Analysis of Acoustic Waves Excited in Near-Surface Soils by Means of the Electromagnetic Pulse Source "Yenisei"

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2 – 12 March, 2019

The Grandfather

The First Pillar

The Feathers

Contents

Introduction

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 acoustic waves are the subject of analysis using high-performance computing in this presentation.

GEOTECH SEISMIC SERVICES

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

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 [1 – 3]. The source exists in wheeled, sledge, mobile and water variants.

"Yenisei" is quite competitive in comparison with sources of explosive and vibrational types by efficiency and quality of exploration works, and it has undeniable advantages in the economical and environmental aspects.

[1] V. P. Smirnov: Electromagnetic sources of seismic oscillations of the series "Yenisei–SEM, KEM". *J. Devices Systems Explor. Geophys.* 3(1): 21–25, 2003 [in Russian]

[2] V. A. Detkov, P. Yu. Schadin, V. V. Ivashin: Pulsed electromagnetic seismic sources "Yenisei": Features of technical solutions and applications. *J. Devices Systems Explor. Geophys.* 22(4): 30–33, 2007 [in Russian]

[3] V. A. Detkov: Stimulation of seismic waves by pulsed nonexplosive sources. *J. Sib. Fed. Univ.: Math. Phys.* 2(3): 298–304, 2009 [in Russian]

Introduction

The use of electromagnetic source “Yenisei” is incomparably cheaper, and it is almost the only possible means when working near buildings and constructions, in water protection zones and in areas where there are a lot of rivers and lakes.

It is also applied on ice coverings of reservoirs, in shallow waters and on offshore.

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 [4, 5].

[4] V. P. Smirnov: Technical means and the content of checking the sources of the “Yenisei” series in the cycle of accumulation of single and group impacts. *J. Devices Systems Explor. Geophys.* 12(2): 45–48, 2005 [in Russian]

[5] P. Yu. Schadin. Properties of seismic wave field generated by pulse energy sources “Yenisei”. *Seismic Technol.* 10(4): 74–80, 2013 [in Russian]

Mathematical models

In the present work, computational technology is presented, 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.

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. Mathematical models of elastic-plastic, granular and porous media, taking into account different resistance of materials to tension and compression, were worked out. 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.

Equations of the model in elastic blocks

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 velocities v and stresses σ, is fulfilled:

$$\rho\,\frac{\partial v}{\partial t} = \nabla\cdot\sigma, \quad \frac{\partial \sigma}{\partial t} = \rho\left(c_1^2 - 2\,c_2^2\right)(\nabla\cdot v)I + \rho\,c_2^2\left(\nabla v + \nabla v^*\right) \qquad (1)$$

- ρ – density, c_1 and c_2 – velocities of longitudinal and transverse elastic waves
- ∇ – gradient over spatial coordinates, I – unit tensor
- asterisk denotes conjugate tensor, conventional notations of tensor analysis are used

The initial velocities and stresses are assumed to be zero. On a part of the boundary, external stresses caused by the action of concentrated load are preset. On the planes of symmetry, if any, the symmetry conditions are formulated. A part of the boundary can be a non-reflecting surface, on which the conditions for passage of waves without appreciable reflection are simulated. At the internal interfaces, the continuity conditions are set for vectors of velocities and stresses at the contact areas of the blocks.

Matrix form of the systems for dynamic theory of elasticity and plasticity

The system of equations of dynamic elasticity is written in the next form:

$$A\,\frac{\partial U}{\partial t} = \sum_{i=1}^{n} B^i\,\frac{\partial U}{\partial x_i} + Q\,U + G \tag{2}$$

When taking into account the plastic deformation of a material, the system (2) is replaced by the variational inequality

$$(\widetilde{U} - U)\Big(A\,\frac{\partial U}{\partial t} - \sum_{i=1}^{n} B^i\,\frac{\partial U}{\partial x_i} - Q\,U - G\Big) \geqslant 0, \qquad \widetilde{U},\ U \in F \tag{3}$$

