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The problem of transforming an industrial explosion wave field to a pulsed form*

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Abstract. The problem of simulation of an industrial explosion for a vertically inhomogeneous medium has been considered in a general form. An algorithm to transform a wave field to a pulsed form, which uses a priori information about the space distribution of charges and delay times in a quarry explosion, is proposed. The distributed short-delay explosion is considered as a set of point sources of one type located at the same depth under the surface with an arbitrary distribution on the plane. Each source is characterized by its own temporal function and its own delay time. Recording a seismic signal from an explosion at the far zone profile, that is, at distances much longer than its typical size, is considered. The process of formation of a seismogram from a distributed explosion at the profile is investigated, and an algorithm to reduce it to the pulsed form is proposed. In the spatial-time domain, a pulsed seismogram is obtained after the 2D inverse Fourier transform. The transformation function is determined as product of the spectra matrix of individual explosions and the vectors of phase delay functions for frequency and wave number.

1. Introduction

The problem of studying the deep Earth's crust structure with the use of the energy of powerful industrial explosions is rather important. Industrial explosions with a power of 10–500 tons are widely used in the mining industry of all industrial countries of the world. The greatest number of blasting operations is performed in the Altai-Sayan region, where the largest quarries and mines of the Kuznetsk Basin are concentrated, and which, along with the Wyoming region (USA), has the greatest in the world "man-caused seismicity".

In industrial explosions, a considerable part of the chemical energy is transformed into the energy of seismic waves. Therefore, from the geophysics stand-point, such industrial explosions are powerful controlled seismic events, which have some peculiarities. The main feature is that each large explosion is a totality of smaller explosions that are distributed in time (short- and long-delayed blasts) and in space (in the area and depth). A specific character of powerful industrial explosions is determined both by the technology of mining works and the requirements to ecology and safety, decreasing the seismic loading on buildings and people.

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Scientific interest to the investigation of wave fields from powerful industrial explosions is caused by the fact that they can be used as sources of powerful seismic waves to study the Earth's crust structure and to perform regional calibration of seismological stations of national and international networks. In addition, the problems of recording powerful industrial explosions are the major ones in the International Monitoring System of the Comprehensive Nuclear Test–Ban Treaty (CTBT) [1].

2. Characteristics and models of industrial explosions

Although industrial explosions are of considerable seismic power, their use in geophysical investigations of the Earth's crust by methods of deep seismic sounding (DSS) involves certain difficulties, because they generate seismic signals whose duration is only several seconds and form a complex interference wave field. The energy distribution in time considerably decreases the seismic effect of a distributed explosion at the recording at large distances and makes it more difficult to analyze seismograms. Therefore, it seems important to develop a method to reduce the wave fields of such explosions to the "classical" form, which corresponds to a concentrated explosive excitation of a sounding wave. This makes it possible to use well-developed methods of interpretation of seismic fields.

Many experimental and theoretical works are devoted to the investigation of seismic radiation from powerful industrial explosions [1–4]. Seismograms of the distributed pulsed excitation of waves by a short-delay explosion are analyzed. These publications contain a detailed description of the peculiarities of seismograms caused by the time delays of individual explosions and the space distribution of pulsed actions. In some papers, the "technological" characteristics of quarry explosions are investigated. Also, some particular problems are solved, for instance, the search for informative features in seismograms, which make it possible to reliably distinguish between concentrated and distributed sources of radiation. Of considerable interest are those papers in which the possibilities of using methods of "inverse filtration" of seismograms are investigated. They state that in order to obtain a good result, one should accurately specify the shape or spectral characteristics (the model) of a sounding seismic signal.

