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Influence of Natural Disasters on Ground Facilities

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Abstract—The purpose of this article is to study the problem of the propagation of waves that result in earthquakes in different geological media: homogeneous, multilayer, gradient, with fractured layer, and karst cavern. The authors pose the problem of analyzing the impact of waves on ground structures: buildings and dams. Numerical solutions of problems of wave propagation in heterogeneous media are obtained. On the basis of the analysis of wave patterns, the types of waves propagated from the focus of the earthquake are qualified. The comparison of the impact of elastic waves on the day surface for the cases of different geological media is done. Synthetic seismograms for these media are obtained. The influence of elastic waves on the stability of ground structures is qualitatively examined. The grid-characteristic method for triangle meshes with the formulation of boundary conditions on interfaces of rock–crack, building–rock, rock–water, and dam–water, as well as free surfaces in an explicit form, is used in this paper.

Keywords: computational methods, computer science, mathematical modeling, parallel computing, continuum mechanics, safety of buildings.

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1. INTRODUCTION

All the geological media are usually substantially heterogeneous and gradient. The heterogeneity of such media is caused by the presence of interfaces (probably numerous), reservoirs, karst units, cracks, and systems of cracks. To solve the problems of continuous media mechanics, stated in such media, all these peculiarities of a geological medium must be described either in terms of averaged models, or via mathematically correct distinguishing of all (or a part of) heterogeneities, for example, with the help of the analytical solution of the contact discontinuity problem on the interfaces between media. It should be taken into consideration that in order to achieve the correct numerical solution of problems of elastic wave propagation (such problems are reduced to a dynamical hyperbolic system of equations in particular derivatives, namely, equations of elasticity theory and those of acoustics) the approach that corresponds to the character of such problems must be chosen or developed.

It is known that the methods, which can describe complex wave processes in substantially heterogeneous media in the most adequate way, must take the characteristic properties of the corresponding system of equations of continuous media mechanics into consideration. The hybrid grid-characteristic method [1] for numerical solution of problems in terms of deformed solid body mechanics had been developed for these purposes; this method is able to take the mentioned peculiarities of heterogeneous geological media into consideration. It enables us to construct the correct algorithms on the contact boundaries and on the boundaries of the integration domain; to take into consideration, to a certain degree, the physical conditions of a problem (propagation of discontinuities along characteristic surfaces); and it possesses the property of monotonicity that is important for the discussed problems.

In the present work, this approach is utilized as well. We study the propagation of elastic waves that originated when an earthquake occurred in geological media with a complex structure. The influence of elastic waves on the rigidity of ground facilities is analyzed.

2. PROBLEM STATEMENT

In the present work, we used the slip along a fault as an initial disturbance for modeling the earthquake focus [2, 3] (Fig. 1): the geometry of the initial disturbance domain is a rectangle of 500×40 m in size, the initial velocity of the medium is 10 cm/s. The source of initial disturbance was located at a depth of 1500 m in the center of the computational domain. The total width of the integration domain is 5000 m and its depth is 4000 m. On the surface, a sequence of 41 seismic receivers was placed; its center coincided with

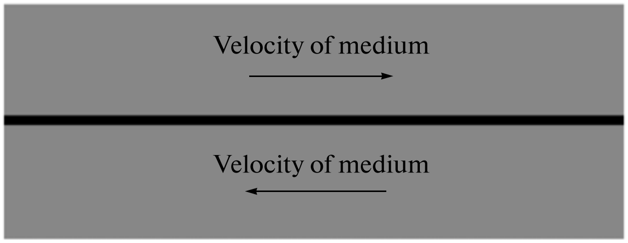

Fig. 1. Slip along a fault.

