]. Nevertheless, it should be noted that the dependence of these effects on external factors, such as the wind direction and strength, temperature inversion, atmospheric turbulence, and the surrounding area relief and landscape, has been poorly studied. This is all the more important since the influence of such factors can greatly enhance the destructive ecological action of explosions on the environment. Taking into account the above factors, it is necessary to predict the geoecological risk from powerful explosions, which calls for additional investigations of the physical effects of propagation of

*Supported by the Russian Foundation for Basic Research under Grants 10-07-00387-a, 11-07-10000-k, and 12-01-00773.

seismic and acoustic waves from mass explosions. The objective of this paper is to present a methodological approach to carrying out such investigations and obtaining experimental and numerical results. The approach proposed is based on seismic vibrators as sources imitating explosions, but having, in contrast to them, a much smaller power. In this case, as compared to explosions, ecological cleanness and repeatability of experiments are achieved. This is due to a high-precision power and frequency-temporal characteristics of vibrational sources [4]. The approach proposed to prediction with seismic vibrators was used because of the ability of vibrators to simultaneously generate both seismic and acoustic oscillations. This was proved earlier both theoretically and in numerous experiments for this class of sources [5–6].

2. Acoustoseismic effects of seismic vibrators and explosions

Earlier it was shown that seismic and acoustic waves generated by powerful CV-100 and CV-40 vibrators can propagate to tens of kilometers from the source owing to the effect of acoustoseismic induction, at which the acoustic wave propagates in the surface waveguide. This wave excites in the Earth a surface seismic wave recorded by seismic sensors. This wave will be called acoustoseismic. In this case, the velocities of the both wave types are the same and are equal to the infrasound propagation speed [7]. To estimate the quantitative effects of wind on the propagation of acoustic oscillations on the vibroseismic Bystrovka test site (Novosibirsk), a number of autonomous seismic stations "Baikal" were installed. The stations were arranged in a circle with a radius of 6 or 12 km, with a CV-40 vibrator at the center. This source has a perturbing force of 40 tf in an operating frequency range of 6–12 Hz. A scheme of sensor arrangement at points 1–7 of the circle is presented in Figure 1. The figure shows the possibilities for simultaneous recording by seismic sensors of seismic and acoustic waves from the seismic vibrator.

This figure presents, as results of recording and processing, vibrational correlograms, obtained by the correlation convolution between the reference signal, whose shape is the same as that of the sounding signal, and the recorded initial signal [5]. The obtained vibrational correlograms are analogs to pulsed seismograms. They illustrate the seismic waves arrivals (waves of the first arrivals) at times of 0.96–1.05 s and the acoustic waves arrivals (secondary waves) at times of 16–19.5 s. The latter are the waves recorded by seismic sensors as a result of the above-mentioned process of acoustoseismic induction. This type of waves will be called acoustoseismic. It follows from Figure 1 that acoustoseismic waves are well-defined in seismograms if the directions of the wind and of the acoustic wave propagation front coincide. In this figure, an arrow indicates to the wind direction and

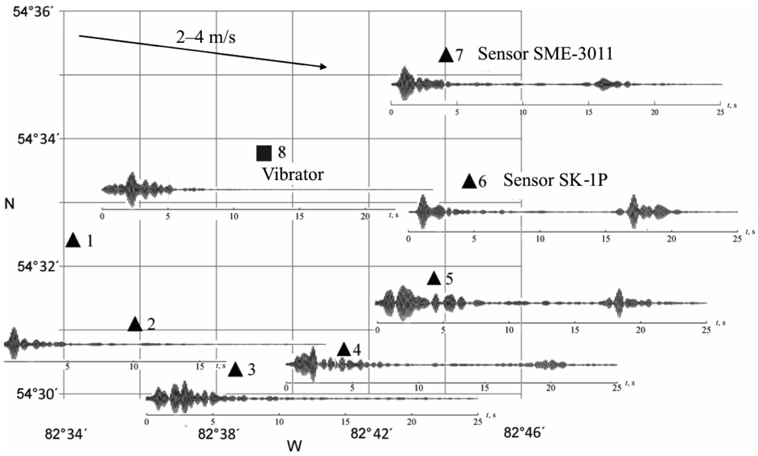

Figure 1. Arrangement of the seismic stations "Baikal" with three-component seismic sensors SK-1P and SME-3011 located at a circle of a radius of 6 km. Vibrational correlograms illustrate the arrivals of seismic and acoustic waves. The wind direction is shown by an arrow

velocity (2–4 m/s in this case). This peculiarity of the acoustic wave propagation is known in acoustics as an increase in the efficient sound speed and a decrease in attenuation at the tail wind [7]. This reveals the role of meteorological conditions at the long-distance propagation of acoustic waves. In the experiments with a vibrator, the detected effect of the directivity of the acoustic wave field can be quantitatively estimated when seismic sensors have a circular arrangement.