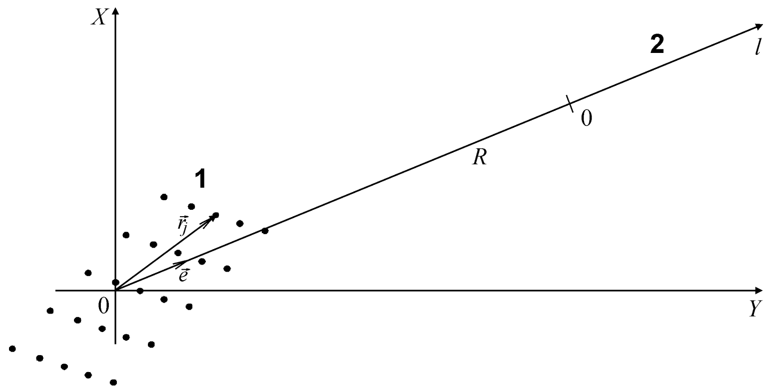
It follows from general physical grounds that a wave field from a quarry explosion is determined to a great extent by the following factors: the geometry of the spatial distribution of unit charges (sources), a blasting pattern of individual charges or groups and time delay, the characteristics of individual explosions as sources of elastic waves, and a medium structure in the quarry region. If we consider general characteristics of signals from quarry explosions, we will see that they are of pulsed nature, but characterized by the spatial and time distribution of individual pulses. A most typical feature of the short-delay quarry explosions is that the time interval between individual explosions and the time of wave propagation between adjacent charges is much smaller than the duration of the wave packets they excite. Therefore, a seismic signal from a quarry in the far zone is the sum of many mutually delayed packets, that is, it has a complex interference pattern.

Simple models of quarry explosions take into account only the delays by the same time of one-type wave packets of individual explosions. These models show that the total wave field is formed as wave field from a single explosion that passed through a filter whose transition function depends only on the number of explosions and the delay time. In the spectral region, this manifests itself as appearance of periodic zeroes in frequency and a rise of the low-frequency spectral region. The spectral-time pattern of such an explosion has well-defined bands with zeroing of some frequencies and enhancement of other frequencies in the entire seismogram. This property of short-delay explosions manifests itself in experiments, and is a distinctive feature of “well-made” quarry blasts from “hidden” nuclear tests.

The characteristics of the filter that transforms signals from individual components of an industrial explosion were determined both theoretically and experimentally: the spectra of signals from single fired and short-delay explosions have been compared. The knowledge of the properties of this filter would make it possible to perform inverse filtration to transform the field of a short-delay explosion to the form of a pulsed source. However, the application of this approach, which is based only on the time characteristics of an explosion, to real data failed to demonstrate its high effectiveness. In particular, the effect of considerable directivity of the quarry explosion as a source of various types of waves remained unexplained. In our opinion, this effect is associated mainly with the spatial geometry of a system of charges. Therefore, the problem of inverse filtration developed in this paper is based on the construction of an algorithm to realize the space-time transformation of the total wave field.

3. Spatial-time model

The problem of modeling an industrial explosion for a vertically inhomogeneous medium is considered in the general form. An algorithm to transform the wave field to the pulsed form, which uses a priori information about the spatial distribution of charges and the delay times in a quarry explosion, is proposed. The distributed short-delay explosion is considered as a set of point sources of one type located at the same depth under the surface with an arbitrary distribution on the plane (the figure). No restrictions are imposed on the size of a zone with charges. It is comparable to a typical wavelength of a single explosion or larger than it. Each source is characterized by its own temporal function $f_j\ (t-\tau_j)$ with its own delay time τ_j, its location on the plane (x, y) being given by the vector r_j.



A spatial-time model of a short-delay explosion: 1 — location of charges, 2 — recording profile

Recording a seismic signal from an explosion in the far zone, that is, at distances R much longer than its typical size, is considered. The wave field is determined at the profile in the direction of the vector $\boldsymbol{e}$ from the source. The profile length is assumed to be much longer than typical wavelengths at the recording point. The coordinate along the profile is l. The seismic trace of a distributed short-delay explosion, which is the sum of seismic traces from single explosions, corresponds to each point of the profile. The sum of seismic traces at the profile gives the total seismogram S_Σ (a 2D function of time and coordinate) equal to the sum of seismograms from individual explosions S_j:

$$S_\Sigma(t,l) = \sum_{j=1}^{N} S_j(t-\tau_j, l-l_j), \qquad l_j = \vec{r}_j \cdot \vec{e}, \tag{1}$$

where τ_j and l_j are the time and the spatial shifts for an individual explosion. The spatial shift at the recording profile is equal to the scalar product of the vector of location of the individual explosion and the vector of the explosion-profile direction.

