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Algorithms and methods for the numerical simulation of seismic wave fields in cavernous zones*

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Abstract. A developed toolkit (parallel programs and visualization tools) for the numerical simulation of the elastic wave propagation in 3D and 2D nonhomogeneous elastic media, comprising cavernous inclusions applicable to the on-site inspection, is described. According to the results obtained, groups of waves were identified, and synthetic data reflecting the influence of a cavernous inclusion upon the general picture of wave field were interpreted. Application of the cluster supercomputer NKS-30T favored to successful investigations.

1. Introduction

With regard to solving the tasks, related to the problem of the on-site inspection [3], examination of peculiarities of the seismic waves propagation in the media with an inclusion in the form of a cavity, plays an essential role. Earlier [1], the method of the Earth's vibrational sounding for the detection of cavernous inclusions in nonhomogeneous media was offered. This method is based on matching seismic wave field parameters, recorded at the output of a cavernous area and in the adjacent zones. One of the key questions of the methods is associated with the choice of distinctive informative parameters of the seismic fields, that characterize the adjacent areas. The answer to this question can be given from the numerical simulation. It is obvious that the completeness of the forming picture of the field will depend on the choice of a model of the medium under consideration, on the frequency band of the sounding vibroseismic oscillations and on other factors to be examined. With regard to this, a set of programs for the numerical simulation of the processes of elastic waves propagation in the media of such a type has been developed.

A wide spectrum of computational methods, applied for the simulation of complete wave fields in nonhomogeneous elastic media is known [5]. Most flexible for the case of the 3D complex subsurface nonhomogeneous elastic

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geometries are a difference method and a finite element method. Application of methods of numerical simulation requires high computational costs even when applying a cluster supercomputer. Depending on the input parameters and the accuracy of calculations, the simulation of seismic fields can require significant computational resources. Therefore, there is a need for parallel computing in order to accelerate the computing, as well as in providing the assurance of the possibility of performing calculations for "large" models of elastic media and application of a fine grid for the detection of necessary effects.

2. Mathematical simulation and appropriate tools

The numerical simulation of seismic waves propagation in complex subsurface elastic nonhomogenous geometries is performed on the basis of solution to a complete system of equations of elasticity theory with the corresponding initial and boundary conditions. Statement of the problem is presented in terms of a vector of displacement velocities and stress tensor, in which for a 3D case it is assumed that the Lame parameters $\lambda = \lambda(x, y, z)$, $\mu = \mu(x, y, z)$ and the density of the elastic medium $\rho = \rho(x, y, z)$.

With the use of a finite-difference method, a parallel program for the numerical simulation of elastic waves propagation in a 3D nonhomogeneous elastic medium was developed. The program includes, first of all, the implementation of forming up a complex 3D model of an elastic medium with an inclusion of distinctive heterogeneities, characterized by various elastic parameters. Secondly, the part which is directly responsible for carrying out numerical simulation with a finite difference scheme is realized in it. A plotter, for creating rather complex models that are close to real objects of research, has been developed. The finite difference scheme applied has second order of approximation of time and space. The applied scheme is constructed with allowance for the integrated conservation laws. In order to eliminate elastic waves reflections from the boundaries of a computational domain, the absorbing boundaries are used. A general algorithm of forming up a finite-difference scheme for the 3D problems of computational simulation, as well as the description of elastic models plotter and parallelization are described in detail in [2, 4].

The created program has been successfully applied for the simulation of seismic waves propagation within the 3D elastic media, characteristic of muddy-volcanic structures [4]. The tested algorithm was adapted for simulation of the elastic waves propagation from a concentrated source for more complicated cases of the elastic media structure. Such elastic media are understood as 3D elastic media, which may contain various inclusions of cavernous type, in particular, the areas resulted from carrying out nuclear tests on test sites.

In this paper, we consider a case of the 2D model of elastic media, but the problem can be generalized to the 3D case as well.

3. Numerical experiments on studying wave field properties on various models

For the investigation into the structure of a wave field which can occur when carrying out field experiments on test sites, test calculations for various models were performed. The influence of the model geometry upon the structure of a wave field of the elastic medium containing a cavity was under investigation, first of all, for the purpose of identifying distinctive properties of a wave field, caused by the presence of such a cavity. All the numerical calculations were carried out with the use of the parallel program on the cluster NKS-30T SSCC developed in the Institute of Computational Mathematics and Mathematical Geophysics of the Siberian Branch of the Russian Academy of Sciences.

Figure 1 shows the 2D model of a nonhomogeneous elastic medium with linear sizes of 3.4 km in Ox-direction and 1.0 km in Oz-direction, containing one sub-area as a cavity *4*. The cavity is surrounded by two external rings: ring *3* is completely homogeneous and ring *2* simulating a fracture zone is filled-in with equidistributed inclusions. The sizes of these inclusions expressed in the unit cells with a side of $5.23 \cdot 10^{-4}$ km are one cell along Ox-axis and two cells along Oz-axis.