- F – convex and closed set, determined by the criterion of plasticity
- $U(t,x)$ – m-dimensional unknown vector–function, $\widetilde{U}$ – varied vector
- A – symmetric positive definite matrix of coefficients under time derivatives,
  B^i – symmetric matrices of coefficients under derivatives with respect to the spatial variables,
  Q – antisymmetric matrix, G is a given vector
- n – spatial dimension of a problem (1, 2 or 3)
- dimension m of the system (2) and concrete form of matrices–coefficients is determined by the used mathematical model

Matrix form of the systems for dynamic problems of granular and porous materials

In the problems of mechanics of granular media with plastic properties a more general variational inequality takes place

$$(\tilde{V} - V)\left(A\,\frac{\partial U}{\partial t} - \sum_{i=1}^{n} B^i\,\frac{\partial V}{\partial x_i} - Q\,V - G\right) \geqslant 0, \qquad \tilde{V},\ V \in F \tag{4}$$

Vector–functions V and U are related by the equations

$$V = \varsigma\,U + (1-\varsigma)\,U^\pi, \qquad U = \frac{1}{\varsigma}\,V - \frac{1-\varsigma}{\varsigma}\,V^\pi \tag{5}$$

Similar inequality describes dynamic behavior of porous materials taking into account the increase in stiffness after collapse of pores

- U^π is the projection of the vector of solution onto the given convex cone K, by means of which the different resistance of a material to tension and compression is described
- $\varsigma \in (0, 1]$ is the parameter of regularization of the model characterizing the ratio of elastic moduli in tension and compression

Structure of numerical algorithms

- The algorithm of numerical implementation of the variational inequality (4), having the most general form, is explicit in time and is constructed by means of the splitting method with respect to physical processes in the following way:
  - first, the elastic problem is solved at each time step
  - next, the obtained solution is corrected to take into account plastic, granular and porous properties of a material
- For the solution of elastic problem the two-cyclic splitting method with respect to the spatial variables is used
- One-dimensional hyperbolic systems of equations of the form

$$A\,\frac{\partial U^{(k)}}{\partial t} = B^i\,\frac{\partial U^{(k)}}{\partial x_i} + G^i \qquad (6)$$

$k = \overline{1, 2\,n}$ – number of the splitting stage, $i = \overline{1, n}$ – direction of splitting

in spatial directions are solved by means of the monotone finite-difference ENO–scheme of the "predictor–corrector" type; piecewise-linear splines, discontinuous at the boundaries of meshes, are constructed by a special procedure of limit reconstruction, which enables one to improve an accuracy of a numerical solution

- Plasticity, granularity and porosity of materials are taken into account by means of a special algorithms for the correction of stresses, used in computations

Two-cyclic splitting for the solution of elastic problem

The splitting method leads to a series of seven 1D problems, three of which are considered on the time interval $[t_n, t_n + \tau/2]$, and the last three on the interval $[t_n + \tau/2, t_n + \tau]$, where τ is the time step of grid:

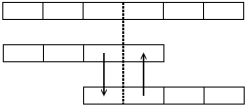
$$
\begin{aligned}
&A\,\frac{\partial U^{(1)}}{\partial t} = B^1\,\frac{\partial U^{(1)}}{\partial x_1} + G^1, \quad && U^{(1)}(t_n) = U(t_n)\\
&A\,\frac{\partial U^{(2)}}{\partial t} = B^2\,\frac{\partial U^{(2)}}{\partial x_2} + G^2, \quad && U^{(2)}(t_n) = U^{(1)}(t_n + \tau/2)\\
&A\,\frac{\partial U^{(3)}}{\partial t} = B^3\,\frac{\partial U^{(3)}}{\partial x_3} + G^3, \quad && U^{(3)}(t_n) = U^{(2)}(t_n + \tau/2)\\
&A\,\frac{\partial U^{(4)}}{\partial t} = Q\,U^{(4)}, \quad && U^{(4)}(t_n) = U^{(3)}(t_n + \tau/2)\\
&A\,\frac{\partial U^{(5)}}{\partial t} = B^3\,\frac{\partial U^{(5)}}{\partial x_3} + G^3, \quad && U^{(5)}(t_n + \tau/2) = U^{(4)}(t_n + \tau/2)\\
&A\,\frac{\partial U^{(6)}}{\partial t} = B^2\,\frac{\partial U^{(6)}}{\partial x_2} + G^2, \quad && U^{(6)}(t_n + \tau/2) = U^{(5)}(t_n + \tau)\\
&A\,\frac{\partial U^{(7)}}{\partial t} = B^1\,\frac{\partial U^{(7)}}{\partial x_1} + G^1, \quad && U^{(7)}(t_n + \tau/2) = U^{(6)}(t_n + \tau)
\end{aligned}
\tag{7}
$$