The wave field directivity diagrams (DD) corresponding to this effect within azimuths of $-180 \div +180$ degrees for the above arrangements are shown in Figure 2. Here the zero azimuth corresponds to the wind direction. The acoustic pressure values (in Pa), corresponding to the azimuth directions are presented along the axis y. Quantitatively, the directivity effect can be characterized by the DD width in degrees at a level of 0.7 from a maximum value. It follows from the figure that in the case of a circular arrangement

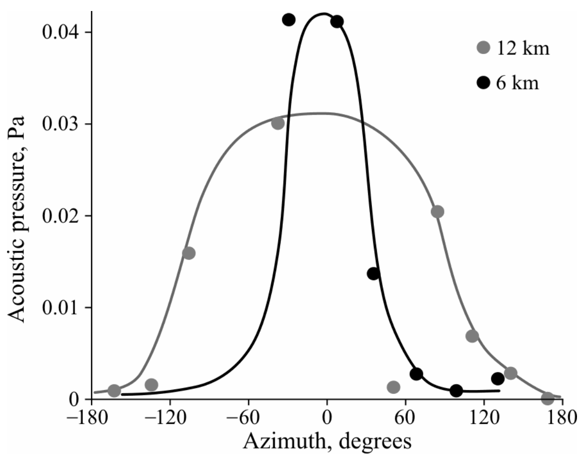

Figure 2

radius of 6 km the DD width is 60 degrees, and in the case of 12 km it is 160 degrees. The plots show a clear dependence of acoustic pressure on wind. For instance, in the first case the ratio between the maximal and minimal acoustic pressure values reaches 50. This acoustic pressure redistribution in space brings about an important conclusion that even low-power explosions can be ecologically dangerous because of a great energy flow increase in a certain direction.

By analogy with the experiments with a vibrator, the wind dependence of acoustic pressure on another source having a direct destructive action on the environment, namely, the test site explosions of an utilizable ammunition stock, was studied. In recent years, such explosions have been regularly made on various test sites in Russia, in particular, on the Shilovo test site (Novosibirsk region). Seismoacoustic oscillations from the Shilovo explosions are regularly recorded using the seismic sensors. For the experimental conditions in Figure 3 the acoustic pressure versus azimuth within $-180 \div +180$ degrees with a wind speed of about 1 m/s is shown. By analogy with vibroseismo-acoustic waves, it also shows a well-defined “wind-dependent” effect of the directed acoustic wave field propagation. A DD width of 80 degrees corresponds to the dependence obtained.

The results of experiments on detecting meteo-dependent acoustic effects make possible to describe them using the directivity function $f(\theta)$, which can be determined by an amplitude rise of acoustic waves within a given angle sector. In this case, it can be said that we have the effect of focusing in space of acoustoseismic oscillations.

