Multifactorial Prediction of Geoecological Risks from Powerful Explosions with Application the Vibroseismic Method

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***Abstract*—The multifactorial problem of estimation of the geoecological risks to environment and social infrastructure from mass technogenic and natural explosions such as quarry, test ground, earthquakes, etc., are considered. The explosions generate infrasound seismic waves in the Earth and acoustic waves (infrasound) in the atmosphere. Influence of the explosions to environment is defined with shock impact of the both waves types. The effects of the acoustic waves impact strongly depend of the complex of the meteorological factors and geological conditions on the tracks of waves propagation. In the paper, the results of theoretical analysis and experimental studies of these dependences through original vibroacoustic method are represented.**

Keywords—Geoecological risks; multifactorial problem; technogenic and natural explosions; vibroacoustic method; infrasound

I. Introduction

The problem of predicting the geoecological risk of various technogenic and natural explosions, namely, short-delay quarry blasts [1, 2], falling rocket stages [3], etc., for the natural environment and social infrastructure is very actual. Powerful natural explosions include, first of all eruptions of magmatic and mud volcanoes [4] and falls of celestial bodies. Major geoecological effects of powerful explosions are due to the formation of air-shock and underground seismic waves [1, 5]. Investigation of the seismic and acoustic effects of mass explosions damaging industrial and residential objects and of the shock action on bioobjects is of great interest. Such effects were considered earlier by some authors [6, 7]. Nevertheless, it should be noted that the dependence of these effects on meteo 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 their influence 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 of powerful explosions, which calls for additional investigations of the physical effects of propagation of seismic and acoustic waves from mass explosions. The purpose of this paper is to present a methodological approach to the performance of such investigations, experimental and numerical results. This approach is based on seismic vibrators as sources imitating explosions, but having, in contrast to them, a much smaller power. In this case, in comparison to explosions, ecological cleanness and repeatability of experiments are achieved . This is due to high-precision power and frequency-time characteristics of vibrational sources [8]. The proposed approach to prediction with seismic vibrators is used because of the ability to vibrators to simultaneously generate both seismic and acoustic oscillations. This was proved earlier both theoretically and in numerous experiments for this class of sources [9, 10].

II. Problem Statement

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

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

Here $\rho\, c$ is the specific acoustic impedance of air equal to 42 g/(cm^2·s); $p(t)$ is the acoustic pressure recorded at the acoustic sensor outlet; and T is the duration of the acoustic wave. Admissible acoustic actions on objects of social infrastructure are determined by critical values of specific energy density (in J/m^2).

In (1), the acoustic pressure is a function of many parameters determined by the conditions of radiation and far propagation of acoustic oscillations. This dependence can be presented as some functional:

$$p(t) = F[Q\ f_1(c, \varphi, w, \alpha), f_2(T), \delta(H), \psi(t)] \qquad (2)$$

Here Q is the source power; $f_1(c, w)$ is the functional dependence of the acoustic pressure on the velocity c and direction φ of the acoustic wave propagation from the source on the one hand, and the velocity w and azimuthal direction α of the wind on the other hand; $f_2(T)$ is the air temperature distribution at a height; $\delta(H)$ is the function of the Earth’s daily surface inhomogeneity; $\psi(t)$ is the factor of atmospheric inhomogeneity, which depends, in particular, on the air humidity. Thus, in the general case the problem of ecological risk estimation is multi-parametric. In this statement, it is difficult to obtain the estimate (1), since there is no full a priori information. An analytical dependence can be obtained for some particular cases; the most interesting of them are considered below. Another way of avoiding a priori indefiniteness is to obtain the estimate (1) in experiments using vibrators and explosions as radiators of acoustic oscillations of infralow frequency. The both variants of the solution are considered in the present paper.

