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# Active seismology with powerful vibrator

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A new method for seismological investigation of the Earth's crust and the upper mantle, geodynamic processes and earthquake preparation zones has been developed using powerful vibrational sources of seismic waves. Since nuclear explosions have been prohibited, this method remains the only active method for deep seismic sounding of the Earth. Advances in the experimental research with powerful vibrators make it possible to consider the active seismology method as a new tool for studying the Earth, whose technology is similar to seismic prospecting methods. The paper considers experimental investigations with powerful vibrators and mathematical problems of geophysics connected with active seismology.

## 1. Introduction

A team of researchers from the two departments of the Institute of Computational Mathematics and Mathematical Geophysics (the former Computing Center), Siberian Division of the Russian Academy of Sciences is engaged in the works on studying an opportunity of application of powerful vibrators for the solution of tasks of active seismology.

Researchers from the Department of Mathematical Problems of Geophysics (headed by academician Anatoly S. Alekseev) develop the theory and numerical methods of the solution of direct and inverse problems of seismology. In particular, both the direct and inverse problems of definition of dilatancy of seismic prone zones and zones very close to the free surface with respect to the field of displacements and pressure are being solved. The estimation of factors of anisotropy of a medium that are included in a dilatancy zone with respect to the field of main pressure has been obtained. The problem of definition of geometrical and mechanical parameters of dilatancy zones with respect to the wave fields of longitudinal, transverse and exchange waves arising in response to vibroaction is considered. The programs, realizing the algorithms for numerical calculation of seismic fields, generated from various kinds of deeply located sources, including mine sources of the hydroresonant type, have been created. A number of calculations for the estimation of the power characteristics of seismic waves of various types arising in response to vibroactions of the deeply located sources have been carried out.

Researchers from the Department of Applied Geophysics (headed by prof. Boris M. Glinsky) are enqaged in the creation of technical means for the solution to problems of active seismology. The basic principles of construction of powerful seismic vibrators of the hydroresonant type, their computer control systems, multichannel systems of recording of vibroseismic signals of the field type, the system of temporal synchronization of processes of radiation and recoding of vibroseismic waves are developed on the basis of the GPS-receivers. The technique of application of the developed systems for solving some problems of active seismology has been created. A number of experiments with the developed systems have been conducted. Some of the works conducted are presented in the given volume. The developments of the two departments presented here lie at the basis of creation of methods of active seismology with the use of powerful seismic sources.

Powerful vibroseismic sources make it possible to realize an active method of seismological investigations of the Earth's structure, study the geodynamic processes and rheological characteristics of anomalous zones of earthquake preparation. Since nuclear explosions are prohibited, the vibroseismic method is the only active method for deep Earth's sounding [1, 2].

In comparison to passive methods based on studying waves from earthquakes, the main advantages of active methods are as follows: the coordinates of the source and the time of its action can be determined exactly; multiple identical actions on the medium being studied (replication of experiments) are possible; oscillations of desirable form and polarization can be excited; experiments can be controlled on a computer. The vibroseismic methods can be used in various regions, including densely populated areas. They are safe for the environment, because recorded signals are at the level of microseismic noise, and the required signal-to-noise ratio is provided by the method of accumulation of weak signals [3].

Active monitoring is not only control of artificial fields, but also regular processing of observations using mathematical models of phenomena being studied to obtain characteristics, that cannot be measured directly, such as anisotropy, permeability, plasticity, cracking and stresses in the zone under control [4].

The main problems that can be solved by the method of active seismology using powerful sources, include investigation of inhomogeneities in the Earth's crust, mantle and core by methods of seismic tomography. Modern digital seismological networks and superpowerful vibroseismic sources can be used for the investigations. Geodynamic processes can be studied by long–term observations of the velocities and polarization of vibroseismic waves at fixed distances, systems of active monitoring of seismic prone zones for medium–range and short–range earthquake prediction. Vibroseismic methods can be used for active microseismic zoning of large areas, investigation of stability of deep substructures in regions of exploitation of ecologically dangerous engineering constructions, large chemical enterprises, atomic power stations, dams in mountainous regions, etc.; study of physical–mechanical and chemical properties of rocks and other materials under vibroseismic actions.

