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ANALYSIS OF SEISMIC WAVES EXCITED IN NEAR-SURFACE SOILS BY MEANS OF THE ELECTROMAGNETIC PULSE SOURCE "YENISEI"

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Abstract. The northern territories of Eastern Siberia are characterized by a permafrost-taiga structure of the surface layer of soil, which reduces the efficiency of geological exploration using seismic sources of explosive and vibratory types. Therefore, Geotech Holding Company developed a special eco-friendly electromagnetic pulse source "Yenisei", which seismic waves are the subject of analysis using high-performance computing in this paper. Computational technology, worked out previously for solving the problems of the dynamics of viscoelastic, elastic-plastic, granular and porous media, is applied to the analysis of wave motion of a soil near a point of perturbations. It is shown that the main frequency of generated strain waves substantially depends on the elastic characteristics of a soil in the near-surface zone. A comparison of the results of computations obtained in the framework of the model of static loading with instant unloading and the model taking into account the monotone loading stage with subsequent pressure relief showed the validity of the hypothesis about the presence of added mass of a soil under the loading platform. This mass accumulates impact energy and emits seismic waves due to oscillatory motion.

Keywords: blocky-layered geomedium, electromagnetic pulse source, seismic oscillations, elastic waves, parallel computational algorithm, supercomputer modeling

1. Introduction

Electromagnetic source of seismic oscillations "Yenisei" is a non-explosive surface pulse seismic source with an electromagnetic actuator that contains one, two or four short-stroke electromagnets, working synchronously, with an autonomous power supply system from a capacitive storage of electric energy and a device for charging and discharging. The source exists in wheeled, sledge, mobile and water variants (see Fig. 1). "Yenisei" is quite competitive in comparison with sources of explosive and vibratory types by efficiency and quality of exploration works, and it has undeniable advantages in the economical and environmental aspects. The use of this source is incomparably cheaper, and it is almost the only possible means when working near buildings and constructions, in water protection zones and in areas with a lot of rivers and lakes. It is also applied on ice coverings of reservoirs, in shallow waters and on offshore.

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Fig. 1. Seismic sources of the "Yenisei" series:
http://gseis.ru/our-business/field-seismic-works/impulse-technique/

In the process of creation, modification and improvement of operational and technical characteristics, the electromagnetic pulse source "Yenisei" was subjected to careful experimental analysis and testing [1,2]. In the present work, computational technology is used, the ultimate goal of which is detailed mathematical modeling of wave fields excited by the "Yenisei" source in blocky-layered geomaterials with different mechanical characteristics of blocks (clay soils, granular, porous and fluid-saturated media). The results of modeling will be used to optimize regimes of functioning the source during seismic surveys.

2. Mathematical model

Computational technologies for analysis of seismic waves in blocky soil massifs, based on the equations of the dynamics of an elastic medium, were developed in [3–5]. Viscous properties of a soil were taken into account in [6–8]. More complex equations accounting irreversible plastic shear, blocks rotation and friction under slipping of blocks relative to each other were used to the modeling of wave motion by the authors of [9,10].

We worked out new mathematical models and numerical algorithms for rheologically complex media – elastic-plastic granular and porous media, taking into account different resistance of materials to tension and compression, [11–13]. Equations of the Cosserat continuum describing wave motion of structurally inhomogeneous media, in which along with translational degrees of freedom, independent rotations of the material particles are taking into account, were also realized numerically [14]. The processes of wave propagation in a medium consisting of a large number of blocks interacting through compliant interlayers were analyzed in [15].

Constitutive relationships of geomaterials, described by the complex rheological models, are constructed on the basis of the generalized rheological method [12,15]. Using only conventional rheological elements – a spring simulating elastic properties of a material, a plastic hinge and a viscous damper, it is impossible to construct the rheological scheme for a medium with different resistance to tension and compression. To make it possible, we supplement the rheological method by a new element, called "rigid contact". It is represented schematically as two horizontal parallel plates in Fig. 2. Combining rigid contact with elastic, plastic and viscous elements, one can construct rheological models of different complexity taking into account features of the deformation process.

As a simplest version, we consider the model of an ideal granular medium with elastic particles, whose rheological scheme under uniaxial tension–compression is shown in Fig. 2a. It describes usual elastic material under compression, which has no resistance in tension. The scheme in Fig. 2b imitates the behaviour of a bimodular elastic medium, differently resisting in tension and compression. It should be noted that a rigid contact, using in the given approach to take into account different compression and tension strength properties of the material and being in fact a nonlinearly elastic element, describes a thermodynamically reversible process. Irreversible deformation, which results in dissipation of mechanical energy, can be taken into account only when viscous or plastic elements are involved into the rheological scheme. Figure 2c shows the rheological scheme of a porous material taking into account plastic properties. The distance between plates of the rigid contact in this scheme associates with the initial porosity ε_0. Under tensile stress σ_s^+, the material goes into the state of yielding flow, and under compressive stress $-\sigma_s^-$, a loss of stability and plastic flow of the porous skeleton begins.