The vector–function $U^{(7)}(t_n + \tau)$ is a desired solution on the time layer $t_n + \tau$.

Structure of parallel program

Computational algorithms are implemented as parallel program systems for the solution of dynamic problems in structurally inhomogeneous deformable media (granular and porous materials, Cosserat continuum and multiblocky medium) on multiprocessor computers by means of the SPMD technology in Fortran using the MPI library.

1. Preprocessor program
   - grid generation
   - uniform distribution of initial data between parallel computational nodes
   - packing of its part of data in binary files of direct access by each node of a cluster
2. Main program
   - step-by-step numerical computation of a problem on each node of a cluster
   - data exchange between the processes
   - special conservation of resulting data in the control points



The scheme of exchange with contour meshes

3. Postprocessor program
   - compression of files, containing the results of computations in the control points
   - graphical representation of results

Verification of the software was performed on exact solutions – formulas of geometric seismics for the hodographs of reflected and refracted waves.
Parallel program systems were registered in Rospatent.

Our parallel software

Parallel program systems for the solution of two-dimensional and three-dimensional elastic-plastic problems of the dynamics of granular media

Programs:
2Dyn_Granular, 3Dyn_Granular

Certificates of state registration of computer programs No. 2012613989 and No. 2012613990 from 28.04.2012 (Rospatent)

Parallel program systems for the solution of two-dimensional and three-dimensional dynamic problems of the Cosserat elasticity theory

Programs:
2Dyn_Cosserat, 3Dyn_Cosserat

Certificates of state registration of computer programs No. 2012614823 and No. 2012614824 from 30.05.2012 (Rospatent)

Parallel program system for numerical modeling of dynamic processes in multi-blocky media on cluster systems

Program
2Dyn_Blocks_MPI

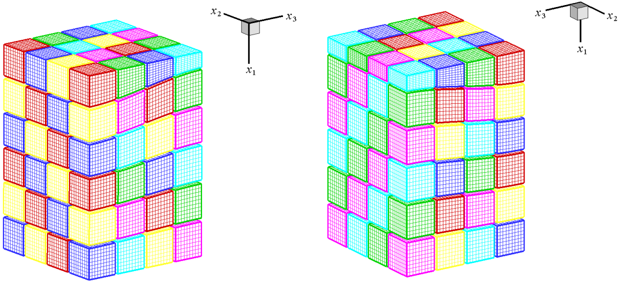
Certificate of state registration of computer program No. 2016615178 from 17.05.2016 (Rospatent)

Preliminary series of computations was fulfilled with the goal of validating the software package *3Dyn_Granular* by basic parameters of the source – the frequencies and amplitudes of oscillations. Comparison of the numerical results with the available experimental data showed a satisfactory quantitative correspondence.

Distribution of computational load between nodes

Let's consider a two-layered massif of an elastic medium of $60\,\text{m} \times 40\,\text{m} \times 40\,\text{m}$.
The upper 10-meter layer may be more compliant and, conversely, more rigid as compared with the lower 50-meter basic layer.

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 $50 \times 200 \times 200$ cells, and in the lower layer – $250 \times 200 \times 200$ cells, that is, each cluster node performs computations on a grid of $50 \times 50 \times 50$ cells. For visibility, the difference grids in Figures is thinned 5 times in each direction.

