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Procedia Computer Science 154 (2019) 305–310

Procedia Computer Science

www.elsevier.com/locate/procedia

8th International Congress of Information and Communication Technology, ICICT 2019

Investigation of Seismic Stability of High-Rising Buildings Using Grid-Characteristic Method

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Abstract

The purpose of this work was the numerical simulation of dynamic wave processes in heterogeneous media with the subsequent evaluation of their influence on various structures. The effect of earthquakes on ground buildings and underground structures was studied. In the work, we used the grid-characteristic method, which allows taking into account the physics of arising wave processes. The use of hierarchical grid systems allows the calculation of seismic waves directly from the earthquake source to ground-based buildings and underground structures. The work investigated the destruction of high-rise buildings under the influence of seismic loads. The emerging areas of fractures in various structures were studied. The effect of the earthquake on the underground structure was considered. The influence of the depth of the earthquake source was analyzed. Images of wave processes in structures and places of destruction were obtained. Note that we do not calculate the damage caused by falling of some collapsed parts of the building to others, but we calculate only damage caused directly by seismic activity. This type of damage is of the greatest interest, since it is necessary to avoid precisely this primary destruction. Also we investigate the nature of this type of damage, e.g, internal, near the surface, causing collapse, asymmetric. The novelty of the approach used also lies in the fact that we solve a linear elastic wave equation with constant coefficients in various subdomains of the integration domain, between which contact conditions are established. And the size and shape of these subdomains vary over time and depend on the solution. That is, the complete boundary problem of the elastic wave equation is nonlinear.

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Selection and peer-review under responsibility of the 8th International Congress of Information and Communication Technology, ICICT 2019.
10.1016/j.procs.2019.06.044

Keywords: wave phenomena, grid-characteristic method, seismic resistance, elastic wave equation in time domain, nonlinear elasticity.

1. Introduction

The earthquake is shocks of the ground and earth surface oscillations. Earthquakes reflect the process of geological transformation of the planet. The main cause of earthquakes are global geological and tectonic forces, at present their nature is not entirely clear. Temperature inhomogeneity in bowels of the earth causes the appearance of geological and tectonic forces. Most earthquakes occur on contacts of tectonic plates.

Many scientists around the world are engaged in numerical modeling of seismic stability of buildings. One of the most advanced method for estimating the seismic resistance of structures is to carry out numerical simulation of dynamic processes by the finite-element method1. There are also attempts to take into account the non-determinism of the process of the earthquake initiation, e.g. the usage of statistical models2. These used numerical methods have drawbacks, i.e. problems with the correct formulation of boundary conditions, which reduces the reliability of estimates obtained.

In our work, it was decided to use the grid-characteristic numerical method, proposed by Kholodov and Magomedov3, developed by the team leading by Petrov4,5, and developed on hierarchical grids by Favorskaya6, for numerical modeling of the influence of earthquakes on the day surface and underground structures. It was previously successfully applied to seismic resistance estimation7,8. This method explicitly takes into account the internal features of the determining system of equations and is deprived of the indicated disadvantage. Note that the proposed approach to the study of seismic resistance by solving a direct elastic wave equation in a heterogeneous medium with boundaries of complex shape can be applied with the use of other numerical methods for elastic full-wave simulation in time domain, e.g. discontinuous Galerkin method9,10,11, spectral elements methods12, finite-difference time-domain (FDTD) methods13,14, and finite volume methods15.

This paper is organized as follows. In Section 2 we discuss the mathematical formulation of the problem. In order to describe wave phenomena in solids we use elastic wave equations. Section 3 deals with the development of the grid-characteristic method. We consider a sequence of nested hierarchical grids in Section 4. We discuss the dependence of the destruction on the hypocenter depth in Section 5. Section 6 concludes the paper.