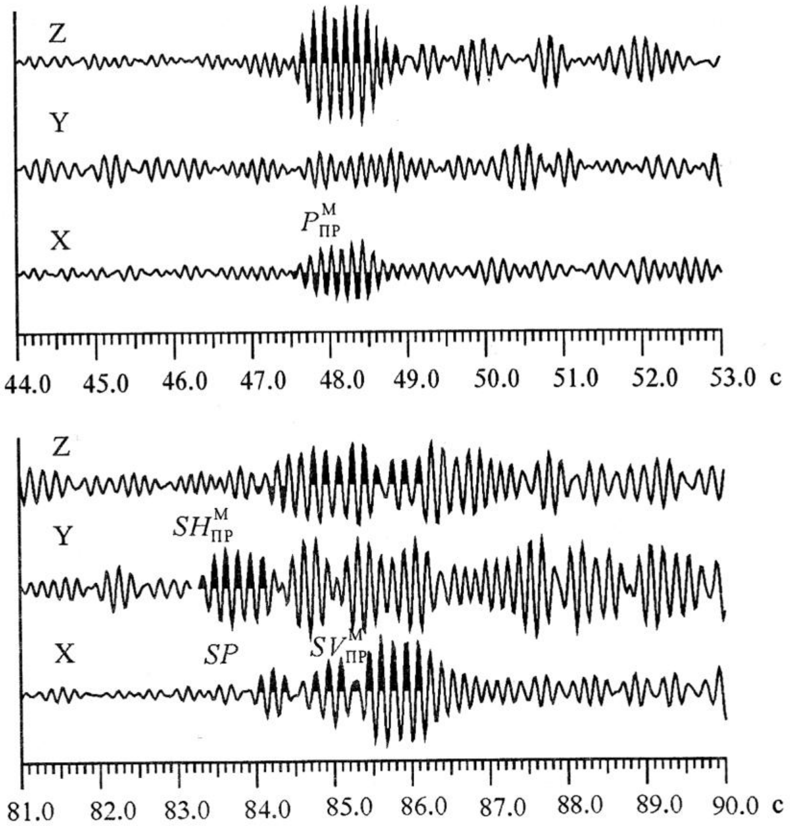
## 2. Experimental investigations with powerful vibrators

Creation of powerful controllable seismic radiators (vibrators), that can simulate (after accumulation) a wave effect of medium–power earthquakes, is an important problem of active seismology. Such vibrators can be used to solve classical problems in seismology. Several types of powerful vibrators have been developed in the Siberian Branch of the Russian Academy of Sciences. The most powerful stationary centrifugal vibrator CV-100 provides actions onto the ground of up to 100 tons in a frequency range of 5–9 Hz [5]. A mobile vibrator CV-40 that is based on the same principle provides actions onto the ground of up to 40 tons in a frequency range of 6–10 Hz. New hydroresonant vibrators HRV-50 and HRV-200 with vibrational actions onto the ground of 50 and 200 tons, respectively, have also been created [1]. They are based on resonant oscillations of large volume of liquid.

In the creation of powerful vibrators, a "quasiresonant" method of radiation has been theoretically and experimentally substantiated. This method is more effective in the range of seismological frequencies than the method of "forced" oscillations used in seismic prospecting. Owing to this method, the distance of recording from a 100-ton vibrator exceeded 1000 km in the harmonic regime and 300 km in the regime of sweep signals. The figure shows three-component vibrational seismograms at a distance of 312 km that have been obtained by correlation of recorded and radiated sweep signals from the vibrator CV-100. Longitudinal (48.15 s) and transverse waves with vertical and horizontal polarization (83–86 s) refracted by the Moho boundary are prominent in the seismogram.

The scheme and technical design of hydroresonant vibrators can be used for creation of sources of various power. They make it possible to develop a project of a superpowerful vibrator with an action of 10000 tons for global seismology, abandon the concept of mechanical engineering and use a technology of other type, namely, mine construction [2]. The basis of the vibrator is a water-filled shaft 12 m in diameter and 100 m deep, in which a liquid column with a mass of 10000 tons oscillates resonantly. Such a source will provide a distance of recording of up to 10 thousand kilometers in a range of seismological frequencies of 0.5–5 Hz. Owing to the creation of superpowerful seismic vibrators global seismic tomography of the Earth using controllable artificial sources becomes quite real.

Powerful seismic vibrators can help to solve the problem of active vibroseismic monitoring of seismic prone zones. A concept of an information system with a network of stationary 100-ton sources and small seismic arrays for continuous control of the tensely deformed state of the medium in an area of 40000 km$^2$ has been developed [6]. This system that uses up-to-date processing methods of vibroseismic data and mathematical simulation with




Three–component vibrational seismograms at a distance of 312 km

the solutions to direct and inverse problems of geophysics makes it possible to detect zones of anomalous internal stresses 10–20 km in diameter.