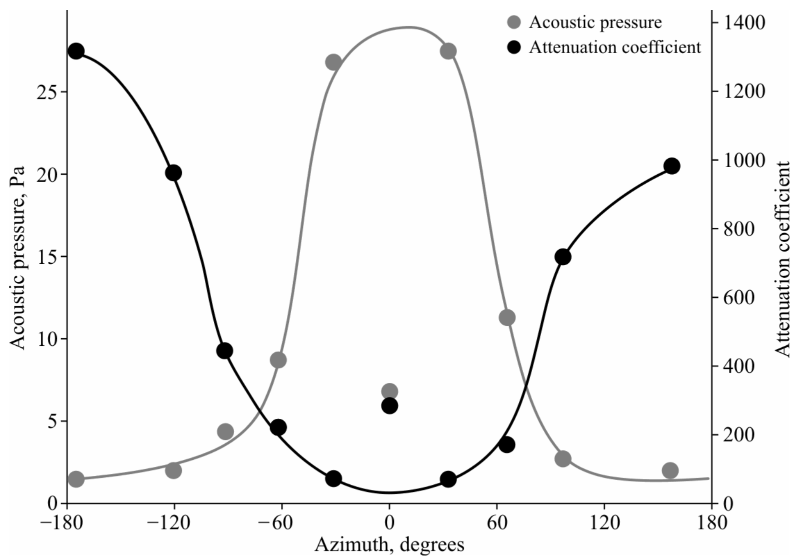

Figure 3

A pressure decrease with distance and direction was estimated by acoustic pressure measurements with circularly arranged sensors and at the reference point located at a distance of 0.457 km from the explosion epicenter. Curve 2 is, respectively, presented in Figure 3. The attenuation coefficient values are given along the y-axis on the right.

According to Figure 3, minimal values of the coefficient correspond to the wind direction and lie within 70–72, whereas its maximal value for these experimental conditions is about 1,300. Thus, at a distance of 10 km from the explosion source, the air wave acoustic pressure decreases more than three orders of magnitude. In this case, the ratio between the maximal and minimal values of the acoustic pressure attenuation coefficient determined by the contribution of wind is about 20.

Let us compare the acoustic pressure levels of a vibrator and a test site explosion. The maximal acoustic pressure of the CV-40 vibrator at a distance of 12 km was 0.03 Pa, whereas that of an explosion at a distance of 10 km was almost 30 Pa. Thus, at comparable distances from the vibrator the acoustic pressure value is three orders of magnitude less than that of the explosion. This proves that vibrators as instruments for experimental investigations are ecologically clean.

3. Estimation of geoecological effects of acoustoseismic waves from explosions on the environment

The ecological action of explosions is estimated by the specific energy density

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

Here ρc is the specific acoustic air impedance of 42 g/(cm^{2}s), $p(t)$ is the acoustic pressure recorded at the acoustic sensor output, and T is the acoustic wave duration. The wave pulse energy value is calculated using experimentally obtained records. Admissible acoustic effects on objects of social infrastructure are determined by the specific energy density values given in J/m^2. As for test site explosions with a TNT equivalent of about 125 kg, according to (1), we obtained specific acoustic energy estimates at the points of a circular arrangement radius of 10 km and at the reference point, located at a distance of 0.457 km from the explosion epicenter. As an example, Figure 4 shows the azimuthal distribution of energy in space within $-180 \div +180$ degrees. A peculiarity of this curve is in that it demonstrates a well-defined phenomenon of the acoustic energy focusing in space, in this case within an azimuth angle of about 50 degrees. Figure 5 shows the specific energy values of explosions versus critical (admissible) ones for various objects. Column numbers 1–4 are object types, and 5–6 are the specific energy values of explosions at distances of 0.5 and 10 km, respectively. The admissible and the

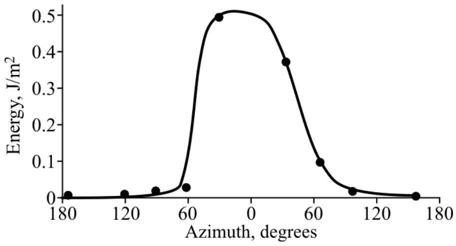

Figure 4. Explosion energy distribution versus azimuth with the wind velocity of 1 m/s, the air temperature and the humidity of 4 degrees and 44 %, respectively

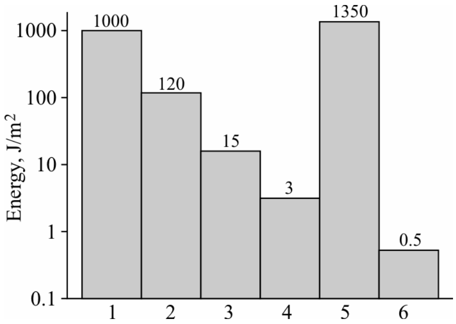

Figure 5. Critical specific energy values for constructions: 1 — residential building at a single explosion; 2 — residential building at several explosions; 3 — 2–3 mm thick window glass; 4 — for humans. Explosion energy values: 5 — at a distance of 0.5 km from the explosion; 6 — at a distance of 10 km from the explosion

measured specific energy values are given above every column. This figure shows the hazard level of explosions of such a power for various types of objects. One can see that an explosion with a TNT equivalent of 125 kg is destructive for buildings; it is even more dangerous for humans, since the admissible norm is exceeded about 400 times.