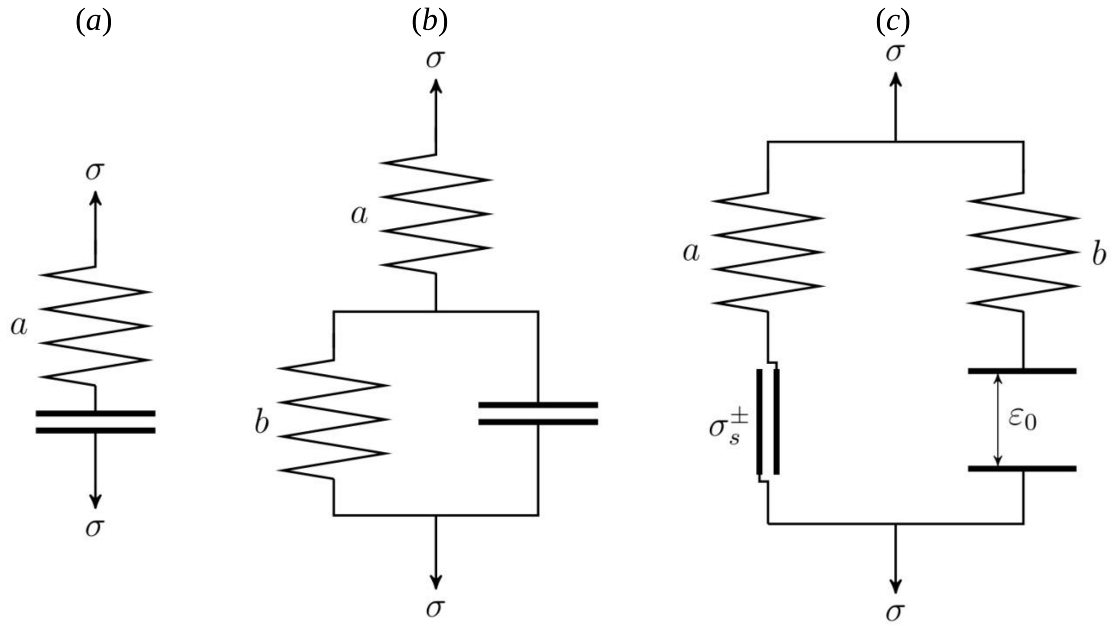

Fig. 2. Rheological schemes of an elastic granular material (*a*), a heteromodular elastic material (*b*), an elastic-plastic porous material (*c*)

Let's consider a 3D dynamic problem for layered or blocky medium. It is assumed that the structure of a medium is known and represented by a set of heterogeneous blocks with curvilinear boundaries. Each block is characterized by its homogeneous material with corresponding governing equations. In the simplest case of an elastic block, a system of equations of the linear dynamic elasticity, written in terms of the velocity vector v and the stress tensor σ, is fulfilled:

$$\rho \frac{\partial v}{\partial t} = \nabla \cdot \sigma, \quad \frac{\partial \sigma}{\partial t} = \rho \left(c_p^2 - 2 c_s^2 \right) \left(\nabla \cdot v \right) I + \rho c_s^2 \left(\nabla v + \nabla v^* \right). \tag{1}$$

Here ρ is the density, c_p and c_s are the velocities of longitudinal and transverse elastic waves, ∇ is the gradient over spatial coordinates, I is the unit tensor. Asterisk denotes a conjugate tensor, conventional notations of tensor analysis are used. In computations of the action of a seismic source with one electromagnet on a plane-layered medium, the equations of axisymmetric motion, written relative to the cylindrical coordinate system, were used instead of 3D equations.

In a more complex case of a porous medium, according to the rheological scheme in Fig. 2c, the tensor of total stresses is represented as a sum of the tensor of stresses in a skeleton and the tensor of additional stresses induced by the pore collapse. Elastic compliance of a material is characterized by the fourth-rank tensors a and b, satisfying the conditions of symmetry and positive definiteness. Constitutive relationships in the form of variational inequality of the von Mises principle of maximal plastic dissipation of energy together with the system of equations of motion and kinematic equations for strain rate tensor compose a closed mathematical model of dynamic deformation of an elastic-plastic porous medium. This model can be represented by means of the following system [13]:

$$\rho \frac{\partial v}{\partial t} = \nabla \cdot \sigma + f, \quad \sigma = s + \pi(q + q_0),$$

$$(\hat{s} - s) : \left(a : \frac{\partial s}{\partial t} - \nabla v \right) \geq 0, \quad s, \hat{s} \in F, \quad b : \frac{\partial q}{\partial t} = \frac{\nabla v + \nabla v^*}{2}, \tag{2}$$

where q is the tensor of trial stresses expressed in terms of the strain tensor ε by the linear Hooke law $b : q = \varepsilon$; q_0 is the stress tensor, such that $b : q_0 = \varepsilon_0$; tensor s characterizes stress state of the skeleton; $\hat{s}$ is an arbitrary element of a convex set F in the stress space bounded by the yield surface; π is the projector onto the set of admissible stresses with respect to the energy norm $|\sigma|^2 = \sigma : b : \sigma$; colon means double convolution of tensor.

Natural geomaterials have a complex blocky-layered structure and may include blocks of granular, porous and fluid-saturated materials. For numerical modeling of the processes of propagation of strain waves in rheologically complex media, we developed computational algorithms and software complexes, oriented to multiprocessor computing systems of cluster architecture.

Under numerical implementation of the models, independent (uncoordinated) computational grids are constructed in the blocks. An algebraic method, consisting in the finding a one-to-one mapping of the computational domain in the form of a unit cube with uniform grid onto the physical domain, is used. The system of equations (1) (or the system (2), or another system of governing relationships in blocks) is solved by means of the splitting method with respect to spatial variables. The splitting with respect to physical processes is used for the solution of variational inequality in (2). It leads to a special procedure of solution correction, similar to the well-known stress correction by Wilkins. The technology of parallelization is based on the method of two-cyclic splitting. In 3D case, it involves six stages: the stage of solution of 1D problem in the x_1 direction on the half-step by time variable, the similar stages in the x_2 and x_3 directions, the stages of recomputation of a problem in the x_3, x_2 and x_1 directions on the second half-step by time. For the solution of 1D systems of equations we apply an explicit monotone finite-difference ENO–scheme of the "predictor–corrector" type with piecewise-linear distributions of velocities and stresses over meshes, based on the principles of Godunov's grid-characteristic methods. The details of numerical algorithm one can find in [12].

The developed method of solution was implemented as a software package in the Fortran language by means of the MPI library. Technology of parallelization is based on the uniform distribution of computational domain between the nodes of a cluster. Verification of the software was performed on exact solutions – formulas of geometric seismics for the hodographs of reflected and refracted waves. Parallel program system was registered in Rospatent [16].