Some elements of the system of vibroseismic monitoring have been tested during the 1995 Russian–Japanese experiment, in which the vibroseismic field of powerful vibrators on a 100 km profile has been explored in detail. Time variations in the parameters of the vibroseismic field at distances of 400–500 km have been investigated by methods of vibroseismic interferometry in 1996 experiments. A correlation between the time variations in amplitudes and phases of harmonic signals from vibrators and lunar–solar tides has been detected for the first time.

## 3. Mathematical simulation of active monitoring

Active vibroseismic monitoring is one of the most promising methods in searching for physical precursors of earthquakes in seismic prone zones.

The method of active vibroseismic monitoring makes it possible to study variations in the stressed state of a medium in seismic prone zones using variations in the dynamic characteristics of seismic waves that propagate in the zone of an expected earthquake.

There arises the following question: what variations in the dynamic characteristics of seismic waves can serve as precursors of possible earthquakes?

Now some earthquake precursors are known. These are variations in the velocity ratio of $P$- and $S$-waves in a seismic prone zone a few months before an earthquake, changes in the electrical conduction of a medium, etc. The effects mentioned above and some other effects can be explained in terms of dilatancy of rocks. Dilatancy means an inelastic increase in the volume of rocks due to the appearance of cracks and their growth. In this case, a rock becomes anisotropic, and we deal with the so-called extensive–dilatancy anisotropy. This physical model is taken as a basis for construction of a mathematical model.

In some theoretical papers, a medium containing aligned ellipsoidal cracks is replaced by a homogeneous transversely isotropic medium. Calculation of these effective moduli which take into account the orientation, density, and the aspect ratio of cracks, changes in the crack–fluid content is the next step.

Several theories have been developed to calculate the effective elastic constants of media that contain aligned ellipsoidal cracks [10, 14]. They are based on scattering of waves at cracks. These theories have been used to analyze wave propagation in cracked media and to explain the anisotropy observed. The basic assumptions of these theories are as follows: the dimensions of cracks are small with respect to the seismic wavelength, cracks are in dilute concentration and have small aspect ratios (the ratio of the length of an ellipsoidal crack to its width).

A theory that is valid for large concentrations of cracks has been proposed in [15] and is based on [9]. In accordance with this theory, a crack can be considered as the limiting case of an ellipsoid. Here we assume a small aspect ratio for cracks, as in other models.

A subroutine for computation of effective coefficients of anisotropy has been developed on the basis of this theory.

The input parameters for the subroutine are as follows: the angles between the plane, that contains cracks, and the axes of coordinates; the aspect ratio; the density of cracks; the coefficient of fluid compressibility; Poisson's ratio for an uncracked (solid) medium; the shear modulus for an uncracked medium; Young's modulus for a solid medium.

The output data are the coefficients of anisotropy induced by cracks. These coefficients are the initial data in simulation of propagation of seismic waves in cracked media. It is assumed that the parameters of cracking and, hence, the effective coefficients of anisotropy are arbitrary functions of spatial coordinates. 3D seismic simulation of propagation of seismic waves in anisotropic media is carried out using a numerical-analytical algorithm (see, e.g., [7, 8, 11]).

The main idea of this algorithm is splitting of 3D problems into a series of 1D problems and their successive solution with the help of the finite difference technique.

In accordance with the variation in the anisotropy coefficients, we have algorithms of two types. The first type is based on a combination of the analytical method of separation of variables using double Fourier transforms with respect to two horizontal coordinates and 1D finite difference techniques along the vertical coordinate and time. This type of algorithm is used, when the coefficients of anisotropy are arbitrary functions of the vertical coordinate.

In contrast to the first type of algorithm, there is no complete separation of variables in the second type, because the coefficients depend on all coordinates. When double Fourier transforms are applied, the problem is reduced to solving a system of equations with coefficients, which are the finite Fourier integrals of the effective anisotropy moduli that vary along the horizontal coordinates. This approach is an extension of the standard techniques of separation of variables to the solution of problems with complex subsurface geometries [12, 13].

The dynamic and polarization characteristics of seismic waves that are reflected from cracked zones with different fluid content in cracks are investigated using the above algorithms.

At present we continue to investigate the influence of such parameters as the density, orientation, and the aspect ratio of cracks on the dynamic characteristics of various types of seismic waves. We hope that this investigation will help to create a theoretical basis of vibroseismic monitoring of seismic prone zones.

## 4. An inverse dynamic problem of wave diffraction in seismic monitoring

A linearized statement of an inverse dynamic problem on reconstruction of local 3D inclusions in a known (or homogeneous) reference medium is considered in [16]. The statement is based on the spectral approach to constructing the solution and the methods of field continuation, which make it possible to obtain effective algorithms of the solution.