Elastic parameters of the elements composing the model under study, are given in the table below. In the table, V_p is the compressional P-wave velocity, V_s is the shear S-wave velocity, ρ is the density of the elastic medium.

For the simulation of seismic waves propagation, a source of the "center of pressure" type was used, that was located near to the free surface ($z = 0$), with the coordinates of the source along Ox-axis equal to 0.3 km.

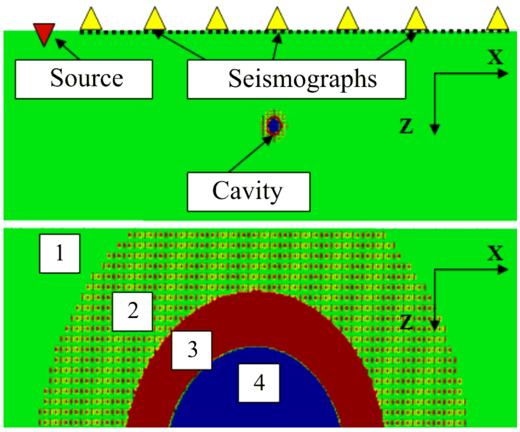

Figure 1. Scheme of the 2D model of an elastic medium in xOz-plane (the upper half of the figure) and detailed scheme of the A-zone with a cavity (the lower part of the figure)

Elastic parameters of the 2-D model (see Figure 1)

Item	V_p (km/s)	V_s (km/s)	ρ (g/cm^3)	Radius (km)
Background medium 1	2.2	1.1	2.65	—
Ring 2, fracture zone	5.0	3.0	2.8	0.089
Ring 3	5.0	3.0	2.8	0.054
Cavity 4	0.0	0.0	0.0	0.037

Dominant frequency in the source function is 30 Hz. Elastic parameters of the model and the frequency of the source were selected in such a manner that the size of cavity be two minimal wave-lengths. The monitoring system involving 290 seismographs is located on a day surface, a distance between seismographs being 0.01 km. Coordinates of the first seismograph along Ox-axis are 0.4 km. Results of calculations are synthetic seismograms and snapshots of the wave field. Basically, one of components of the wave field, namely, U_z, corresponding to the vertical component of the seismic field (Oz), has been considered. The time of seismograms calculation for the model under investigation is 3 s.

Figure 2 provides a synthetic seismogram for U_z component in the rectangular coordinate system which presents the coordinates of seismographs along the horizontal line and along the vertical line — the arrival times of different waves are given.

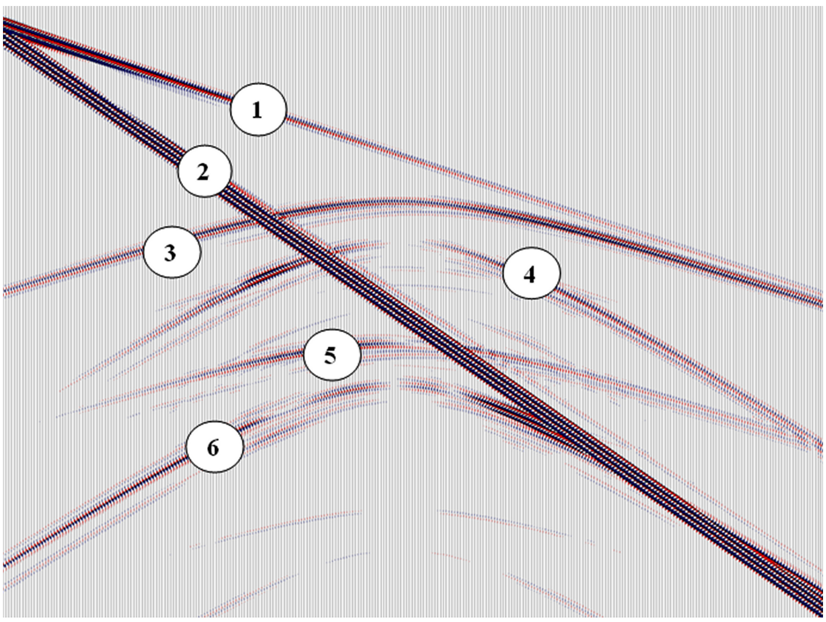

Figure 2. A computed synthetic seismogram for U_z component. The horizontal linear size of the model is 3.4 km

In the synthetic seismogram, one can clearly observe several groups of elastic waves, marked with numbers from 1 to 6. Judging from the arrival times of the waves to seismic receivers, the identified groups correspond to the following wave types: 1 — the direct P-wave; 2 — the Rayleigh surface wave; 3 — P-wave, reflected from the cavity; 4 — S-wave, reflected from the cavity; 5 — SP-wave, reflected from the cavity; and 6 — SS-wave, reflected from the cavity. Thus, the groups of waves, marked with numbers 3–6, are generated to the presence of a cavity. In such a case, wave 3 possesses rather a high amplitude and can be a forerunner of the cavity presence.