3. Computational results

Preliminary series of computations was fulfilled with the goal of validating the software package by basic parameters of the electromagnetic pulse source – the frequencies and amplitudes of oscillations. Comparison of the numerical results with the available experimental data showed a satisfactory quantitative correspondence.

The problem was solved for a two-layered massif of an elastic medium of $60 \times 40 \times 40$ m^3, in two variants, when the upper 10-meter layer is more compliant and, conversely, more rigid as compared with the lower 50-meter basic layer. To demonstrate the capabilities of the program, the interface between layers was curved, as it is shown in Fig. 3, where the computational domain is distributed uniformly between 96 computational nodes: 16

nodes in the upper layer and 80 nodes in the lower one. Each node of the cluster performs computations in parallel mode. The difference grid in the upper layer of a massif is 50 × 200 × 200 cells, and in the lower layer – 250 × 200 × 200 cells, that is, each cluster node performs computations on a grid of 50 × 50 × 50 cells. For visibility, the difference grid in Fig. 3 is thinned 5 times in each direction.

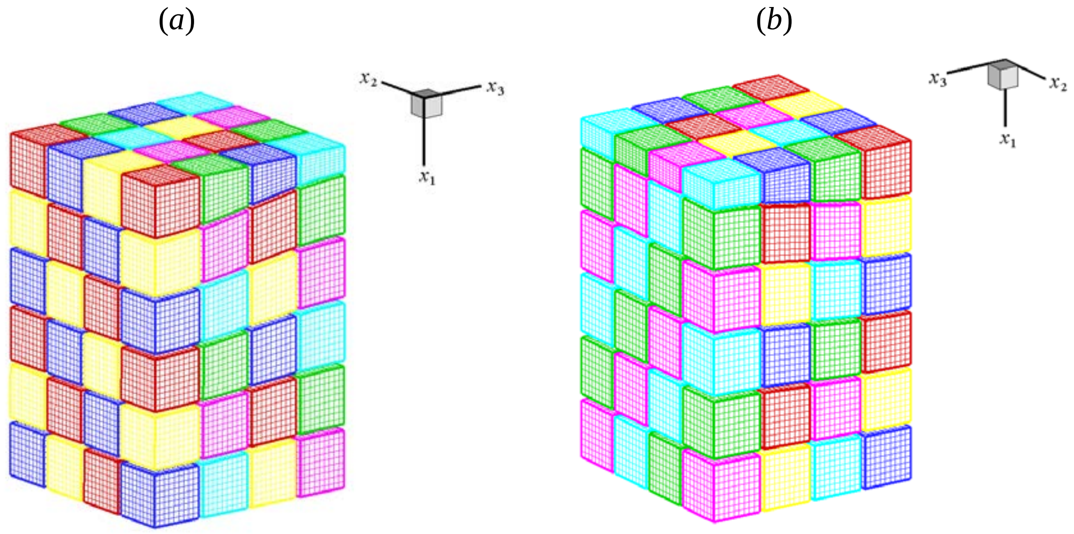

Fig. 3. Two-layered computational domain with curvilinear boundary (views from different sides): Uniform distribution of computational load between 96 cluster nodes

At the upper boundary of computational domain a localized action from the wheel source with four electromagnets is set. Taking into account the symmetry, computations are made for a quarter of the whole massif bounded by vertical coordinate planes. On the left and right boundaries of computational domain (see Fig. 3b) the symmetry conditions are given. The back boundaries and the lower base are considered as non-reflecting surfaces, on which the conditions for passage of waves without appreciable reflection are simulated. At the stages of solving 1D systems of the splitting method, the boundary values of Riemann invariants corresponding to outgoing characteristics are assumed to be zero on these surfaces that is equivalent to the absence of reflected waves in 1D problem. At the internal interfaces, the continuity conditions are set for vectors of velocities and stresses at the contact areas of the blocks. It is assumed that the pulse source acts in a circle of area 1 m^2, which is located at the distance of 2.5 and 1.25 m from the left and right boundaries of symmetry, respectively. A pressure from the source was determined on the basis of experimental measurements of the acceleration of reactive mass of the electromagnet. Densities and velocities of elastic waves in the layers are given in Table 1.

Table 1. Mechanical parameters of materials

Materials	ρ, kg/m^3	c_p, m/s	c_s, m/s
clay	2100	1800	1100
ground	2400	4500	2700
rigid ground	2600	6000	3500

Figure 4 shows the characteristic level surfaces of normal stress in the case of compliant upper layer (Fig. 4a) and in the case of rigid upper layer (Fig. 4b) at different time moments.