III. Results of Numerical Simulation

The dependencies of acoustic pressure on other parameters, such as air temperature and humidity, can be obtained from the generalized expression for the state of gas $f(p,\rho,t)=0$, which relates the air pressure, density (compression), and temperature. It follows from the Laplace definition of the speed of sound in air

$c_L = \sqrt{\gamma \frac{P}{\rho}}$ that the pressure $p = \frac{\rho}{\gamma} c_L^2$, where $\gamma = \frac{c_P}{c_V}$ is the ratio between the heat capacity of air at constant pressure and that at constant volume, is a quadratic function of the speed of sound, which depends on the air temperature and humidity. For instance, the speed of sound in moist air is $c_0 = 20.1\sqrt{T(1+0.273\ e/p)}$, where e is the air humidity, $T = t + T_0$, where $T_0 = 273K$. At normal pressure $T = T_0 = 273K\ \ (0^\circ C)$; the speed of sound in dry air is 331 m/sec. In the presence of wind in the atmosphere, there appears a drift of the sound speed with allowance for this drift, the speed of sound consists of that in unperturbed atmosphere (c_0) and the wind speed (w_0): $c = c_0 + w_0 \cos$, where φ is the angle between the direction of wind and that to the sound observation point taking into account the above-listed meteorological factors, we can represent the integral dependence of pressure (4) as follows:

$$p = \frac{\rho}{\gamma}(331 + 0.6t + 0.07e + w_0 \cos\ \ )^2 . \qquad (3)$$

One can see from (5) that the pressure increases quadratically with increasing air temperature and humidity.

Numerical calculations were made to estimate the effects of directivity of the acoustic wave field of infralow-frequency sources in a moving medium, that is, on the background of wind characterized by direction and velocity. They were performed using a method from [11]. A point source of infrasound located at a height h over the Earth’s surface was considered a model. The Earth’s surface was assumed to be flat and the atmosphere was taken to be layered and inhomogeneous.

The sound and wind speed depended only on the vertical coordinate, and the wind speed had only the horizontal component. At infralow 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, axis z points up from the Earth’s surface, and the direction of axis x at height h coincides with the wind direction. The initial direction of the ray is characterized by the spherical angle 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 equal to the ratio between the infrasound intensity in an inhomogeneous moving medium and its intensity in an infinite moving medium [11]:

$$f = I[z,\theta,\varphi]/I_0 . \qquad (4)$$

Here $I_0 = Q/4\pi[x^2 + y^2 + (z-h)^2]$, Q is the source power. The equation (4) for the focusing factor has the following form:

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

where $c_0 = c(h)$ is the ray velocity modulus, w_0 is the wind velocity along axis x, and t is the time of sound propagation along the ray. Expressions for ζ 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 $\eta = (1/c_0)\sin\theta\left(w_x \cos\varphi + w_y \sin\varphi\right)$

IV. Experimental Investigations of Acousto-Meteo Effects by Seismic Vibrators and Explosions

Seismic vibrators simultaneously generate seismic waves in the earth and acoustic waves in the atmosphere. Infrasound acoustic waves can propagate to tens of kilometers from the source. The process of propagation of acoustic waves is accompanied by the phenomenon of acoustoseismic induction, at which the acoustic wave excites a surface seismic wave in the Earth. This wave will be called acoustoseismic. In this case, the velocities of the both wave types are the same and equal to the propagation speed of infrasound [12]. The principle of recording of acoustic waves by seismic sensors is based on this effect.

The above-noted physical effects open up new opportunities for regular studies of the interaction of acoustic and meteo-fields with the use of exact instruments, such as seismic vibrators and seismic sensors.

Taking into account these possibilities, we performed some experiments to estimate the quantitative effects of meteorological parameters, such as the wind direction and speed, on the characteristics of acoustic fields, their levels, and space focusing. As sources of acoustic oscillations we used the CV-40 seismic vibrator. Oscillations were recorded by circularly arranged sensors (denoted by triangles) with the source at the center. The radius of circular arrangement of autonomous seismic stations and seismic sensors were 6 and 12 km and for the test site explosions 10 km. Figure 2 presents, as results of recording and processing, vibrational correlograms obtained by correlation convolution between the reference signal, whose shape is the same as that of the sounding signal, and the recorded initial signal [8].

The obtained vibrational correlograms are analogs of pulsed seismograms. They show the arrivals of seismic waves (waves of first arrivals) at times of 0.96–1.05 s and the arrivals of acoustic waves (secondary waves) at times of 16–19.5s. This type of waves will be called acoustoseismic. It follows from Fig.2 that acoustoseismic waves are well-defined in seismograms if the directions of the wind and of the acoustic wave propagation front coincide. In the figure, an arrow shows the wind direction and velocity (2–4 m/s in this case). This peculiarity of acoustic wave propagation is known in acoustics as the phenomenon of increase in efficient sound speed and decrease in attenuation at tail wind [13].

