DOI: 10.17725/rensit.2019.11.345

Calculation the earthquake stability of various structures using the grid-characteristic method

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Received 15.10.2019, peer reviewed 23.10.2019, accepted 31.10.2019

Abstract. Building in earthquake-prone regions requires the development of new methods for computer simulation in order to assess the safety of exploitation of constructed structures and design new structures. In this paper, we propose to use the grid-characteristic method on structured curvilinear grids to calculate the elastic and acoustic wave fields in the structure under consideration, containing the geological massif and surrounding water bodies. Then, based on the calculated field of the Cauchy stress tensor, the possible damaged regions are determined. To highlight the complex shape of the boundaries, multiple contacting separate computational grids are used, between which the contact condition of continuity of speed and traction is used. Test calculations of the earthquake resistance of a multi-story residential building, metro station, footbridge with elevator shaft and dam of hydroelectric power station were carried out. The used grid-characteristic method allows us to accurately solve the boundary-value problem of elastic and acoustic wave equations in the integration domain of complex shape.

Keywords: computer simulation, grid-characteristic method, structural curved grids, earthquake resistance, residential building, footbridge, dam, metro station

UDC 519.63

Acknowledgments: The study was carried out at the Moscow Institute of Physics and Technology with a grant from the Russian Science Foundation (project No. 17-71-20088).

For citation: Favorskaya A.V., Petrov I.B. Calculation of seismic resistance of various structures using the grid-characteristic method. *RENSIT*, 2019, 11(3):345-350; DOI: 10.17725/rensit.2019.11.345.

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1. INTRODUCTION

Nowadays the study of earthquake resistance is carried out using high-quality computer

modeling. The finite element method is mainly used [1-3] for this in up-to-date software. For simulation the propagation of seismic waves through the geological rock, finite-difference methods might be used [4].

The grid-characteristic method was proposed in [5]. Recently, new modifications of this method [6] and the corresponding computational algorithms for high-performance

computer systems [7] are being developed. The grid-characteristic method has been successfully applied to solve direct [8-10] and inverse [11] seismic prospecting problems. The grid-characteristic method was also applied to investigate the seismic stability of high-rise buildings [12,13], seismic isolation [14], composite oil pipelines [15], and nuclear power plants [16].

2. MODELS AND METHODS

To describe the behavior of the simulated materials and water under intense seismic influences, the boundary-value problem of elastic wave equation:

$$\rho \frac{\partial}{\partial t} \mathbf{v}(\mathbf{r}, t) = (\nabla \boldsymbol{\sigma}(\mathbf{r}, t))^T, \quad (1)$$

$$\begin{aligned} \frac{\partial}{\partial t} \boldsymbol{\sigma}(\mathbf{r}, t) = & (\rho c_p^2 - 2\rho c_s^2)(\nabla \cdot \mathbf{v}(\mathbf{r}, t))\mathbf{I} + \\ & + \rho c_s^2 (\nabla \otimes \mathbf{v}(\mathbf{r}, t) + (\nabla \otimes \mathbf{v}(\mathbf{r}, t))^T). \end{aligned} \quad (2)$$

and acoustic wave equation:

$$\rho \frac{\partial}{\partial t} \mathbf{v}(\mathbf{r}, t) = -\nabla p(\mathbf{r}, t), \quad (3)$$

$$\frac{\partial}{\partial t} p(\mathbf{r}, t) = -\rho c^2 (\nabla \cdot \mathbf{v}(\mathbf{r}, t)). \quad (4)$$

is solved jointly.

Hereinafter, $\mathbf{v}$ is the vector field of the local velocity of the medium (displacement derivative on time), $\boldsymbol{\sigma}$ is the tensor field of the symmetric second-order Cauchy stress tensor, p is the scalar field of pressure in the acoustic medium, ρ is the density, c_p , c_s are the longitudinal (P-) and transverse (S-) waves speeds in an elastic medium and the speed of sound in an acoustic medium, respectively, ∇ is the gradient vector, $\mathbf{I}$ is the unit tensor of the second rank, $\otimes$ is the symbol of the tensor product of vectors, $\cdot$.