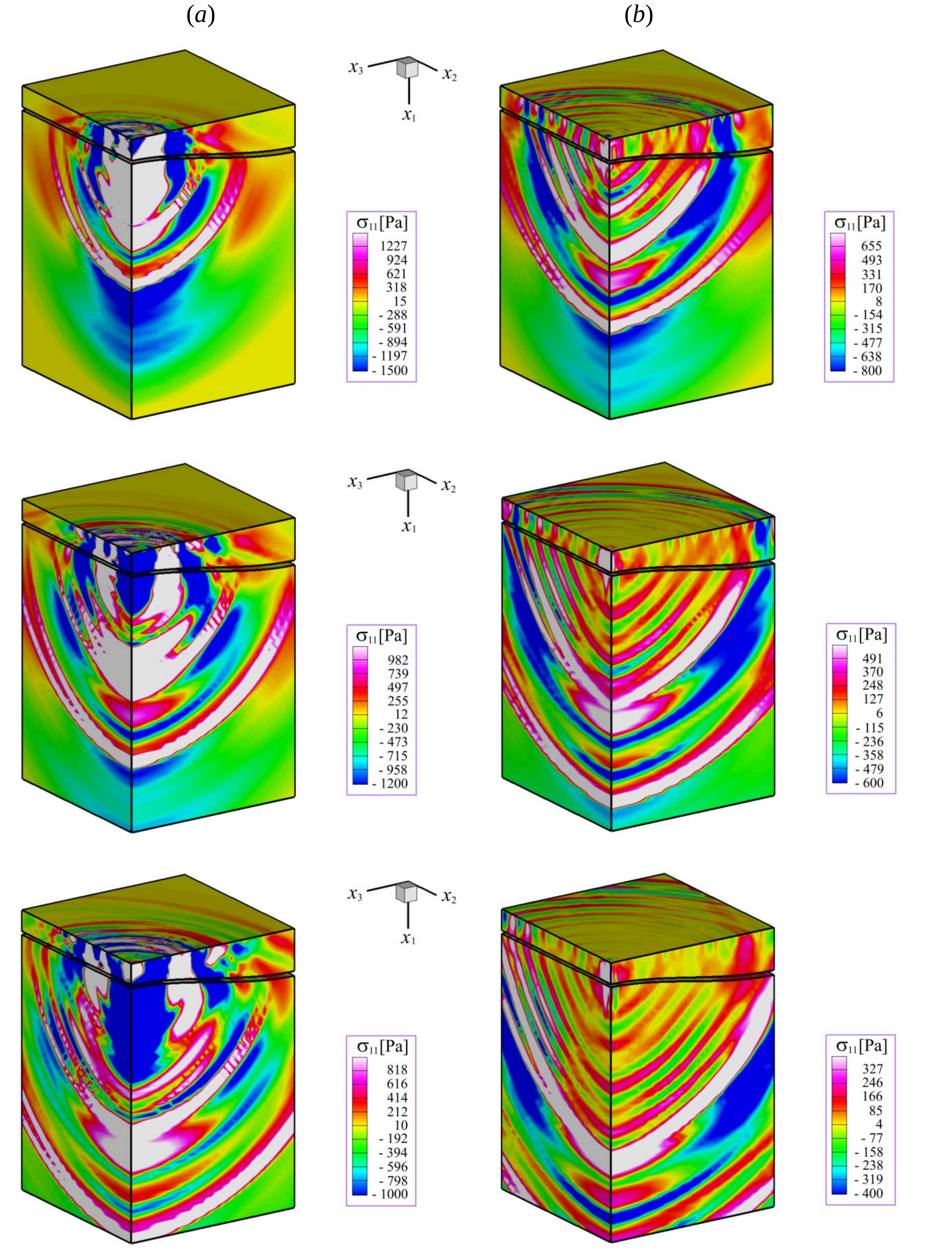

Fig. 4. Level surfaces of the normal stress σ_{11} in the vertical direction; Lower layer is ground, upper layer is clay (*a*) and upper layer is rigid ground (*b*): t = 15, 18 and 21 ms

In Figure 5 one can see seismograms of the acceleration a_1 in the vertical direction x_1 for different materials of the upper layer. Receivers are located along the x_2 axis at the symmetry plane. In Figure 6 seismograms of the acceleration a_2 are represented, when receivers are located along the x_2 axis, at the distance of 3.75 m from the plane of symmetry.

In both Figures, the hodographs of multiple reflected and refracted waves can be seen, the extremums of which are shifted to the zone of localized impact.

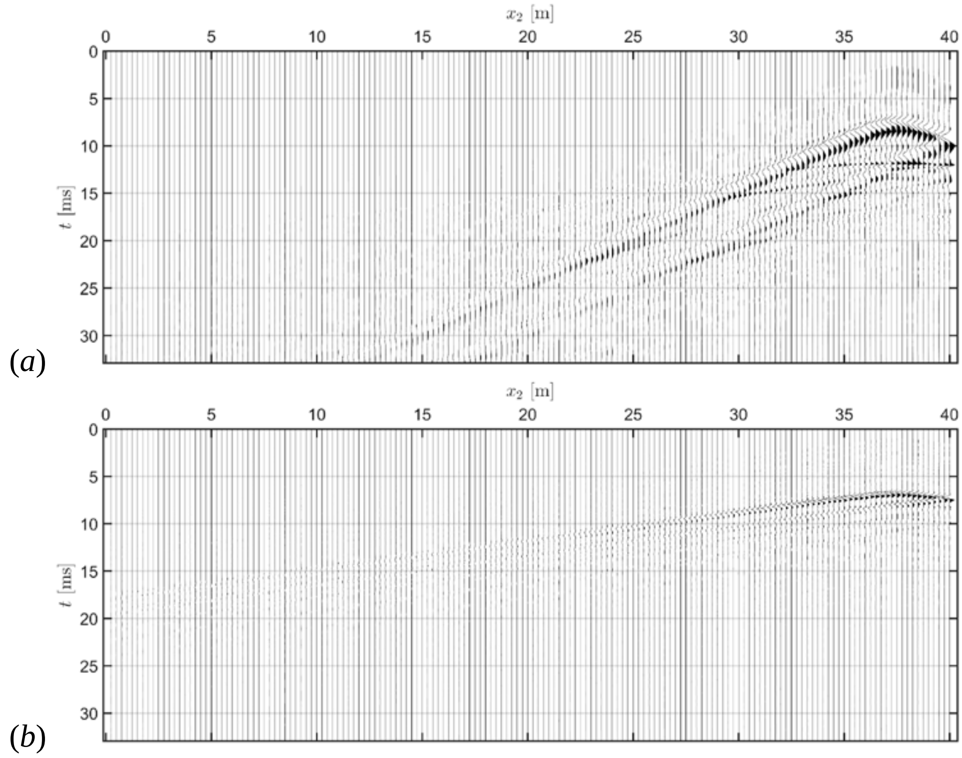

Fig. 5. Seismograms of the acceleration a_1 in the direction x_1:
Lower layer is ground, upper layer is clay (*a*) and upper layer is rigid ground (*b*)