2. Mathematical Formulation of the Problem

In accordance to works5,15,16, the system of equations describing wave processes in a continuous linear-elastic medium can be written as follows:

$$\rho \mathbf{v}_t = \left(\nabla \cdot \boldsymbol{\sigma}\right)^{\mathrm{T}} \tag{1}$$

$$\boldsymbol{\sigma}_t = \left(\rho c_{\mathrm{P}}^2 - 2\rho c_{\mathrm{S}}^2\right)\left(\nabla \cdot \mathbf{v}\right)\mathbf{I} + \rho c_{\mathrm{S}}^2\left(\nabla \otimes \mathbf{v} + \left(\nabla \otimes \mathbf{v}\right)^{\mathrm{T}}\right) \tag{2}$$

where ρ is the material density; $\mathbf{v}$ is the velocity of the motion; $\boldsymbol{\sigma}$ is the Cauchy stress tensor; c_{P} and c_{S} are velocities of P-waves and S-waves, respectively. The damage (fracture) is taken into account by using a criterion based on the principal stress17.

The grid-characteristic method[6] is used on a six sequences of nested hierarchical grids. In Fig. 1, the main grid (1, in red color) is visible and six other grids (2–7, in green color) are superimposed on it. And the last (7, in yellow color) thickening grid is divided into 3 grids and surrounds the building.

3. Grid-Characteristic Method

System (1), (2) was solved numerically by applying the grid-characteristic method on structured grids, which performs well near boundaries and interfaces, where there are discontinuities in the wave propagation velocity and (or) density. This method also provides the opportunity of using curvilinear structured and hierarchical grids.

In the two-dimensional case, system (1), (2) can be represented in the form

$$\mathbf{q}_t + \mathbf{A}_1\mathbf{q}_{x_1} + \mathbf{A}_2\mathbf{q}_{x_2} = 0 \quad (3)$$

where $\mathbf{q}$ is the vector composed of two velocity components and three stress tensor components (the stress tensor is symmetric):

$$\mathbf{q} \in \{v_1, v_2, \sigma_{11}, \sigma_{22}, \sigma_{12}\}^{\mathrm{T}} \quad (4)$$

Application of the dimensional splitting method to (3) yields two one-dimensional systems

$$\mathbf{q}_t + \mathbf{A}_j\mathbf{q}_{x_j} = 0 \quad (5)$$

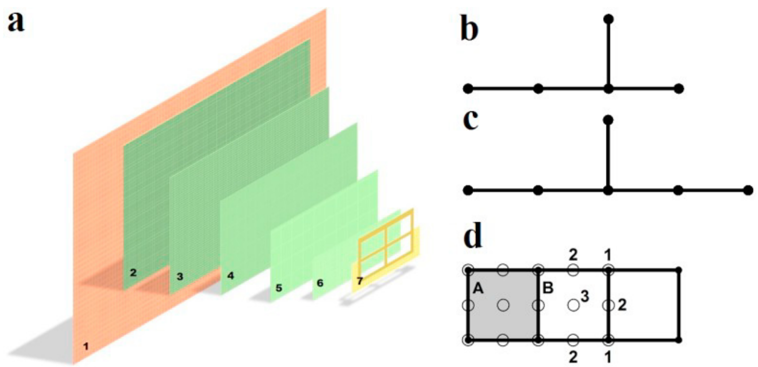

Fig. 1. (a) location of 6 nested hierarchical grids around the country house; difference scheme templates: (b) for positive eigenvalues; (c) total stencil; (d) nested hierarchical grids.

