Journal of Physics: Conference Series

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Computational problems in Arctic Research

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Abstract. This article is to inform about main problems in the area of Arctic shelf seismic prospecting and exploitation of the Northern Sea Route: simulation of the interaction of different ice formations (icebergs, hummocks, and drifting ice floes) with fixed ice-resistant platforms; simulation of the interaction of icebreakers and ice-class vessels with ice formations; modeling of the impact of the ice formations on the underground pipelines; neutralization of damage for fixed and mobile offshore industrial structures from ice formations; calculation of the strength of the ground pipelines; transportation of hydrocarbons by pipeline; the problem of migration of large ice formations; modeling of the formation of ice hummocks on ice-resistant stationary platform; calculation the stability of fixed platforms; calculation dynamic processes in the water and air of the Arctic with the processing of data and its use to predict the dynamics of ice conditions; simulation of the formation of large icebergs, hummocks, large ice platforms; calculation of ridging in the dynamics of sea ice; direct and inverse problems of seismic prospecting in the Arctic; direct and inverse problems of electromagnetic prospecting of the Arctic. All these problems could be solved by up-to-date numerical methods, for example, using grid-characteristic method.

1. Introduction

Many natural impacts on industrial structures in the Arctic regions can be numerically simulated with a high degree of reliability by the models of continuum media, and by the advanced numerical methods for solving the corresponding systems of partial differential equations, and using correct problem definitions and high-performance multiprocessor computing algorithms.

Since the full-scale experiments in the study of Arctic processes are expensive and sometimes difficult to make, the appropriate computer modeling is the only realistic approach.

Attention to the development of the Arctic shelf of the Russian Federation explained the real need for a major exploration and development of oil-fields and gas-fields, as well as the real need for international use of the Northern Sea Route. On the Arctic shelf of Russian Federation there are eight fields discovered in 1983-1992 with estimates of reserves about 2.7 trillions m^3. Five of these eight fields are the largest objects related to the objects of federal significance: Ledovoe, Ludlovskoe, Murmanskoe in the Barents Sea, Pomorskoe, Gulyaevskoe in the Pechora Sea, Leningradskoe, Rusanovskoe in the Kara Sea. For oil production in the Pechora Sea the ice-resistant platform called Prirazlomnaja was installed. For gas production the project of the Shtokman field in the Barents Sea is designed. For these fields the improvement of made earlier estimates of hydrocarbon reserves volumes is required. A significant complicating factor in the production of hydrocarbons in the North Seas is the existence of ice formations. In the Kara Sea almost during all year there are drifting ice. In the Barents and in the Pechora Sea there are icebergs and ice hummocks. The depths of these North Seas in the industrial zones are reaching up to 300 m.

For the hydrocarbon transportation the pipelines are made in the northern regions of Russian Federation including the bottom zones. Obviously that for the long-term operation of industrial gas hydrotechnical facilities in difficult ice conditions it is necessary to calculate the impacts of different types of ice formations on these objects (platforms, pipelines, ships, icebreakers, etc.).

The creation of the Northern Sea Route for transporting cargo from Europe to America and to the Far East reduces the distance on 30-60 percent and reduces the transportation time on 10 days during comparison to traditional maritime routes (via the Panama and Suez canals). Now days the main cargo flow on this route is associated with delivery of nickel from the port Dudinka and its volume is equal to approximately 1.2 millions tons per year.

The main problems of development of the Northern Sea Route with the extent 2200-2900 nautical miles from the Novaya Zemlya to the Bering Strait are associated with difficult ice conditions and the use of powerful icebreakers that can move into the ice cover with thickness up to 2 m (now the track has 7 icebreakers and diesel-electric icebreakers and ice-class vessels).

Ice hummocks, icebergs, ice is often a serious impediment to these ships. Large ice formations are also a danger to the stationary ice-resistant platforms and sea bed pipelines [1-3].

The movement of ice masses occurs under the action of winds and currents. The ice cover is characterized by the presence of icebergs, ice hummocks, drifting ice, cracks in the ice, spring floods [4-6]. The presence of ice hummocks materially affects on the ice surface roughness and leads to the increase of the friction forces from wind and currents. The average distance between sails of ice hummocks in various regions of the Arctic is about 200-300 meters, the height of the hummock sail can reach several meters, the deep can reach a few tens of meters. The problems of ice ridging is discussed in papers [7-11]. The characteristic dimensions of icebergs are more than several times bigger than the characteristic dimensions of the ice hummocks.

Most time of the year, for example, the Pechora Sea and the Kara Sea are covered with drifting ices, the speed of which ices may exceed 5 m/s, the thickness of plane ice is up to 2 m, the thickness of draft ice hummocks is 20 m. Thus, the structure and parameters of the ice cover of the Northern seas are significant parameters determining the extreme loads at fixed and floating offshore oil and gas industrial structures.

In this regard, the importance of solving the problem of the modeling of dynamic processes in the air, water and soil of the Arctic with the processing of observation results, and prediction of the ice conditions, and the estimation of the further stability of stationary platforms, sea bed pipelines, the further security of icebreakers and ice-class vessels is clear [12,13].

The hydrocarbon exploration in the Arctic area has its own specificity. In particular, one of the layers, through which the seismic signals propagate, is the sea [14-17], the other layer is ice. The icebergs, ice hummocks, drifting ice, ice cover have also contributed to the measured or calculated responses in the seismic prospecting. During carrying out exploration work on the land one must take into account the effect from the permafrost. In addition to seismic technology the electrical exploration of hydrocarbons is an effective approach. The review of studies on this topic is given in [18,19].