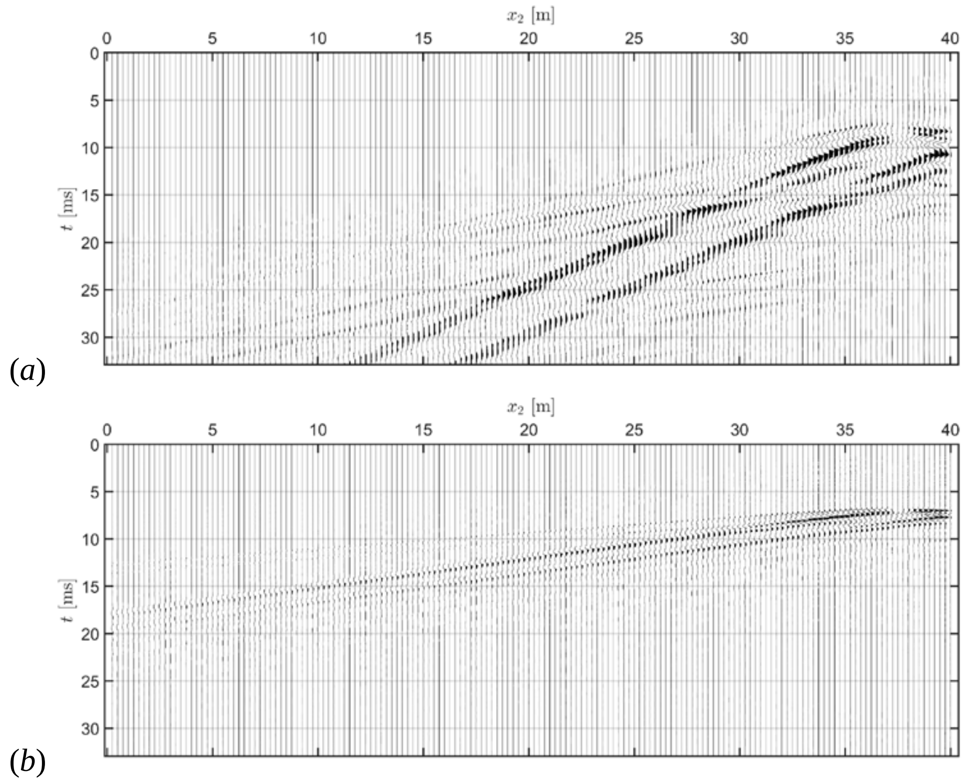

Fig. 6. Seismograms of the acceleration a_2 in the direction x_2:
Lower layer is ground, upper layer is clay (*a*) and upper layer is rigid ground (*b*)

In order to demonstrate practical applicability of the electromagnetic source "Yenisei" in complex geological conditions, similar computations were fulfilled for the surface layer from frozen ground, as well as for the water layer with and without ice cover. The obtained data show stable operation of the source under these conditions.

A large series of computations was performed on the basis of an axisymmetric model for a plane-layered medium with one electromagnet under the assumption that at the stage of monotone loading a static stress state of the soil was formed under the loading platform. Figure 7 shows the fields of level curves of the static stresses σ_{11}, σ_{12}, σ_{22} and the specific elastic energy W in the ground under loading platform. For comparison, in Fig. 8 one can see the results of numerical solution of a dynamic problem with the comparatively short loading time t_0 = 5 ms.

