FULL-WAVE SIMULATION OF THE EARTHQUAKE INITIAION PROCESS*

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The earthquake process leads to the destruction of building and has a significant influence on human life. Nowadays there is no methods to forecast it with the 100 % precision. Scientists around the world make efforts to invent numerical methods for simulation of the earthquake process. With the rapid development of high-performance computing systems more complex physical and mathematical models may be used. In this paper we describe the experience of full-wave seismic waves simulation in layered inhomogeneous medium. The simple earthquake source model was used in 3D case. It allows us to reproduce the anisotropy of the registered seismic signal. The govern system of equations are solved numerically with the grid-characteristic method on structured meshes. To achieve a reasonable computation time, the parallel version of algorithms was applied. The spatial distribution of displacements on the sea surface was successfully simulated.

Keywords: earthquake, seismic waves, numerical simulation, grid-characteristic method

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1. Introduction

During the recent years, different algorithms for simulation of the earthquake process were developed [1]. Most of numerical methods well-established in seismic survey problems of oil and gas deposits were extended to the global seismic problem: finite-difference using staggered grids [2], finite-element method [3], hybrid methods [4].

In this paper we present the results of the application of the grid-characteristic method [5] to the earthquake simulation problems in 2D and 3D cases. The multilayered model was constructed based on geological data of the shelf area. It includes a thin water layer. The contact problem between acoustic and elastic media were solved analytically.

The goal of this article was the estimation of spatial distribution of maximum displacements of the sea surface along all coordinate axes and their comparison among themselves.

2. Mathematical model

The description of the dynamic behavior of the geological massif under the earthquake load in the far field is based on the system of equations of the linear elasticity theory. It consists of the second Hooke's law and rheological relationships between stresses and strains. We decided to highlight all heterogeneities explicitly, so the background model is homogeneous and isotropic, and these equations are valid:

$$\rho \frac{\partial v_x}{\partial t} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z}, \tag{1}$$

$$\rho \frac{\partial v_y}{\partial t} = \frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z}, \tag{2}$$

$$\rho \frac{\partial v_z}{\partial t} = \frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}, \tag{3}$$

$$\frac{\partial \sigma_{ij}}{\partial t} = \lambda \delta_{ij} \delta_{kl} \frac{\partial \varepsilon_{kl}}{\partial t} + \mu\left(\delta_{jl} + \delta_{il}\delta_{jk}\right)\frac{\partial \varepsilon_{kl}}{\partial t}, \tag{4}$$

here σ – the stress tensor, ε – the strain tensor, v_i – the component of the velocity vector, i and j equal $\{x, y, z\}$.

The procedure of the individual layer description was described and verified at [6]. The general approach allows us to describe also geological fractures with arbitrary orientation and geometry [7]. To solve the govern system of equations the grid-characteristic method on structured meshes was used [5]. The system (1) – (4) can be rewritten in the other canonical form with the vector $\vec{u}$ of unknowns

$$\frac{\partial \vec{u}}{\partial t} + A_x \frac{\partial \vec{u}}{\partial x} + A_y \frac{\partial \vec{u}}{\partial y} + A_z \frac{\partial \vec{u}}{\partial z} = 0. \tag{5}$$

After splitting the system (5) along coordinate directions eigenvalues and eigenvectors can be found analytically. And along the characteristic curves these equations will be transformed as

$$\frac{\partial \vec{u}}{\partial t} + \Omega^{-1}\Lambda\Omega \frac{\partial \vec{u}}{\partial \xi} = 0, \tag{6}$$

$$\frac{\partial \vec{q}}{\partial t} + \Lambda \frac{\partial \vec{q}}{\partial \xi} = 0. \tag{7}$$

The system (7) is a set of transport equations with constant parameters. It is solved with 3rd order in space in time with the Rusanov scheme. At the final stage the vector $\vec{u}$ is calculated from the vector $\vec{q}$ multiplying by the matrix Ω^{-1}. Due to the high computational complexity of the problem parallel technologies MPI and OpenMP are intensively used.

We used in this research the simplest model of the earthquake hypocenter. It is called "the slip along the fault" (see Figure 1). In this model the crack plane exists a long period of time. At some moment due to the increase of regional stresses the smallest movement is occurred. One part of the massif moves with the constant vector $\vec{V}$ and the second part with the opposite vector $\overrightarrow{-V}$. Three independent angles are necessary to specify the model uniquely (see Figure 1). The magnitude of $\vec{V}$ can be estimated based on the day surface displacement map.