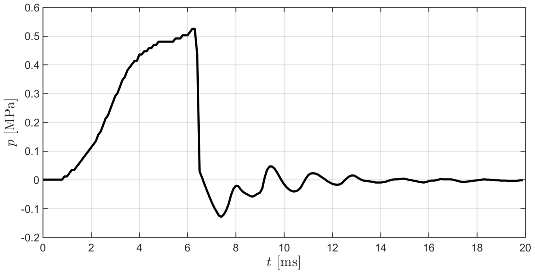


Two-layered computational domain with curvilinear boundary (views from different sides):
Uniform distribution of computational load between 96 cluster nodes

Impact action from the pulse source "Yenisei"

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 the symmetry conditions are given. The back boundaries and the lower base are considered as non-reflecting surfaces. 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 problems.

Loading zone – a circle of area $1\,\text{m}^2$, which is located at the distance of 2.5 m and 1.25 m from the left and right boundaries of symmetry, respectively.



Pressure in this form was determined on the basis of experimental measurements of the acceleration of reactive mass of the electromagnet.

Dependence on time of pressure from the source in the localization zone

Elastic parameters of materials

Computations were performed for two-layered and three-layered media. In the first case the upper 10-meter layer is more compliant (clay) and, conversely, more rigid (rock) as compared with the lower 50-meter basic layer (ground). Similar problem was considered for the case, when the upper layer is water, and for a three-layered medium consisting of the upper 3.5-meter layer from ice, the middle 10-meter layer of water and the lower thick layer of ground.

To demonstrate the capabilities of the program, the interface between layers of ground with different properties (or between water and ground) was curved.

In the case of a three-layered medium, computational domain is distributed uniformly between 16 nodes in the upper layer (ice), 16 nodes in the middle layer (water) and 64 nodes in the lower layer (ground).

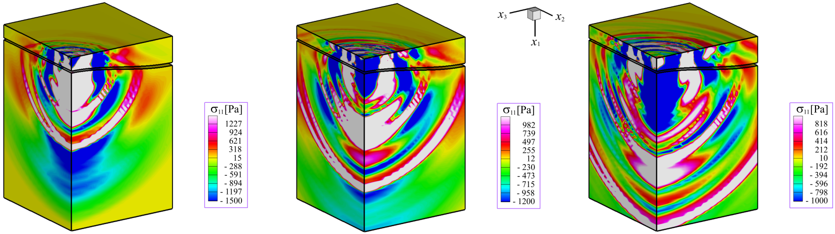
Densities and velocities of elastic waves in the layers from different materials are given in Table.

Mechanical parameters of materials

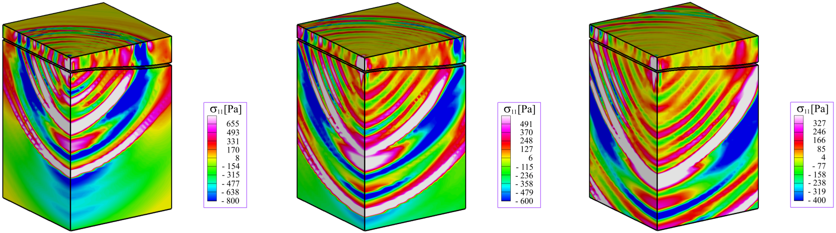
	ρ [kg/m^3]	c_1 [m/s]	c_2 [m/s]
ice	900	3000	1800
water	1000	1450	0
clay	2100	1800	1100
ground	2400	4500	2700
rigid ground	2600	6000	3500

Results for compliant and rigid cover layers

Upper layer is clay, lower layer is ground



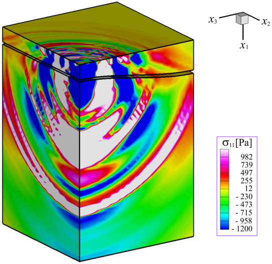
Level surfaces of normal stress σ_{11} in vertical direction: t = 15, 18 and 21 ms



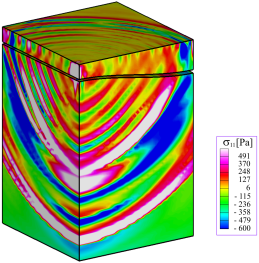
Upper layer is rigid ground, lower layer is ground