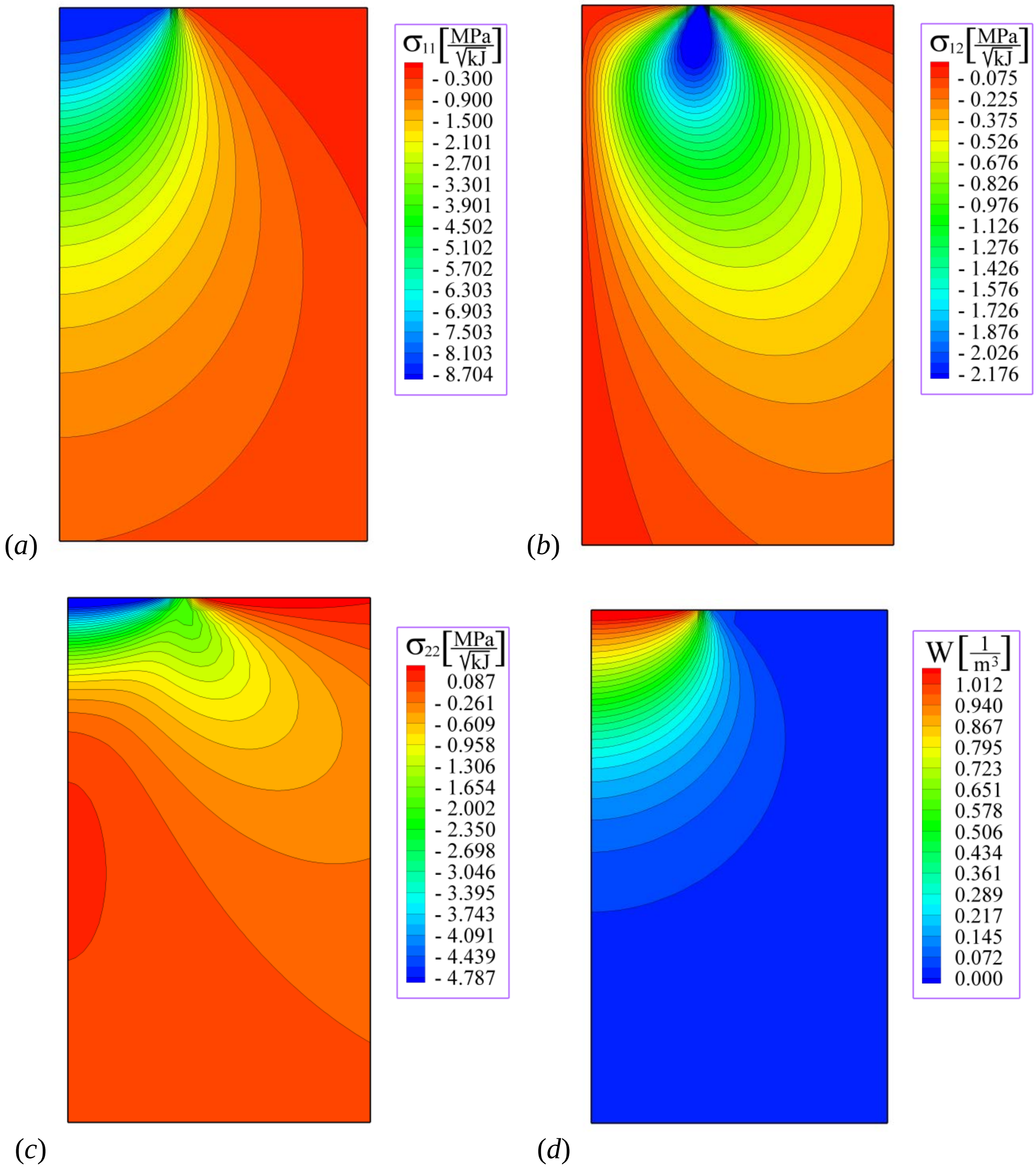

Fig. 7. Level curves of stresses σ_{11} (*a*), σ_{12} (*b*), σ_{22} (*c*) and elastic potential W (*d*) for the static solution

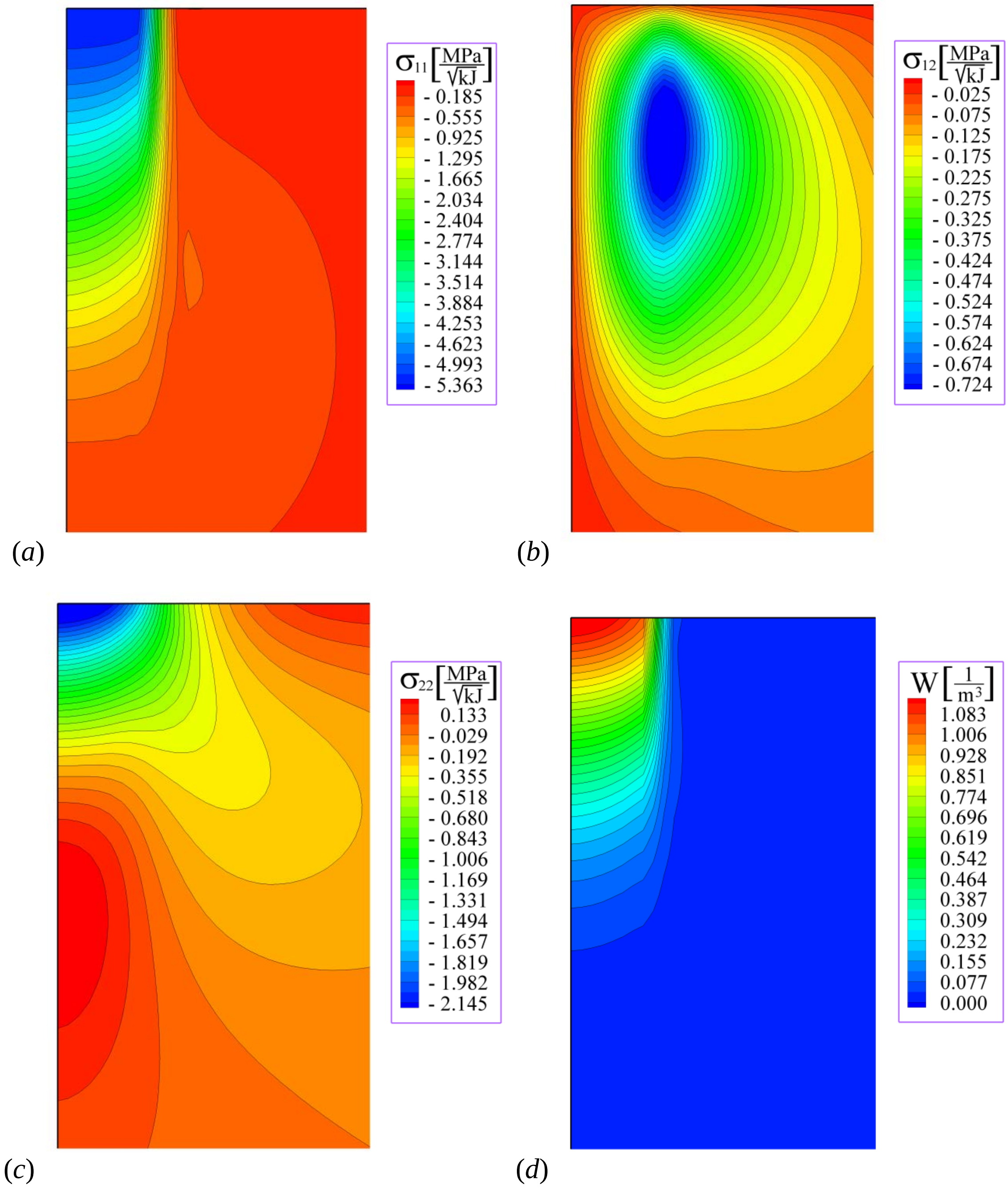

Fig. 8. Level curves of stresses σ_{11} (*a*), σ_{12} (*b*), σ_{22} (*c*) and elastic potential W (*d*) for the dynamic solution (loading time $t_0 = 5$ ms)

Computations were performed for a ground with physical parameters from the Table 1 for a platform of radius $r_0 = 0.57$ m. Numerical values in the Figures are in terms of one kiloJoule of energy of a seismic source. Therefore, pressure and stresses are measured in $\mathrm{MPa}\sqrt{\mathrm{kJ}}$, velocities – in $\mathrm{m}\big/(\mathrm{s}\sqrt{\mathrm{kJ}})$, and potential energy – in 1/m^3. For a given value of energy E_0 kJ, due to the linearity of equations, stresses σ_{kj} and velocities v_k can be obtained by multiplying the reduced values on $\sqrt{E_0}$, and potential energy W – by multiplying on E_0.