This is a problem for the wave equation in an inhomogeneous medium, which we consider as a model problem. The wave equation is an appropriate model of more general equations of seismics (including anisotropic models of some kind). It contains the main physical mechanisms of the relation between the medium's structure, the wave field, and all events of reflection, refraction and diffraction that are important for interpretation of seismic data.

The velocity distribution in the medium is represented as a sum of two terms: a constant (reference model) and a variable addition (velocity "anomaly"). The "anomaly" is assumed to occupy a local area, the whole of which is in a half-space. The inverse problem involves reconstruction of the velocity anomaly over the field scattered (on inclusions), that is recorded on an observation plane.

Our inverse problem is as follows: we find the function $c(\bar{x})$ from the equation

$$\Delta U(\bar{x},t) = \frac{1}{c^2(x)}\frac{\partial^2 U(\bar{x},t)}{\partial t^2} + \delta(t)\delta(\bar{x}-\bar{x}_0), \tag{1}$$

where $\bar{x} \in R^3$, $t \in R^1$, $\bar{x} = \{x,y,z\}$, $U(\bar{x},t) \equiv 0$ for $x \in R^3$, $t \leq 0$ and the data are $U|_{z=0} = U_1(x,y,0,t)$.

We assume that $c^{-2}(\bar{x}) = C_0^{-2} + m(\bar{x})$, where $c_0 = \text{const}$, $m(\bar{x})$ is small and smooth.

The full field is assumed in an approximate form

$$U(x,y,z,t) = U_1(x,y,z,t) + U_0(x,y,z,t),$$

where $U_1$ is a diffracted field and

$$U_0(\vec{x},\vec{x}_0,t) = -\frac{1}{4\pi r}\delta\Big(t-\frac{r}{c_0}\Big), \qquad r = |\vec{x}-\vec{x}_0|.$$

In what follows, the assumption that the velocity anomaly is small plays a substantial role, because it makes it possible to linearize the problems, i.e., to pass from the initial nonlinear problem to the linear one. Physically, this means that the scattered field observed by the receiving aperture is a result of a single wave diffraction.

Two observation systems can be considered: a system with a fixed source and a system with multiple overlaps of sources and receivers.

For the system with a fixed source, the main result can be formulated in the following way: the wave field obtained by the algorithm of continuation from the observation plane into the half-space with the help of the advanced Green function gives at $t = 0$ the values of the Radon transform of the function $f(\bar{\boldsymbol{x}})$ related with the sought-for anomaly $m(\bar{\boldsymbol{x}})$ by the simple formula

$$f(\bar{\mathbf{x}}) = -\frac{c_0}{(4\pi)^2}\frac{m(\bar{\boldsymbol{x}})}{|\bar{\boldsymbol{x}}|^2}, \tag{2}$$

where $m(\bar{\boldsymbol{x}}) = c^{-2}(\bar{\boldsymbol{x}}) - c_0^{-2}$, $c_0$ is the velocity in the reference medium, $c(\bar{x})$ is the sought-for velocity.

Hence, the inverse problem is solved in terms of the Radon inversion [17]. As the Radon transform is closely related to the Fourier transform, that is, the $n$-dimensional Fourier transform is a composition of the 1D Fourier transform and the Radon transform, an alternative result is obtained: the 3D Fourier transform of the continued (at $t = 0$) field gives the 3D spectrum of function (2). Thus, the inverse problem is solved in terms of the Fourier transform. It should be noted that the latter algorithm is most effective from the point of view of computations, because it makes it possible to use the fast Fourier transform. Notice also that the use of the advanced Green function to form the continuation process is important here, since it allows the problem to be reduced to the classical Radon problem.

It should be noted that the use of the whole system of observations, when the point of the receiver $(x, y)$ and the point of the source $(x_s, y_s)$ fill the plane $z = 0$ independently of one another (multiple overlaps), leads to redetermination of the statement: the 3D function is reconstructed using the values of the 5D function. This redundancy of information can be used to regularize the solution, eliminate noise and increase stability of the results of the processing.

In the description of the solutions to the above inverse problems of diffraction with smooth and weak inclusions, we deal with the following two applied problems:

1. Vibroseismic monitoring of the zone of accumulation of rheological changes (increase of cracking and appearance of anisotropic properties of the diffracted volume) in a seismic prone zone of the Earth's crust during earthquake preparation.

2. Seismic monitoring of the physical and geometrical properties of oil and gas deposits in the process of their exploitation.

The experience we have gained [18] in seismic sounding of ore bodies with the help of a sufficiently dense system of sensors in one of Uzbekistan deposits gives us confidence that the approach proposed is promising.

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