The process of formation of the reflected waves given in the synthetic seismogram above illustrates the computed snapshots of the wave field for 12 time intervals (Figure 3).

The snapshot in Figure 3 shows the groups of waves 3, 4 for the time interval t_3 and the groups of waves 5, 6 for the time intervals t_6–t_8. Surface wave 2 is clearly observed in all the snapshots of the wave field. It is worth noting, that as P-waves and S-waves are falling from a source onto a cavity and are further passing through it, the response of the cavity can be observed, namely, the reflected waves on a free (day) surface are visible. With further divergence of waves and their propagation in the holding medium, no resonant effects related to the presence of a cavity are observed. According to the snapshots, no significant changes in the field under the incidence

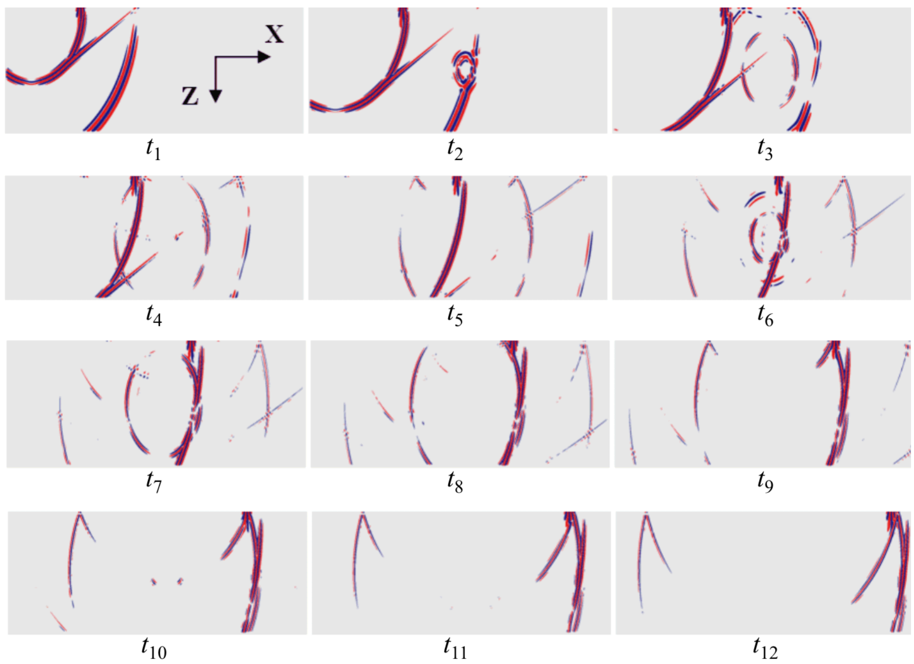

Figure 3. Computed snapshots of U_z component for 12 different time intervals

conditions of elastic waves reflected from the free surface are detected if the waves are incident onto a cavity. Therefore, marked changes of a seismic field, caused by the presence of a cavity, are connected with the passage of the the bulk of elastic waves through it.

Similar calculations were performed for a homogeneous medium as well, which allowed us to compare of its wave field with the above-mentioned results and to construct difference synthetic seismograms. Figure 4 presents a synthetic seismogram, which reflects a difference between the two seismograms that were computed for a model with cavity and for a model of a homogeneous elastic medium. The effect caused by the presence of a cavity in a medium, surrounded by two external rings, including a fracture zone, in the form of the waves (3), S (4), SP (5), SS (6), reflected from the cavity.

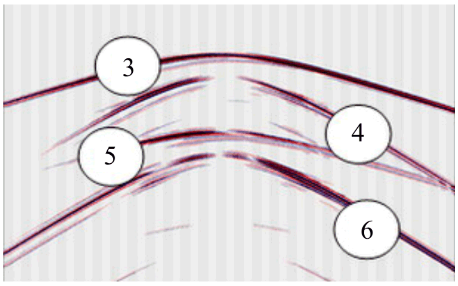

Figure 4. A difference synthetic seismogram for U_z component

At the following stage of this study, the simulation of the elastic waves propagation in the elastic medium without annular zone of fracture (see zone 2 in Figure 1) was carried out. Such a zone can be considered as an analog to an anisotropic subregion. Figure 5 presents the results of numerical calculations in the form of difference synthetic seismograms of the wave field component U_z.

No significant differences in the wave field caused by the presence of an annular zone of fracture 2 in the considered model with a cavity were observed. Phase shift of the main waves due to the presence of an anisotropic body analog is possible. Basically, the picture of the wave field has remained the same.