Analyzing the Figures, we can note the effect of energy accumulation inside the characteristic region with dimensions depending on the platform radius. However, in terms of stress levels, as well as configuration of the region of energy accumulation, the results are consistent only at a qualitative level. Increasing the time t_0 to 10 ms also doesn't give a quantitative similarity.

Computations showed that the dynamics of the process has a significant influence on the stress-strain state before unloading for relatively hard geomaterials. For pliable geomaterials with low velocities of elastic waves, the difference between dynamic and static solutions becomes less perceptible.

Figures 9, 10 show the spectral curves of seismograms of the vertical velocity v_1 for a ground at a depth of 30 m at three points – on the axis of symmetry, on distance 15 and 30 m from this axis (red, green and blue lines, respectively). The computations were performed within the framework of the model of a static stress state with instantaneous unloading for platforms of radii $r_0 = 0.57$ and $r_0 = 0.8$ m. Note that the platform radius is the only free parameter in this model under given characteristics of a ground. Therefore, an interesting question is the dependence of the frequencies and amplitudes of waves on this parameter.

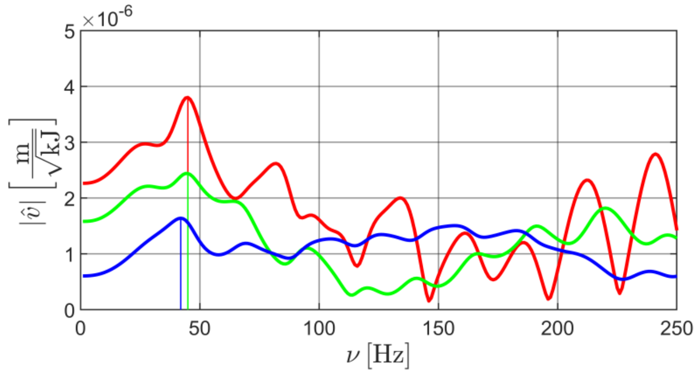

Fig. 9. Amplitude–frequency characteristics of the velocity v_1 for a ground under static loading with instantaneous unloading through a platform of radius $r_0 = 0.57$ m

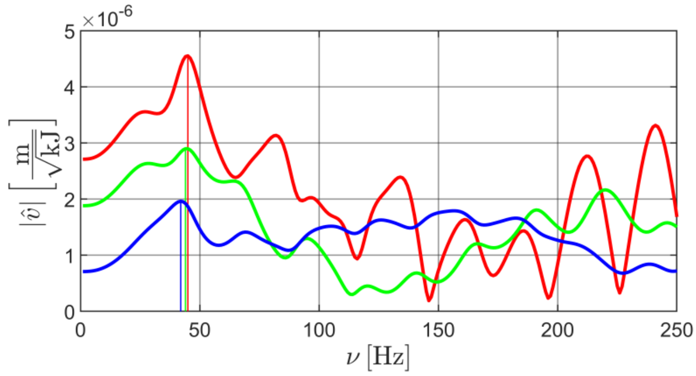

Fig. 10. Amplitude–frequency characteristics of the velocity v_1 for a ground under static loading with instantaneous unloading through a platform of radius $r_0 = 0.8$ m

Seismograms for the construction of spectral curves were computed in the time interval t^*=0.5 s. The spectral curves were constructed by calculating the discrete Fourier transform.

From the comparison of Figures one can see that increasing the platform radius does not lead to a perceptible change in frequencies. In both cases, the main frequency of oscillation, corresponding to the maximum amplitude of the velocity, lies within 40 – 45 Hz, which is consistent with field observations in-situ data.

The spectral curves in Fig. 11 are obtained for a platform of radius $r_0 = 0.57$ m for a rigid ground with high velocities of longitudinal and transverse elastic waves (see Table l). In this case, the characteristic frequencies of waves are about 15 Hz higher than in the case of a ground with lower velocities. Similar results of comparison were obtained in computations for a platform of radius $r_0 = 0.8$ m.

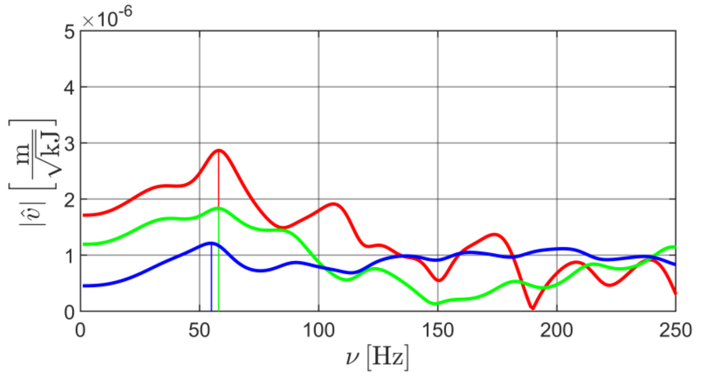

Fig. 11. Amplitude–frequency characteristics of the velocity v_1 for a rigid ground under static loading with instantaneous unloading through a platform of radius $r_0 = 0.57$ m

Spectral curves of velocity in the case of pulsed loading of a ground through a platform of radius $r_0 = 0.57$ m with a time of monotone pressure increase $t_0 = 5$ and $t_0 = 10$ ms are represented in Figs. 12 and 13, respectively. Comparing these Figures and Fig. 9, one can see that the main low frequency is everywhere in the range of 40 – 45 Hz, but at the loading time $t_0 = 5$ ms an additional peak appears with a frequency above 80 Hz, which disappears when $t_0 = 10$ ms, that is, with an increase in time of loading.