4. Results of numerical simulation

Numerical calculations were carried out to estimate the effects of the directivity of the acoustic wave field of infralow-frequency sources occurring in a moving medium, that is, on the background of the wind characterized by direction and velocity. They were performed using a method from [8]. A point source of infrasound located at a height h over the Earth's surface was considered in the model. The Earth's surface was assumed to be flat and the atmosphere was taken to be layered and inhomogeneous.

The sound and the wind speeds depended only on the vertical coordinate, and the wind speed had only horizontal components. At infra-low frequencies, the ray approximation of sound propagation holds, and the sound intensity variation is based on the assumption of geometrical beam divergence. In a rectangular system of coordinates, the axis z is pointing up from the Earth's surface, and the direction of the axis x at a height h coincides with the wind direction. The initial direction of the ray is characterized by the spherical angles θ (zenith angle) and φ (azimuthal angle). The latter is measured from the direction x. The effect of acoustic field directivity is characterized by the *focusing factor*, which is the ratio between the infrasound intensity in an inhomogeneous moving medium and its intensity in an infinite moving medium: $f = I[z, \theta, \varphi]/I_0$. Here $I_0 = Q/\{4\pi[x^2 + y^2 + (z-h)^2]\}$ and Q is the source power. The equation for the focusing factor has the following form:

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

where $c_0 = c(h)$ is the ray velocity modulus, w_0 is the wind velocity along the axis x, and t is the time of sound propagation along the ray. Expressions ξ and η are as follows:

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

where $\eta = c_0^{-1}\sin\theta \cdot (w_x\cos\varphi + w_y\sin\varphi)$.

Figure 6 shows calculated and experimental dependencies of the focusing factor on the observation point azimuth. Calculations are shown by solid curves and the experimental data are indicated by a dashed curve. Calculated curves were obtained with the wind velocity of 4 and 6 m/s, the source height above the ground of 5 m and the "source-receiver" distance of 12 km. The experimental data were measured for the wind velocity of 4–6 m/s and the radius of the sensor circular arrangement of 12 km. It follows from the comparison of the calculated curves with the experimental data that the experimentally estimated focusing factor is more sensitive to the wind than the theoretical one.

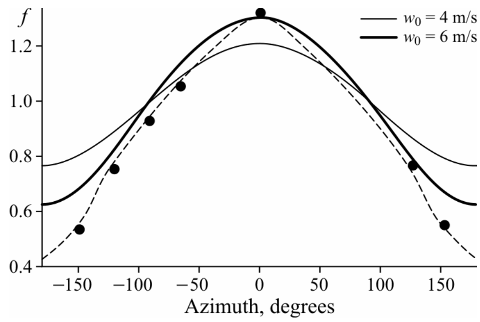

Figure 6

Conclusions

A method for assessment of ecological risks determined by admissible (critical) acoustic energy densities for social infrastructure objects, both from technogenic and natural explosions, has been proposed and implemented. This method is based on seismic vibrators which meet the requirements of geoecological safety and, at the same time, are sources of seismic and acoustic oscillations. Such sources have a precision power and frequency-time characteristics, ensuring a very good repeatability of the results of investigations.

A large series of experiments was performed with the seismic CV-40 vibrator and test site explosions with seismic stations "Baikal". These experiments were aimed at studying peculiarities of the propagation of acoustic and seismic waves in a wide frequency range and in different azimuthal directions with allowance for geological and meteorological conditions and the parameters of both of sources. In these experiments, the effects of focusing of acoustic oscillations in space were revealed and assessed. These effects greatly enhance the geoecological impact of mass explosions on the environment determined by meteorological factors. Specifically, it was proved that even with a weak wind of 2–4 m/s the ratio between a maximal and a minimal acoustic wave levels depending on the azimuthal direction can reach 50. This can be a reason for a great ecological hazard of technogenic explosions.

A comparative analysis of seismic and acoustic wave levels allows us to conclude that the major ecologically dangerous effect of the ground-based test site explosions is due to acoustic waves whose energy is an order of magnitude greater than that of seismic waves.

The calculated azimuthal dependencies of the focusing effect of acoustic waves in the infra-low frequency range with different wind speeds and "source-receiver" distances were obtained. A comparison of the calculations and the experimental data obtained with the same initial parameters was made. It was found that in the experiments meteorological conditions have a greater influence on acoustic wave focusing than that according to theoretical results. This calls for additional analysis of the conditions of the acoustic waves propagation.

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