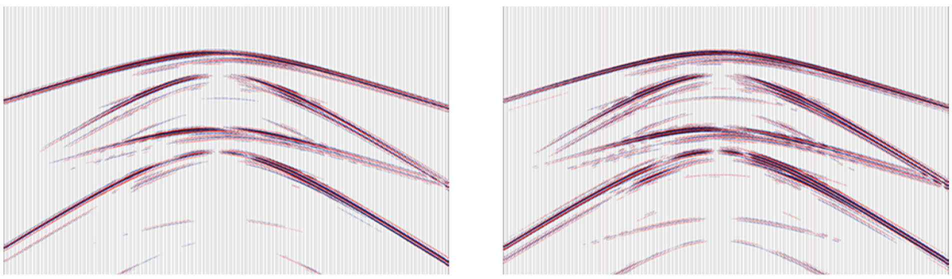

Figure 5. Difference synthetic seismograms for Uz component: the model from Figure 1 without annular zone of fracture 2 compared with a homogeneous model of the medium (left figure) and the complete model compared with the model without annular zone of fracture 2 (right figure)

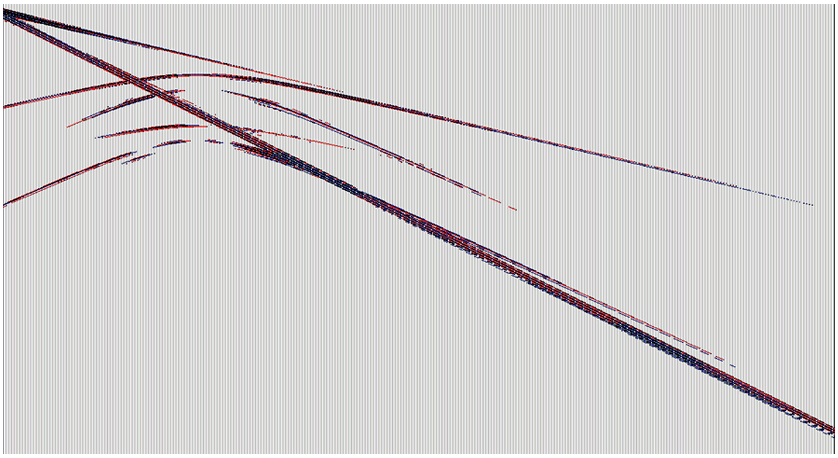

Figure 6. Synthetic seismogram for U_z component. The horizontal linear size is 6.4 km

A series of calculations was performed for a model similar to the basic one under study (see Figure 1), but with partially changed geometrical sizes. The extent of the model in this version was 6.4 km (instead of 3.4 km) in X direction, the number of seismographs was 590 (instead of 290). Location and dimensions of all the rest parameters of the model and the monitoring scheme were not changed with regard to Figure 1. The time for seismograms calculation was 7 s (instead of 3 s). A synthetic seismogram for U_z component of a wave field according to the calculation results with this model are presented in Figure 6.

As was earlier established, in this figure, the same groups of waves, which serve as indicators to the presence of a cavity, are observed. In this case, not all the distinguished groups of waves can be clearly observed at a considerable distance from the center of a cavern.

4. Conclusion

The toolkit (parallel programs) for carrying out the numerical simulation of elastic waves propagation in the 3D and in the 2D nonhomogeneous media containing cavernous inclusions have been developed. The software for visualization of a seismic wave field has been developed. It allows studying the dynamics wave propagation in terms of time and space. The numerical simulation was made on the cluster supercomputer NKS-30 using parallelization technique. Due to this choice and choice of solution methods, the calculation time was significantly reduced and an opportunity of numerical simulation of "large" models with more details was achieved.

With application of the created toolkit, a series of computing experiments for various models of elastic media were carried out with various monitoring systems and geometrically different models of inclusions. Groups of waves associated with a cavernous inclusion have been distinguished in numerical simulations. Obtained synthetic results reflecting the influence of a cavernous inclusion on a wave field picture were interpreted. We plan to carry out a series of computing experiments for more complicated models of media containing several cavities and overlapped with nonhomogeneous layers of various geometries, which will enable us to bring a numerical model nearer to a real situation that takes place on test sites, as well as to develop techniques of detecting new cavities against the already existing ones.

Computational experiments for the model of a nonhomogeneous elastic medium containing a cavity are urgent for studying the features of seismic wave fields in the places of carrying out nuclear tests, as well as for verifying the techniques of studying local zones of underground nuclear explosions, as they make possible to find the most suitable location for a monitoring system (seismic receivers) for the detection of specific abnormal effects, and to localize and characterize more precisely cavities that are local zones of underground nuclear explosions.

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