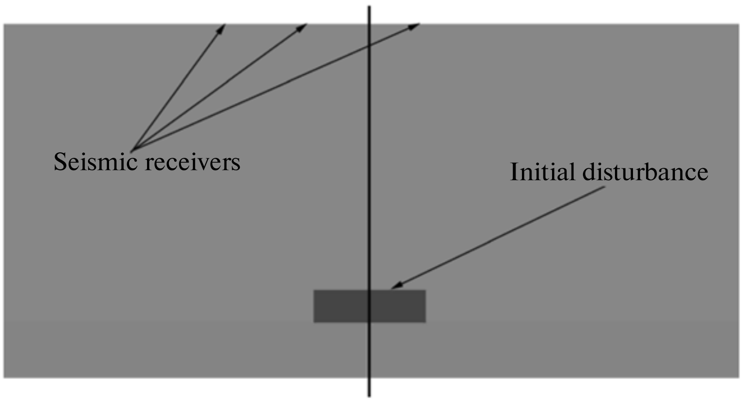

Fig. 2. Statement of the problem.

the earthquake's epicenter and the distance between instruments was 100 m. Figure 2 presents the general scheme of the numerical experiment.

3. MATHEMATICAL MODEL AND NUMERICAL METHOD FOR THE PROBLEM SOLUTION

For the mathematical simulation of wave processes in a solid deformed body, we used the system of dynamic equations that unites equations of motion and rheological correlations in the form [4, 5]

$$\rho \cdot \dot{v}_i = \nabla_j \cdot \sigma_{ij},$$

$$\dot{\sigma}_{ij} = q_{ijkl} \cdot \varepsilon_{kl} + F_{ij}.$$

Here, ρ is the density of a medium; ν_i are the components of displacement speed; σ_{ij} and ε_{kl} are the components of the stress tensor and strain tensor, respectively; ∇_j is the covariant derivative on the jth coordinate; and F_{ij} is the additional right term.

The form of fourth-order tensor q_{ijkl} is determined by a medium's rheology [6]. In the case of a linear-elastic body

$$q_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}).$$

The second group of equations is Hooke's law differentiated in time:

$$\dot{\sigma}_{ij} = \lambda(\dot{\varepsilon}_{11} + \dot{\varepsilon}_{22} + \dot{\varepsilon}_{33})\delta_{ij} + 2\mu\dot{\varepsilon}_{ij}.$$

where λ and μ are the Lame parameters and δ_{ij} is the Kronecker delta.

For the numerical solution of dynamical equations from the mechanics of a solid deformed body, we used the grid-characteristic method [7].

4. THE RESULTS OF NUMERICAL SOLUTION

4.1. Gradient geological medium. We performed simulation for the medium whose characteristic are presented in Fig. 3 (on the left-hand side). The data correspond to the model of the Terek-Caspian trough by Sanina [8]. The density of the medium is assumed to be 2500 kg/m^3. It has been found through the analysis of wave patterns that four waves travel towards the surface, namely, two longitudinal and two shear ones, and the latter have an amplitude higher than the former. The wave pattern is presented in Fig. 3 (on the right-hand side).

4.2. Geological medium with a karst unit. We performed the simulation for the case of a near-surface karst cavern in the homogeneous medium. The karst object was modeled as a rectangular cavern of 80 × 50 m in size with the center at 125 m depth. The characteristics of the enclosing medium are the following: longitudinal wave velocity is 5100 m/s, shear wave velocity is 3400 m/s, and density is 2500 kg/m^3.

In the wave pattern (Fig. 4), the difraction of the incident wave at a karst object is seen, as well as the waves reflected from the day surface.

On the basis of readings from seismic receivers, the comparison was made for surface responses to the initial disturbance for a homogeneous medium in the presence and absence of a karst object. The parameters of a homogeneous medium were chosen to be the same as in the current section. The seismograms are given in Fig. 5: the case of the absence of a karst object is shown on the left and the case when it is present is shown on the right. It is seen that the diffraction of the incident wave at karst objects, as well as repeated reflections from the object's upper boundary, qualitatively and quantitatively influence on the response at the day surface.