Both systems are hyperbolic and have a complete set of eigenvectors with real eigenvalues. Therefore, both systems can be rewritten as

$$\mathbf{q}_t + \mathbf{\Omega}_j^{-1}\mathbf{\Lambda}_j\mathbf{\Omega}_j\mathbf{q}_{x_j} = 0 \quad (6)$$

where $\mathbf{\Omega}_j^{-1}$ is the eigenvector matrix and $\mathbf{\Lambda}_j$ is a diagonal matrix made up of eigenvalues. For all coordinates, the matrix $\mathbf{\Lambda}$ has the form (in what follows, the index j is omitted wherever possible)

$$\mathbf{\Lambda} = \mathrm{diag}\{c_{\mathrm{P}}, -c_{\mathrm{P}}, c_{\mathrm{S}}, -c_{\mathrm{S}}, 0\} \quad (7)$$

After changing to the variable $\mathbf{w} = \mathbf{\Omega}\mathbf{q}$, both systems in (4) split into five independent scalar transport equations:

$$\mathbf{w}_t + \mathbf{\Lambda}\mathbf{w}_x = 0 \quad (8)$$

One-dimensional transport equations are solved by applying the method of characteristics or usual finite-difference schemes.

After all components have been transferred, the solution is recovered as

$$\mathbf{q}^{n+1} = \mathbf{\Omega}^{-1}\mathbf{w}^{n+1} \tag{9}$$

The research software involves second-order accurate TVD difference schemes[18,19], and second-to-fourth order accurate grid-characteristic schemes[8]. It is also possible to use boundary conditions with a given boundary velocity or a given body force, mixed and nonreflecting boundary conditions, and no-slip and free slip contact conditions.

The numerical result presented in this paper were obtained using the third-order accurate grid-characteristic scheme. For a positive eigenvalue of $\mathbf{A}_j$ the stencil is shown at Fig. 1b,c. Since the matrices $\mathbf{A}_j$ in the considered hyperbolic system (1), (2) has both positive and negative eigenvalues, the total stencil has the form depicted at Fig. 1c. For correct computations on the same stencil (Fig. 1c) at interior nodes located on boundaries and interfaces in the integration domain, each grid is supplemented with two layers of additional nodes placed along the boundaries.

This numerical method was implemented in a software package developed by the team leading by Khokhlov[4,6,7,8], as well as by the authors of this paper, i.e. Golubev, Kozhemyachenko and Favorskaya. To set the geometry of the buildings under consideration, author's scripts in the *Python* language, developed by Favorskaya, were also used, which made it possible to significantly save calculation time on preprocessing. The building model consists of separate rectangular calculation grids[4,20], the boundaries between which are set using these preprocessing scripts.

4. Sequence of Nested Hierarchical Grids

Let's consider a sequence of nested hierarchical grids. The spatial element size in neighboring grids differ by a factor of 2. Cells on the boundary between two grids with different element size were depicted at Fig. 1d. The grid with a larger element size includes the nodes marked with solid circles, while the grid with a smaller element size consists of nodes marked with open circles. The grid with a finer spatial step has internal cells of a type A and cells generated by two layers of additional nodes (of type B). At the stage of specifying values at additional nodes, these values at nodes of type 1 are copied from corresponding nodes of the coarser grid, the values at nodes of type 2 are determined by the linear interpolation on nodes of the coarser grid, and values at nodes of type 3 are determined by bilinear interpolation on nodes of the coarser grid.

The sequence of nested hierarchical grids (Fig. 1a) makes it possible to calculate the effect on buildings produced by seismic waves propagating directly from the hypocenter (Fig. 2). Figure 2 shows wave patterns (on different scales) at the same time. In Fig. 2a, the hypocenter is denoted by a rectangle and the arrow indicates the location of a five-story building.

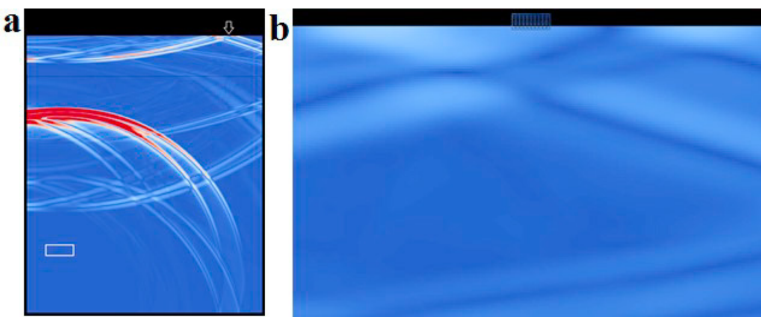

Fig. 2. Computation of the effect produced on a five-story building by seismic waves propagating from the earthquake hypocenter: (a) all integration domain, (b) earth near the five-shore building.