The condition of the free boundary was set at the boundaries with air, having the following forms for systems (1), (2) and (3), (4), respectively:

$$\boldsymbol{\sigma} \cdot \mathbf{m} = 0, \quad (5)$$

$$p = 0.$$

In expression (5), $\mathbf{m}$ is the external unit normal to the boundary.

At the contact boundaries between subdomains with structured and unstructured computational grids and subdomains with various parameters of the media, the contact condition of complete adhesion was used for system (1), (2):

$$\boldsymbol{\sigma}_1 \cdot \mathbf{m} = \boldsymbol{\sigma}_2 \cdot \mathbf{m}, \quad (6)$$

$$\mathbf{v}_1 = \mathbf{v}_2, \quad (7)$$

and system (3), (4):

$$p_1 = p_2, \quad (8)$$

$$\mathbf{v}_1 \cdot \mathbf{m} = \mathbf{v}_2 \cdot \mathbf{m}. \quad (9)$$

In expressions (6)-(9) $\mathbf{m}$ is the external unit normal to the boundary of the body 1; the indices 1 and 2 correspond to different contacting bodies.

At the contact boundaries between elastic and acoustic media, the following condition was used:

$$p = -(\boldsymbol{\sigma} \cdot \mathbf{m}) \cdot \mathbf{m}, \quad (10)$$

$$\boldsymbol{\sigma} \cdot \mathbf{m} - ((\boldsymbol{\sigma} \cdot \mathbf{m}) \cdot \mathbf{m})\mathbf{m} = 0, \quad (11)$$

$$\mathbf{v}_A \cdot \mathbf{m} = \mathbf{v}_E \cdot \mathbf{m}. \quad (12)$$

In expressions (10)-(12), $\mathbf{m}$ is the external unit normal to the boundary of the elastic body; the indices E and A correspond to elastic and acoustic bodies.

To obtain numerically solution the systems of equations (1), (2) and (3), (4), the grid-characteristic method was used, which was described in detail in works [17, 18]. The Rusanov scheme was used [19]. For this, the system of equations is written in the following form:

$$\frac{\partial}{\partial t} \mathbf{q} + \mathbf{A}_1 \frac{\partial}{\partial \xi_1} \mathbf{q} + \mathbf{A}_2 \frac{\partial}{\partial \xi_2} \mathbf{q} + \mathbf{A}_3 \frac{\partial}{\partial \xi_3} \mathbf{q} = 0.$$

Here $\mathbf{q}$ is the vector of unknowns composed of components of $\mathbf{v}$ and p for system (1), (2) and

composed of components of $\mathbf{n}_j$ and $\mathbf{c}_j$ for system (3), (4). The directions of the coordinate system $\mathbf{n}_j$ either coincide with the coordinate axes $\mathbf{c}_j$ when using structured computational grid, or locally in each cell coincide with the axes of a curved computational grid. In this case, one can enter a vector $\mathbf{n}_j$ along the direction under consideration :

$$\mathbf{n}_j = \nabla \xi_j(x, y, z).$$

The eigenvalues of each of the matrices will run through the following sets of values for systems (1), (2) and (3), (4), respectively:

$$\{|\mathbf{n}_j|c_P, -|\mathbf{n}_j|c_P, |\mathbf{n}_j|c_S, -|\mathbf{n}_j|c_S, 0\}, \tag{13}$$

$$\{|\mathbf{n}_j|c, -|\mathbf{n}_j|c, 0\}. \tag{14}$$

The use of curved computational grids requires not only large computational resources, but may also require a decrease in the time step to ensure the stability of the method due to the effective growth of wave propagation speeds in accordance with expressions (13), (14).

Models of structures and the host geological massif were used with the following elastic and acoustic parameters shown in **Table 1**.

The integration steps in time and coordinates were varied for different calculations and for different subregions in one calculation in accordance with **Table 2**. A seismic wave, longitudinal or transverse, with a wavelength of 50 m was set at an angle of 15° to the Earth's surface. The maximum amplitudes of these waves for various calculations are also given in Table 2.

Table 1
Elastic and acoustic parameters of simulated media.

Material	P-wave speed, m/s	S-wave speed, m/s	Density, kg/m³
Concrete	4250	2125	2300
Geological rock	2300	1400	2500
Ground under riverbed	2200	400	2400
Water	1500	-	1000

Table 2
Computational parameters.