Four types cover layers: clay, rock, water and ice

Upper layer is clay, lower layer is ground

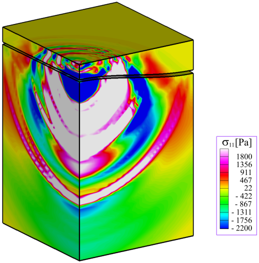


Upper layer is rigid ground, lower layer is ground

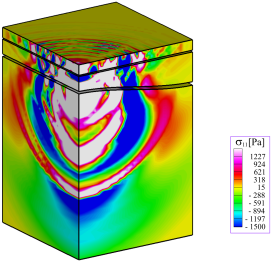


Level surfaces of normal stress σ_{11} in vertical direction: $t = 18\,ms$

Upper layer is water, lower layer is ground



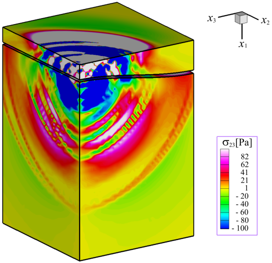
Upper layer is ice, middle layer is water, lower layer is ground

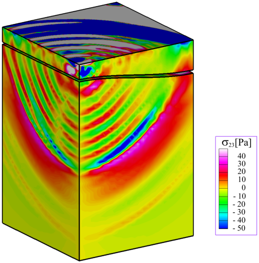


Lower layer is ground, upper layer is rigid ground

Four types cover layers: clay, rock, water and ice

Upper layer is clay, lower layer is ground

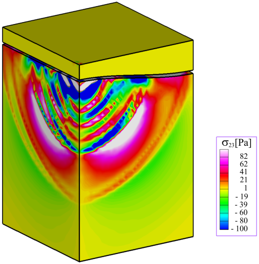


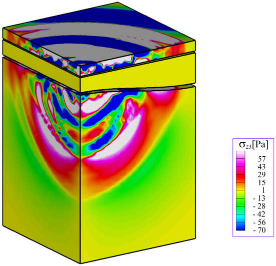


Upper layer is rigid ground, lower layer is ground

Level surfaces of tangential stress σ_{23} in horizontal direction: $t = 18\,ms$

Upper layer is water, lower layer is ground



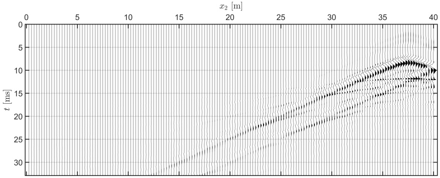


Upper layer is ice, middle layer is water, lower layer is ground

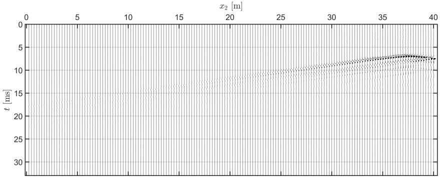
Lower layer is ground, upper layer is rigid ground

Seismograms of elastic waves

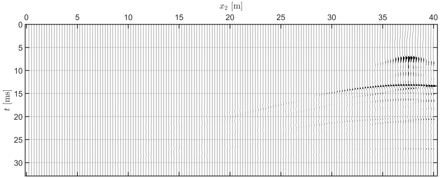
Upper layer is clay



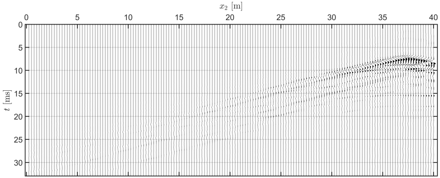
Upper layer is rigid ground



Seismograms of acceleration a_1 in the direction x_1



Upper layer is water



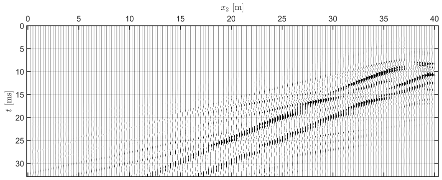
Upper layer is ice, middle layer is water

Lower layer is ground

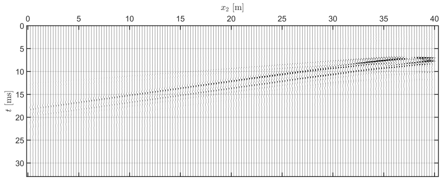
Receivers are located along the x_2 axis at the symmetry plane