5. Dependence of Destructions on the Hypocenter Depth

We have considered different building models discussed in detail at the work[20]. Figure 3 present the damage patterns in buildings located at a distance of (a,d,g) 4000 m, (b,e,h) 2000 m and (c,f) 1000 m from the earthquake epicenter. Figures 3a,b,c and 35d,e,f correspond to five-story buildings, while Figs. 3c,f corresponds to the skyscraper. The hypocenter was at a depth of 3000 m in 3a,b,c, and at a depth of 6000 m in 3d,e,f,g,h.

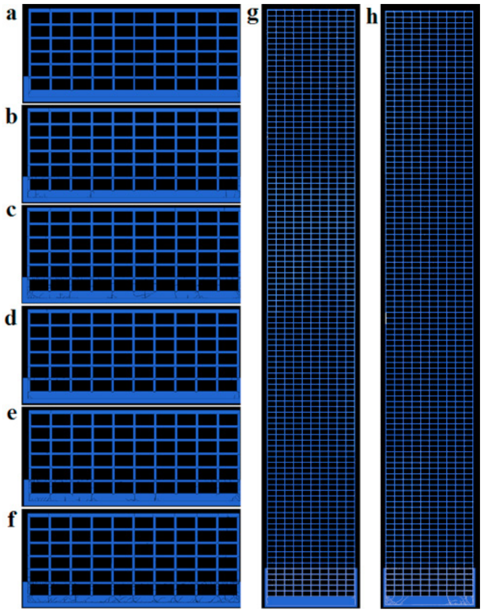

Fig. 3. Damage in different high-rising building types located at the different distances from the epicenter, the hypocenters were at the different depths: (a) five-story building, distance 3 km, depth 4 km; (b) five-story building, distance 2 km, depth 3 km; (c) five-story building, distance 1 km, depth 3 km; (d) five-story building, distance 4 km, depth 6 km; (e) five-story building, distance 2 km, depth 6 km; (f) five-story building, distance 1 km, depth 6 km; (g) skyscraper, distance 4 km, depth 6 km; (h) skyscraper, distance 2 km, depth 6 km.

It was obtained that, for smaller depths, the amount of destruction in the foundation of a building largely depends on its distance from the epicenter. This dependence holds irrespective of the number of floors or the wall thickness. The destruction of walls at upper floors depend on details of elastic wave propagation in a particular building and, hence, on the number of floors, the wall thickness, and the localization and features of the earthquake under consideration. The dependence on the epicenter distance is generally nonlinear. We also note that the work extends the regularities obtained in article[6] and shows that these regularities are also being applicable to high-rise buildings, including skyscrapers.

Note that the calculation with the skyscraper and depth of the earthquake source of 6 km lasted 2 months[20], and visualization of the calculation results at one time step using the open software *Paraview*[21], performed by Breus, required no less than 16 GB of random access memory.

6. Conclusions

Based on the numerical simulation of reflection and diffraction of elastic waves arriving from an earthquake hypocenter, the amount of damages at complex heterogeneous structures, such as multi-story buildings, was analyzed and its dependence on structural parameters and the focal depth was investigated. All calculations were performed using the grid-characteristic method on a sequence of nested hierarchical grids.

Acknowledgements

The reported study was funded by RFBR according to the research project № 18-01-00526 A. This work has been carried out using computing resources of the federal collective usage center Complex for Simulation and Data Processing for Mega-science Facilities at NRC “Kurchatov Institute”, http://ckp.nrcki.ru/.

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