Computation	Maximal coordinate step, m	Minimal coordinate step, m	Time step, mks	Total time, s	Maximal value of v in P-wave/ S-wave, m/s
Building	0.05	0.025	5.875	0.47	0.24/0.25
Dam	0.5	0.07576	30	1.0	0.375/1.0
Station	0.04	0.02	4.7	0.141	0.1/0.1
Foot-bridge	0.02	0.02	4.7	0.47	0.25/0.25

The total time was selected in such a way that after the propagation of the wave under consideration, new damage would no longer be formed.

An example of using separate computational grids to describe the complex geometry of the computational domain is shown in **Fig. 1** on the example of the hall of the metro station. Note that fragments of computational grids at the edges of the figure are shown. The used integration steps on coordinates in different calculation grids for this calculation are presented in **Table 3**.

Fig. 1. Separate computational grids: metro station.

Table 3
Steps of separate computational grids: metro station.

Grids numbers	1, 3, 13, 15	4, 10	2, 14	5, 6, 7, 8, 9, 11, 12
Step along OX, m	0.04	0.04	0.02	0.02
Step along OY, m	0.04	0.02	0.04	0.02
Material	Geological rock	Geological rock	Geological rock	Concrete

Fig. 2. Multi-story residential building.

To simulate the destruction of materials, the criterion for the main stress was used. Concrete with a strength of 1 MPa was considered. In this case, the bearing walls of the footbridge and the columns of the metro station were considered reinforced with a strength of 2.5 MPa. When modeling the dam, soil with a strength of 3 MPa was considered.

3. RESULTS AND DISCUSSION

In **Figs. 2-5** the earthquake resistance calculations of a multi-story residential building, an earth dam of a hydroelectric power station, a metro station, and a footbridge under roadway are shown respectively. A dam with a height of 56 m and a base area of 66 m was considered. The metro station was located at a depth of 25 m.

Fig. 3. Dam of hydroelectric power station.

Table 4

Time moments in wave patterns presented in the paper.

Compu- tation	Building		Dam		Station		Footbridge	
	P- wa- ve	S- wa- ve	P- wa- ve	S- wa- ve	P- wa- ve	S- wa- ve	P- wa- ve	S- wa- ve
Time mo- ment, ms	94	141	43.33	224.1	21.15	35.25	28.2	25.85
Figure number	Fig. 2a	Fig. 2b	Fig. 3a	Fig 3b	Fig. 4a	Fig. 4b	Fig. 5a	Fig. 5b

Figs. 2a, 2c, 3a, 3c, 4a, 4c, 5a, and 5c correspond to the action of the P-wave, Figs. 2b, 2d, 3b, 3d, 4b, 4d, 5b, and 5d correspond to the action of the S-wave. The corresponding time moments are presented in **Table 4**. In Figs. 2a, 2b, 3a, 3b, 4a, 4b, 5a, and 5b the wave patterns are shown, in Fig. 2c, 2d, 3c, 3d, 4c, 4d, 5c, and 5d the areas of destruction are shown.

The calculations performed demonstrate the possibility of joint solution of systems (1), (2) and (3), (4) in heterogeneous regions of complex shape and the subsequent determination of the weaknesses of the structures under consideration depending on the type of seismic impact.

4. CONCLUSION

The grid-characteristic method on structured and combined structured and curved grids allows to successfully calculate the localization of the damaged areas of complex objects: multi-story buildings, metro stations, footbridges, hydroelectric power stations dams. The main features of this modification of the

Fig. 4. Metro station.

Fig. 5. Footbridge over a roadway.

grid-characteristic methods are described in the paper. Particular attention is paid to the use of separate computational grids to describe the complex geometry of the computational domain and to vary the step along the coordinate axes. Test calculations of seismic resistance of various structures were carried out. The use of combined structured regular and curved grids allows to save computing resources and to use more detailed computational grids and models of the structures under consideration. It is shown that the grid-characteristic method allows highly accurate calculation of elastic and acoustic wave processes in heterogeneous objects of complex shape.

ACKNOWLEDGMENTS

This work has been performed at Moscow Institute of Physics and Technology and supported by the Russian Science Foundation, grant no. 17-71-20088.

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