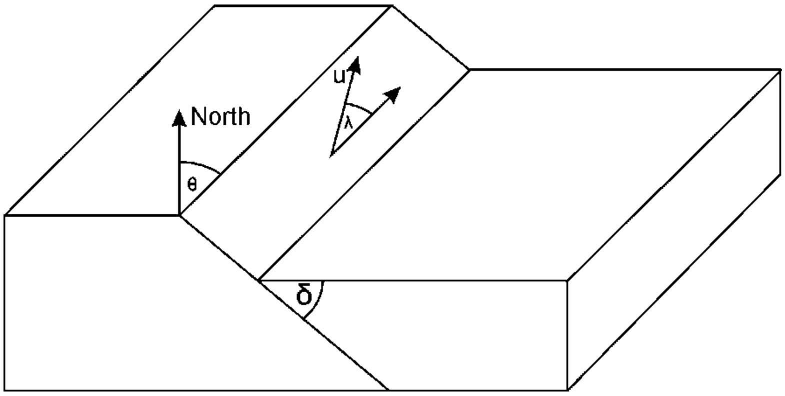

Figure 1. The hypocenter model is called "the slip along the fault"

3. Simulation results

We used the described approach for the simulation of seismic waves in the layered model. It consists of five geological layers with different parameters [8]. The topmost one describes the sea water and was simulated with the usage of the acoustic hyperbolic system of equations. All of others describe geological massif and were simulate with the system (1) – (4). The total size of the whole model was 4 km x 4 km x 1.5 km. The mesh spacing was 5 m in all directions.

The source was submerged at the depth of 1.15 km. It had sizes 50 m x 150 m x 150 m and all angles equal to 45 degrees. For calculations we used the HPC system with 1000 cores based on MPI+OpenMP parallelization technologies.

Both problems (2D and 3D) were successfully simulated for the reasonable time. At Figure 2 the spatial distribution of the velocity vector is depicted for the 2D case. The initial wave propagates along the sea surface and the reflected from the seabed wave is clearly seen. It should be noticed, that all P-waves and S-waves born on contact boundaries carry the information from the hypocenter of the earthquake. The usage of the direct simulation allows us to analyze all of this information in future.

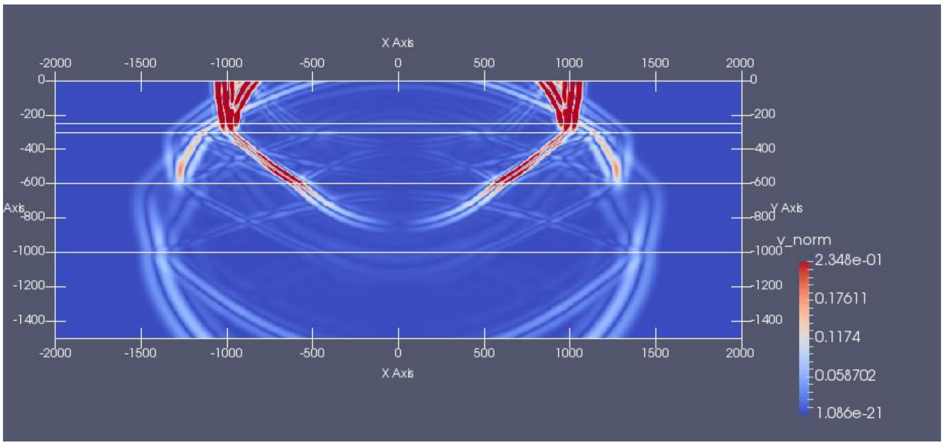

Figure 2. The modulus of the velocity vector in 2D model

According to the boundary condition the pressure at the day surface is constantly zero. In 3D case we decided to estimate the map of maximum displacements at the sea surface. The spatial distribution for all components are presented (see Figure 3). The azimuthal anisotropy is easily identified and it is connected with the orientation of the fault orientation. The vertical displacement is approximately ten times more intensive than both horizontal displacements. In general, using numerical integration of the obtained velocity field we can achieve the first approximation to the wave structure on the sea surface.