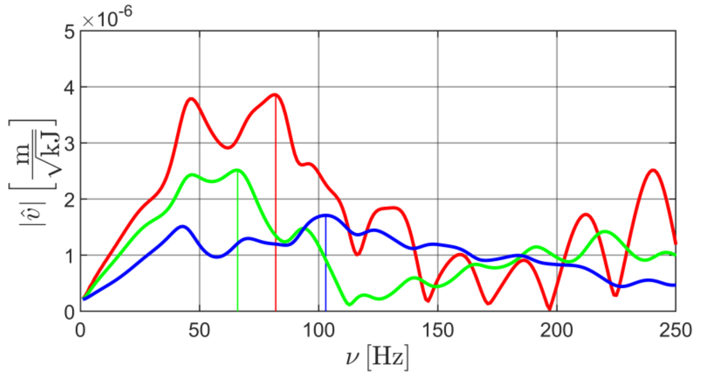

Fig. 12. Amplitude–frequency characteristics of the velocity v_1 for a ground under dynamic loading through a platform of radius $r_0 = 0.57$ m at $t_0 = 5$ ms

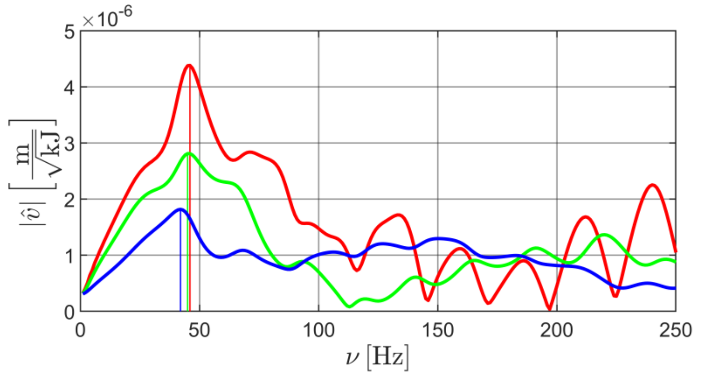

Fig. 13. Amplitude–frequency characteristics of the velocity v_1 for a ground under dynamic loading through a platform of radius $r_0 = 0.57$ m at $t_0 = 10$ ms

Analysis of the spectral curves in Fig. 14 for a platform of radius $r_0 = 0.8$ m shows that an additional peak appears at $t_0 = 5$ ms, regardless of platform radius. But the main low frequency is still present. The same qualitative results with a corresponding increase in the frequencies and amplitudes of waves are demonstrated by computations for a rigid ground.

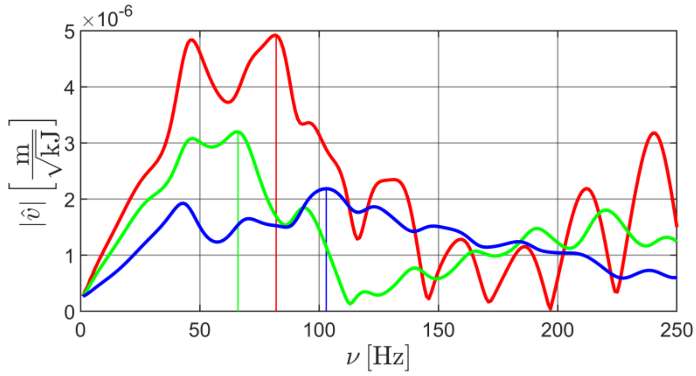

Fig. 14. Amplitude–frequency characteristics of the velocity v_1 for a ground under dynamic loading through a platform of radius $r_0 = 0.8$ m at $t_0 = 5$ ms

Generally, according to the results of a large number of numerical experiments, we can conclude that in the considered time range, characteristic for the electromagnetic pulse source of seismic oscillations "Yenisei", the loading time influences on the amplitude–frequency characteristics of waves in the near region of a ground under a loading platform. However, this influence is not significant for the frequency corresponding to the maximum amplitude of longitudinal velocity. This frequency varies slightly depending on the loading time, on the platform radius and on the depth, and is an individual characteristic of a medium.

Thus, computations confirm the hypothesis of the existence of the added mass and the resonant frequency of a ground, the justification of which on the basis of simple models is given, for example, in [17].

Computations were performed on the MVS cluster of the Institute of Computational Modeling SB RAS (Krasnoyarsk) and MVS–100K cluster platform of the Joint Supercomputer Center of the Russian Academy of Sciences (Moscow).

4. Conclusions

As compared with our previous work [18], the following new results were obtained. It was shown that the process of mechanical action from the source can be considered as a two-stage process. At the first stage, elastic energy accumulates under the platform and a stress-strain state close to static is formed, and at the second one, an instantaneous pressure release occurs with formation of a system of waves due to pulsating motions of the disturbed domain. The frequency of oscillations corresponding to the maximum amplitude in a homogeneous massif is a characteristic of a geomedium, which is weakly dependent on loading time and platform radius. For rigid grounds with high velocities of elastic longitudinal and transverse waves this frequency is higher than for soft grounds with lower velocities.

Computational experiments showed that the developed supercomputer technology allows to reproduce with a high degree of details and accuracy in 3D setting the system of waves near the regions of excitation of seismic oscillations by the electromagnetic pulse source "Yenisei". A necessary condition for this is as well as possible more accurate setting the localized load from the source. Obtained results can be used in working out the optimal modes of the source operation, when the mechanical characteristics of the surface contact layer vary in a wide range from solid grounds with inclusions of rock till granular and clay water-saturated media. Numerical analysis of the wave field near the region of excitation makes also possible to obtain the averaged data, necessary for the adequate simulation of the localized pulse action from the source using simplified mathematical models for calculating the synthetic seismograms of reflected waves over large stretch and at great depth of bedding inhomogeneous layers in complex geomedia.

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