In the experiments with vibrator, the found effect of 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÷ +180 degrees for the above arrangement variants are shown in Fig.3.

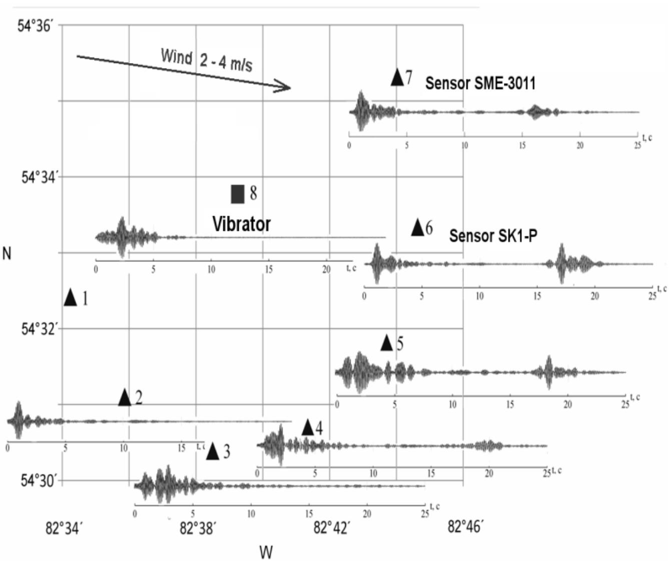

Fig.1. Arrangement of seismic stations “Baikal” with three-component seismic sensors SK-1P and SME-3011 lcated in a circle 6 km in radius. Vibrational correlograms show arrivals of seismic and acoustic waves. Wind direction is shown by an arrow.

Here the zero azimuth corresponds to the wind direction. Acoustic pressure values (in Pa) corresponding to azimuth directions are presented along the y-axis. Quantitatively, the directivity effect can be characterized by the DD width in degrees at a level of 0.7 from the maximum value.

It follows from the figure that in the case of a circular arrangement radius of 6 km the DD width is 60 degrees and in the case when it is 12 km, 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 leads us to the important conclusion that even low-power explosions can be ecologically dangerous because of a great energy flow increase in a certain direction.

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

Experimentally obtained estimations of the infrasound pressure from the vibrator in view of humidity are represented on Fig.3. The obtained results of the experiments show particularly that in same meteo conditions the increasing of humidity up to 95% can lead to 3-5 multiple increasing of the acoustic pressure along wind direction (null direction in Fig.3). From results of experiments is follows that pressure levels sharply decrease above humidity of 95%.

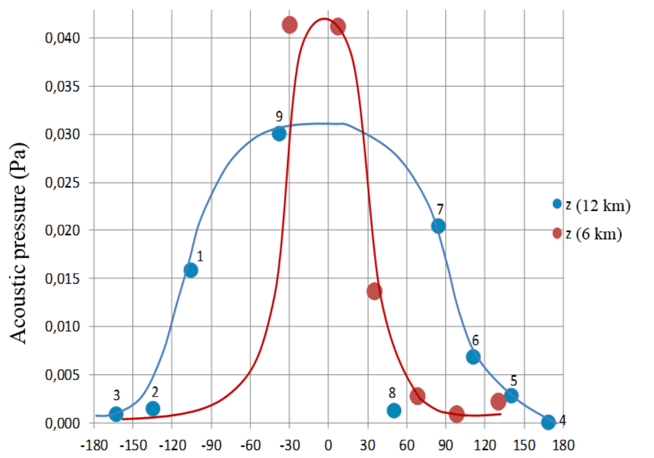

Fig.2. Azimuthal dependence of acoustic pressure (Pa) on wind at recording of CV-40 vibrator oscillations. Circular arrangement of sensors. Red curve: radius: 6 km; wind speed: 2-4 m/s; blue curve: radius: 12 km; wind speed: 4-6 m/s.