Seismograms of elastic waves

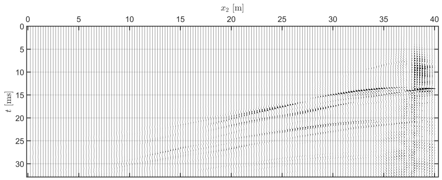
Upper layer is clay



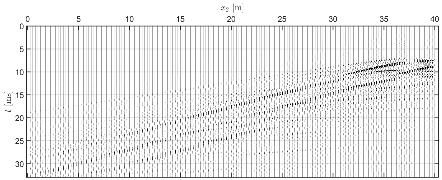
Upper layer is rigid ground



Seismograms of acceleration a_2 in the direction x_2



Upper layer is water



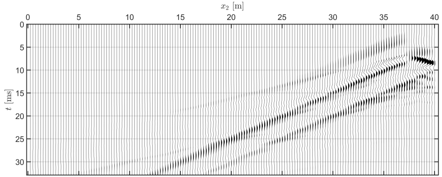
Upper layer is ice, middle layer is water

Lower layer is ground

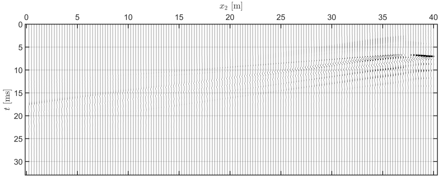
Receivers are located along the x_2 axis,
at the distance of 3.75 m from the plane of symmetry

Seismograms of elastic waves

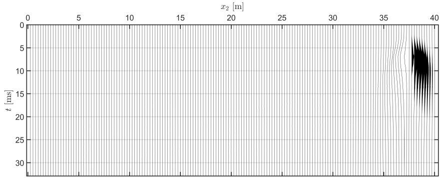
Upper layer is clay



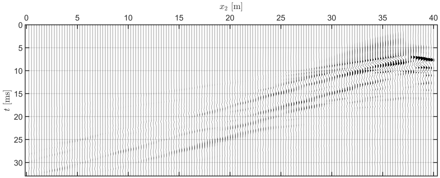
Upper layer is rigid ground



Seismograms of velocity v_2 in the direction x_2



Upper layer is water



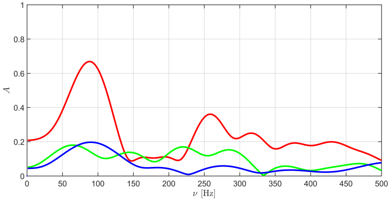
Upper layer is ice, middle layer is water

Lower layer is ground

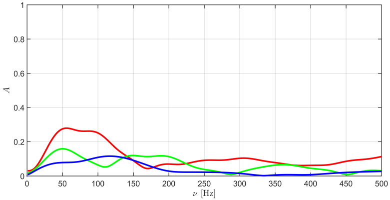
Receivers are located along the x_2 axis,
at the distance of 3.75 m from the plane of symmetry

Amplitude-frequency characteristics

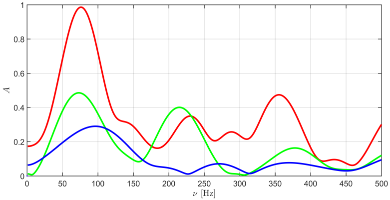
Upper layer is clay



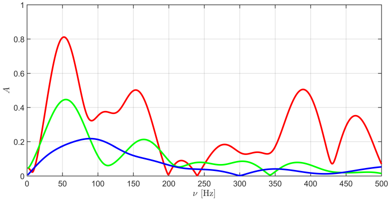
Upper layer is rigid ground



Amplitude-frequency dependences for velocity v_1 at the depth of 30 m



Upper layer is water



Upper layer is ice, middle layer is water

Lower layer is ground

A system of points under the trace passing near the symmetry plane in the direction of x_2 axis:

red line refers to the point under the source,
green line – to the middle point to the left, and
blue line – to the edge left point

Conclusions

- Numerical experiments shown 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 a pulse electromagnetic source "Yenisei".
- 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 scale and at great depth of bedding inhomogeneous layers in complex geomedia.

Many thanks for your attention and for your interest!