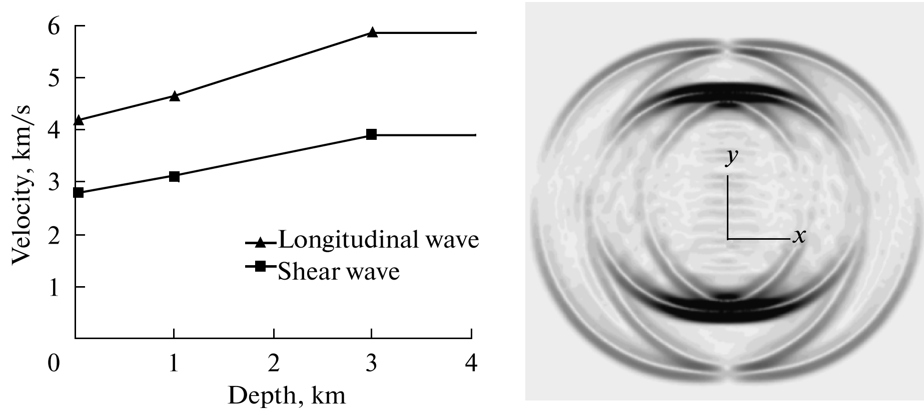

Fig. 3. The model by Sanina (left) and the results of simulation (right).

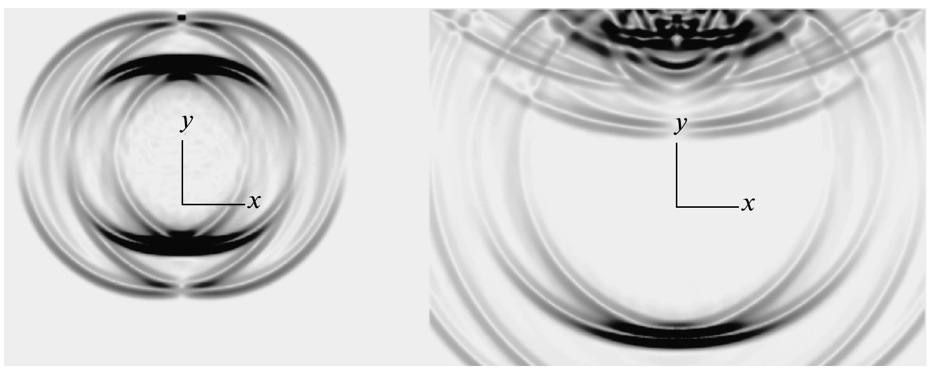

Fig. 4. The medium with a karst object prior to (left) and after (right) wave travel.

4.3. Layered geological medium. When a wave travels through the interfaces between media possessing different characteristics, a reflected wave appears in addition to the travelling one. The simulation was made for a medium consisting of four layers possessing substantially different characteristics (see table).

In the seismogram given in Fig. 6, waves reflected from every interface are clearly seen. The times of their arrival at the epicenter are approximately 0.68, 0.95, and 1.25 s. The readings of receivers in the proximity of the epicenter at the moment of arrival of the reflected waves are marked with ovals.

4.4. Cracked geological medium. The influence of cracks on waves travelling in a geological medium was also studied. The characteristics of the enclosing medium are the following: the longitudinal wave velocity is 5100 m/s, shear wave velocity is 3400 m/s, and density is 2500 kg/m^3.

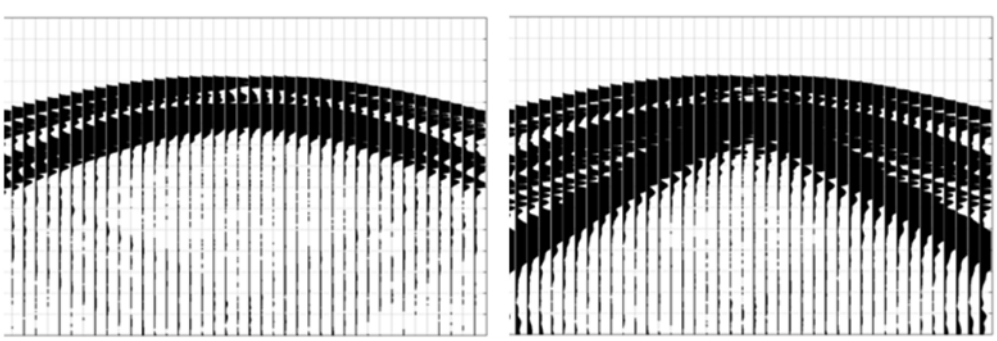

Fig. 5. The influence of presence (right) and absence (left) of near-surface karst object.