Let us compare 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 (Fig.3) was 0.03 Pa, while for explosion pressure has made 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.

V. Estimation of Geoecological Risks from Explosions for Environment

The ecological risks estimated by the specific energy density (1). Admissible acoustic actions on objects of social infrastructure are determined by critical values of specific energy density (in J/m^2) [14]. For instance, at a single explosion the following values are critical: 1000 J/m^2 for residential buildings, 15 J/m^2 for 2-3-mm window glass, and 3 J/m^2, for people. For test site explosions of a power of about 125 kg of TNT, according to (1) we obtained estimates of specific acoustic energy at circularly arranged points 1-11 (Fig.2) and at the control point near the explosion (at a distance of 0.5 km from the epicenter). As an example, Fig. 4 presents relations between the measured specific energy values (1) from explosions and critical values for various objects.

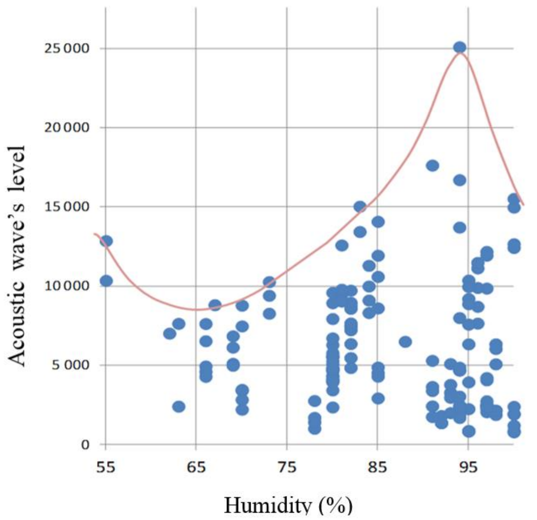

Fig.3. Dependence of acoustic pressure from humidity at recording of CV-40 vibrator acoustic oscillations on distance 50 km

Columns 1-4 denote object types, and columns 5-6, measured specific energy values from explosions at a distance of 0.5 and 10 km, respectively. Admissible and measured values of specific energy are given above the columns. This figure shows the level of hazard from explosions of such power for various types of objects. One can see that an explosion of 125 kg of TNT at a distance of 0.5 km is destructive for constructions and especially dangerous for people, since the admissible norm is exceeded by approximately a factor of 400.

VI. Summary

1. 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 that meet the requirements of geoecological safety and, at the same time, are sources of seismic and acoustic oscillations. Such sources have high-precision power and frequency-time characteristics, which guarantees very good repeatability of the results of investigations.

2. A large series of experiments with the CV-40 vibrator and test site explosions. In these experiments, the effects of focusing of acoustic oscillations in space revealed and quantitatively. These effects greatly enhance the geoecological impact of mass explosions on the environment determined by meteorological factors. Specifically, it proved that even at a weak wind of 2–4 m/s the ratio between the maximal and minimal acoustic wave levels depending on the azimuthal direction can reach 50. This can be a reason for great ecological hazard of technogenic explosions.

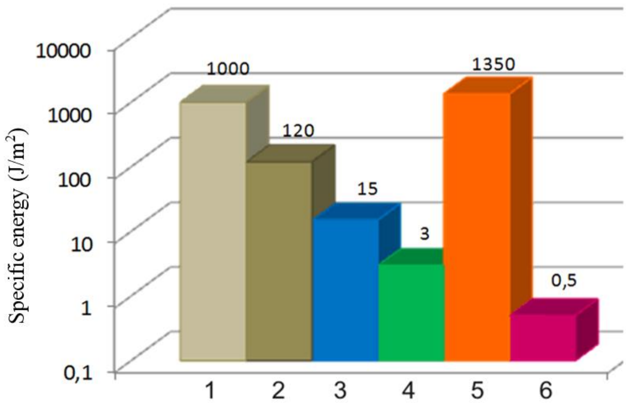

Fig.4. Critical values of specific energy for constructions:1) residential building at a single explosion; 2) residential building at multiple explosions; 3) 2-3-mm thick window glass; 4) for people. Specific energy values from explosions: 5) at a distance of 0.5 km from the explosion; 6) at a distance of 10 km.

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