Since single explosions have different temporal functions, delay times, and spatial shifts from the recording point, a seismogram of a distributed explosion is a complex interference of the individual explosions seismograms. In the general case, they do not coincide with each other and do not allow a simple reduction to the pulsed form in the spatial-time coordinates.

4. Transformation algorithm

In the case of a vertically inhomogeneous medium, whose characteristics depend only on the depth and are constant in the horizontal direction, some regularities, which are sufficiently important for the problem of wave field transformation to the pulsed form, are revealed. For instance, if we consider a single explosion, a time delay leads to the total time shift of a seismogram at the recording profile by this value, without a change in the shape. A change in the location of a single explosion relative to the profile at the same delay time causes a shift of a seismogram along the profile, also, without a change in its shape, as shown by (1). The time and spatial shifts allow a simple analytical description in the spectral region. This is a well-known relation for the phase shifts in the spectrum, which are proportional to the product of frequency and the delay time, and the product of the wave number and a spatial shift.

In the spectral region, a change in the temporal function of a single explosion is also taken into account. It is included as an amplitude factor, which depends on frequency, and represents the spectrum of a seismic signal from a single explosion. Therefore, the total spatial-time spectrum of a seismogram from the distributed explosion $S_\Sigma(\omega, k)$ is represented as the sum of seismograms from a single explosion with the unit spectral function $S(\omega, k)$. The explosion is located at the origin of coordinates with coefficients proportional to the amplitude spectrum $a_j S(\omega, k)$ and the phase shifts depending on the time delays and the spatial shifts of single explosions τ_j and l_j, respectively:

$$\begin{aligned} S_\Sigma(\omega, k) &= \sum_{j=1}^{N} S_j(\omega, k), \\ S_\Sigma(\omega, k) &= \sum_{j=1}^{N} a_j(\omega) e^{-i\omega\tau_j} e^{-ikl_j} S(\omega, k). \end{aligned} \tag{2}$$

From this expression, we determine the 2D spectrum of the seismogram from a single explosion with the given spectral function a_0 (ω, k) located at the origin of the coordinates $(0, 0)$

$$S_0(\omega, k) = a_0(\omega) S_\Sigma(\omega, k) \cdot \left(\sum_{j=1}^{N} a_j(\omega) e^{-i\omega\tau_j} e^{-ikl_j} \right)^{-1}. \tag{3}$$

In the spatial-time region, a seismogram is obtained after the 2D inverse Fourier transform of the spectral function $S_0(\omega, k)$:

$$a_0(\omega) \Rightarrow f_0(t), \qquad S_0(\omega, k) \Rightarrow S_0(t, l). \tag{4}$$

One can see from (3) that the transformation function is determined as the product of spectra of individual explosions with the phase delays in frequency and the wave vector. It is the product of the vectors of phase shifts in time and space and the diagonal matrix of spectra of single explosions:

$$\Psi(\omega, k) = TA\overline{L}^T, \tag{5}$$

$$A = \begin{pmatrix} a_0(\omega) & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & a_N(\omega) \end{pmatrix},$$

$$T = \left(e^{-i\omega\tau_1}, \ldots, e^{-i\omega\tau_N}\right), \qquad L = \left(e^{-ikl_1}, \ldots, e^{-ikl_N}\right).$$

The above-considered model of industrial explosion takes into account the following three main physical factors of the distributed explosion: space distribution, time delays, and the difference in the temporal functions of individual explosions. The algorithm obtained makes it possible to transform the wave field from a distributed explosion to the pulsed form using the inversion of the spectrum of time and spatial frequencies. Its form leads to an important conclusion that if dimensions of a distributed explosion are comparable to a typical wavelength, the complete reduction of a wave field to the pulsed form is possible only in the case of an extended profile recording of the wave field. For one point (one sensor of a seismic station) this transformation in the entire frequency region and in the entire time domain of the seismogram is unrealizable. The possibility of obtaining a pulsed seismogram for one point is still possible at the following two limitations. First, if a seismogram takes into account only low frequencies at whose wavelengths the spatial shifts become negligibly small. Second, if only a part of a seismogram, for instance, a zone of the first wave arrivals, is considered, and one can use a linear approximation of travel time curves at long recording distances to reduce the spatial shifts to time delays.

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