Table

Layer	Thickness, m	Density, kg/m^3	V_P, m/s	V_S, m/s
1	300	2500	4190	2793
2	400	2500	4650	3100
3	500	2500	5250	3500
4	2800	2500	5850	3900

At a depth of 750 m, a fractured reservoir with nonfilled vertical cracks was located; it covered the whole calculated volume in the horizontal direction. The height of the cracks is 100 m and the distance between the adjacent cracks is 100 m. According to the wave patterns given in Fig. 7, when an incident wave travels through a series of vertical cracks, a reflected wave appears; therefore, a weakening of the travelling wave takes place.

4.5. Influence on a building. The study of the influence on ground facilities made by elastic waves produced by an earthquake is of special importance. The influence of a longitudinal wave of 90 cm/s in amplitude on a concrete building was calculated (Fig. 8). The windows are rectangles of 1.5×2 m in size and the door is a rectangle of 1×2 m in size. The horizontal distance between the windows of the upper floor is 1 m and that between the door and the window on the lower floor is 1.5 m. The basement of the building is 1 m thick. The following properties of concrete were set: longitudinal wave velocity is 4000 m/s, shear wave velocity is 2500 m/s, and density is 2500 kg/m^3. The enclosing massif was modeled as an elastic medium: longitudinal wave velocity is 5100 m/s, shear wave velocity is 3400 m/s, and density is 2000 kg/m^3. Figure 9 presents the wave pattern at consecutive time moments. Due to reflections from the free surfaces of windows, a complex superposition of longitudinal and shear waves is observed.

4.6. The influence of an earthquake on a dam. The problem of the influence of a near-surface earthquake on a dam situated in the epicenter was calculated. The initial disturbance was set as a slip along the fault at a depth of 200 m, with the plane oriented at 6 degrees relative to the horizon. The value of the slip was 90 cm/s. The enclosing massif was modeled as an elastic medium with the following parameters: longitudinal wave velocity is 5100 m/s, shear wave velocity is 3400 m/s, and density is 2000 kg/m^3. The geometry of the dam is the following: rectangular trapezium of 60 m in height, with bases of 40 and 25 m. The material of the dam possesses the following properties: density is 2000 kg/m^3, longitudinal wave velocity is 4000 m/s, shear wave velocity is 2500 m/s. Water was modeled in the approach of an elastic body with a small velocity of shear waves; the following elastic properties were chosen: density was 1000 kg/m^3, longitudinal wave velocity was 1348 m/s, and shear wave velocity was 10 m/s. Water rises by a height of 20 m on the rectangular side, and by 40 m on the sloped side. First, a longitudinal wave arrives from the earthquake hypocenter (Fig. 10, left-hand side) and travels through both the material of the dam and water. A more powerful shear wave (Fig. 10, right-hand side) follows the longitudinal one; it poorly penetrates in the water, but causes high shear stresses in the dam, which leads to its destruction.