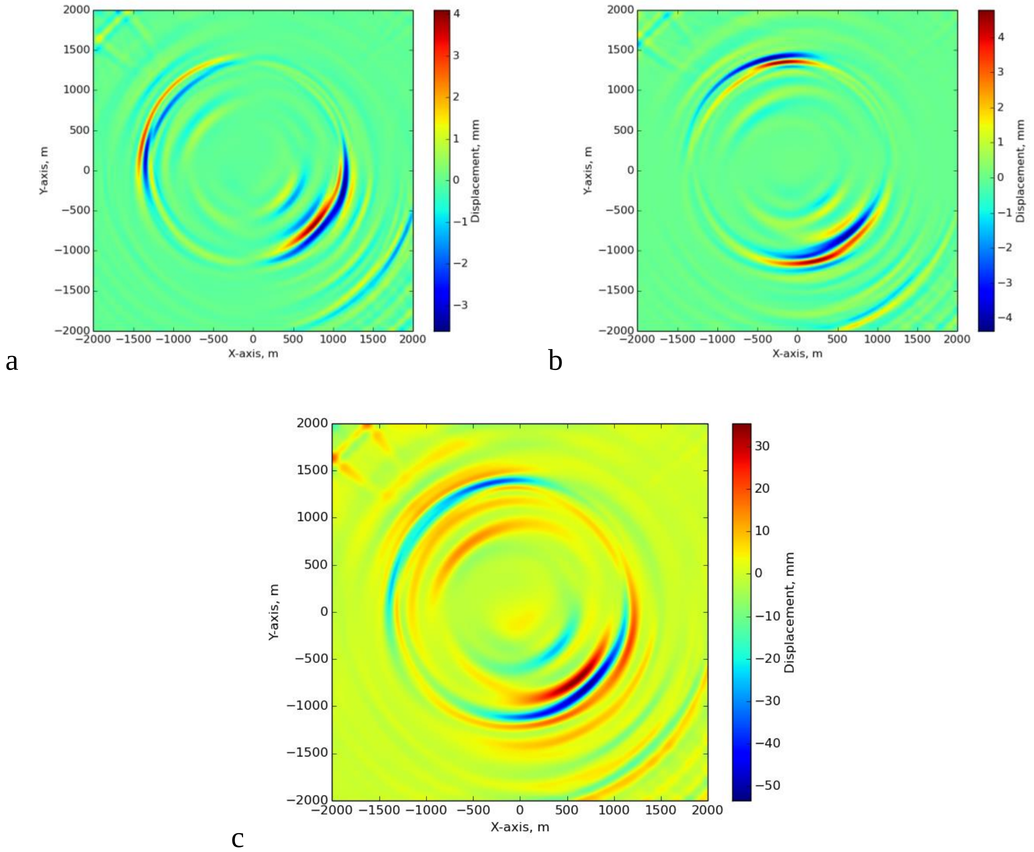

Figure 3. The spatial distribution of maximum displacements at the sea surface. Was measured at the x-component (a), y-component (b) and z-component (c)

4. Conclusion

The full-wave approach for the simulation of seismic waves in the far field occurred during the earthquake process in heterogeneous media was presented. It is based on the numerical solution of the system of the linear elasticity. In this work the grid-characteristic method on structured meshes in 2D and 3D cases was used. The earthquake hypocenter was modelled with "the slip along the fault" approximation. The geological model with the water layer and a set of elastic layers with different parameters was constructed. The distribution of displacement vectors along the sea surface was estimated. The further complicating of the geological model and taking into account the ground structures with complex geometries are possible.

References

[1] Hori, M., Ichimura, T., Wijerathe, L. On some recent achievements of earthquake simulation // Procedia Computer Science. 2011. V. 4, P. 2344-2353

[2] Pitarka, A. 3D elastic finite-difference modeling of seismic motion using staggered grids with non-uniform spacing // Bulletin of Seismological Society of America. 1999. V. 89, P. 54–68

[3] Koketsu, K., Fujiwaraand, H., Ikegami, Y. Finite-element Simulation of Seismic Ground Motion with a Voxel Mesh // Pure and Applied Geophysics. 2004. V. 161, P. 2463–2478

[4] Ichimura, T., Horiand, M., Kuwamoto, H. Earthquake Motion Simulation with Multiscale Finite Element Analysis on Hybrid Grid // Bulletin of the Seismological Society of America. 2007. V. 97, P. 1133–1143

[5] Golubev, V.I., Petrov, I.B., Khokhlov, N.I. Simulation of seismic processes inside the planet using the hybrid grid-characteristic method // Mathematical Models and Computer Simulations. 2015. V. 7, P. 439-445

[6] Golubev, V.I., Gilyazutdinov, R.I., Petrov, I.B., Khokhlov, N.I., Vasyukov, A.V. Simulation of dynamic processes in three-dimensional layered fractured media with the use of the grid-characteristic numerical method // Journal of Applied Mechanics and Technical Physics. 2017. V. 58, I. 3. P. 539-545

[7] Golubev, V.I., Khokhlov, N.I. Estimation of anisotropy of seismic response from fractured geological objects // Computer Research and Modeling. 2018. V. 10, I. 2. P. 231-240

[8] Zaslavskii, Yu.M., Kerzhakov, B.V., Kulinich, V.V. Vertical seismic profiling on the sea shelf // Acoust. Phys. 2008. V. 54, P. 420–425