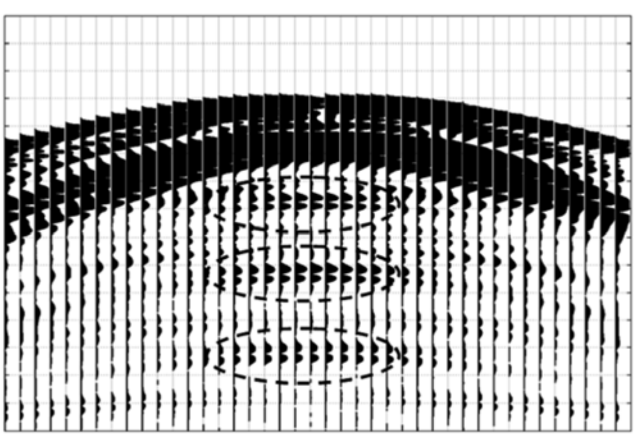

Fig. 6. Reflections from the interfaces between layers.

4.7. Influence on a surface dome construction. We calculated a problem of the influence of a shear wave of 10 cm/s in amplitude on a dome construction located on the ground surface. The elastic characteristics of the material composing the central element of the construction corresponded to those of stainless steel. Density was 7700 kg/m^3; longitudinal wave velocity was 5740 m/s; and shear wave velocity was 3092 m/s. The enclosing massif which modeled the Earth's crust possessed a density of 2000 kg/m^3; longitudinal wave velocity 5100 m/s; and shear wave velocity 3400 m/s. Figure 11 presents the wave pattern of waves travelling within the construction at consecutive time moments. Reflecting from the free boundaries of the building and interfering elastic waves propagate towards the central element of the construction. In addition to the travelling waves, in Fig. 11, one can

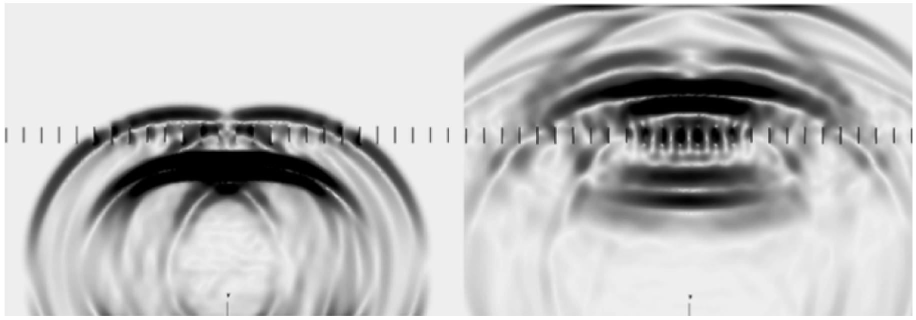

Fig. 7. Travel of waves through the series of vertical cracks.

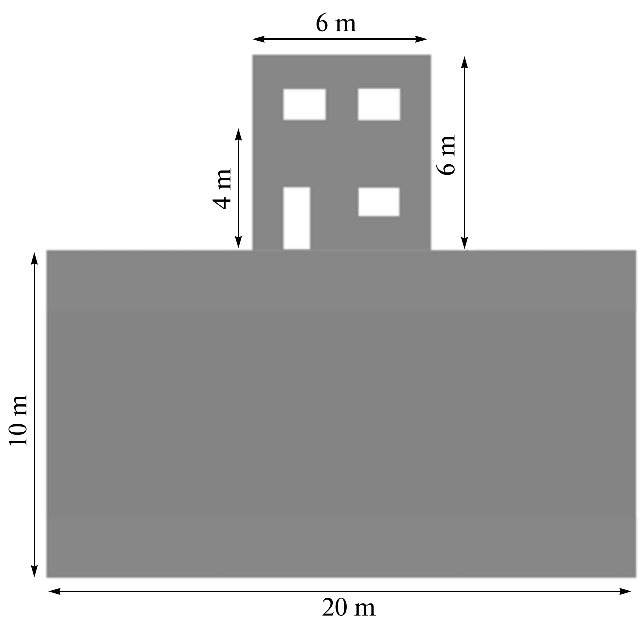

Fig. 8. The geometry of the building and the part of the enclosing massif where the initial disturbance is set.

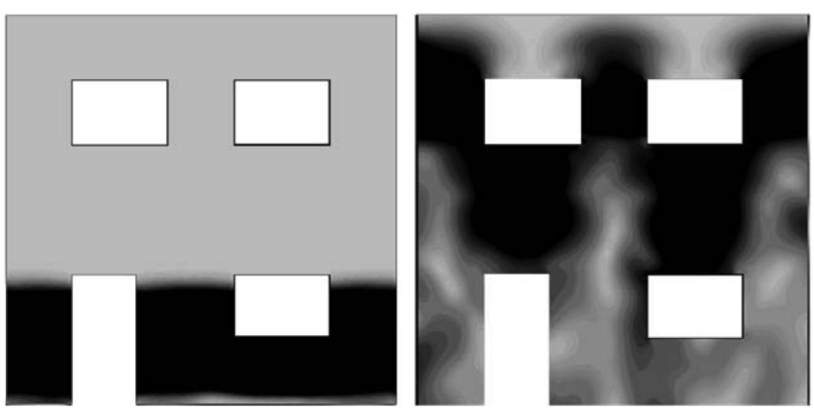

Fig. 9. Elastic waves travelling within the building at time moments of 0.0011 s (left) and 0.0021 s (right).

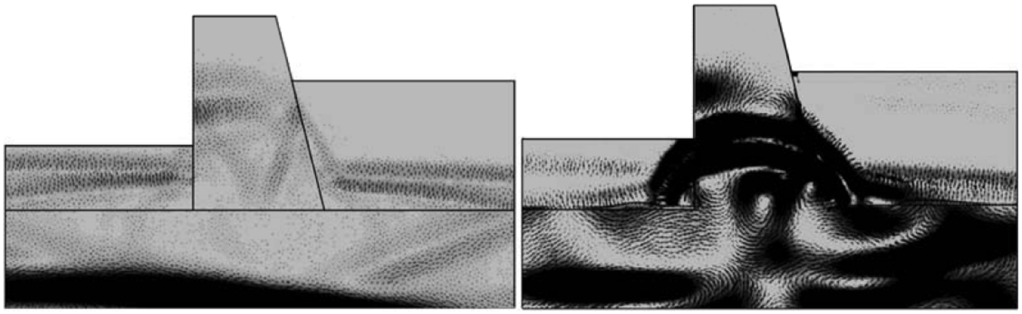

Fig. 10. Wave patterns of elastic waves' travelling within the dam. Arrivals of longitudinal (left) and shear (right) waves.

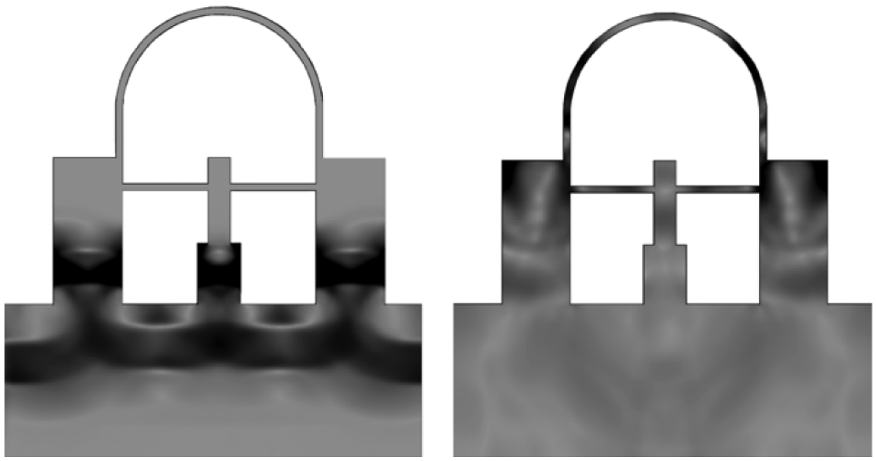

Fig. 11. Wave patterns of elastic waves travelling within the surface dome construction at time moments of 0.01 s (left) and 0.028 s (right).

also see the waves reflected from the free ground surface.

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