We can highlight some of the major classes of problems at the Arctic area, which can be solved by numerical simulations on high-performance computing systems:

- Simulation of the interaction of different ice formations (icebergs, ice hummocks, and drifting ice floes) with fixed ice-resistant platforms;
- Simulation of the interaction of icebreakers and ice-class vessels with ice formations;
- Modeling of the impact of the ice formations on the ground pipelines;
- Neutralization of damage for fixed and mobile offshore industrial structures from ice formations;
- Calculation of the strength of the ground pipelines;
- Transportation of hydrocarbons by pipeline;

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- The problem of migration of large ice formations;
- Modeling of the formation of ice hummocks on ice-resistant stationary platform;
- Calculation the stability of fixed platforms;
- Calculation dynamic processes in the water and air of the Arctic with the processing of data and its use to predict the dynamics of ice conditions;
- Simulation of the formation of large icebergs, ice hummocks, large ice platforms;
- Calculation of ridging in the dynamics of sea ice;
- Direct and inverse problems of seismic prospecting in the Arctic;
- Direct and inverse problems of electromagnetic prospecting of the Arctic.

The system of equations for modeling of these processes is the system of equations which describes continuum mechanics, in particular, solid state physics, acoustics, and fluid dynamics [20-53].

For the numerical solution of the relevant problems it is necessary to develop or adopt adequate modern computational methods and algorithms for high-performance computers [21-53].

2. Examples of numerical modeling

We can give some examples of numerical solutions to some up-to-date problems of oil and gas industry in the Arctic conditions.

Figure 1 shows the results of numerical modeling of the impact of the ice floes on the oil platform.

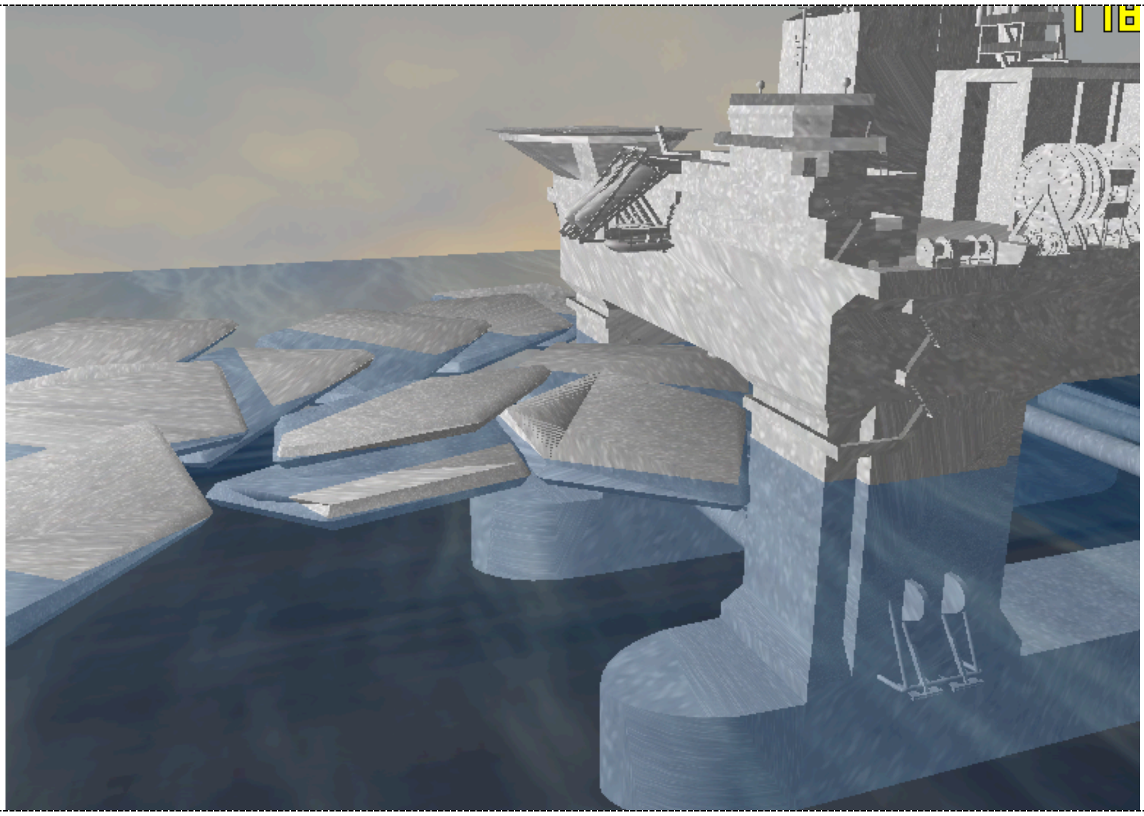

Figure 1. The impact of the ice floes on the oil platform.

Figure 2 shows the wave pattern that occurs under the influence of an iceberg, white color shows the image of the system of the cracks. The colors scale shows the velocity module, the red color corresponds to the maximum value, and the blue color corresponds to the zero value. The calculation was made using grid-characteristic method [40-52], the destruction was calculated on the basis of the criteria of main stress. Hereafter, we solve the systems of equations describing the state of the linear-elastic body [21] and the system of equation describing acoustic waves [20].

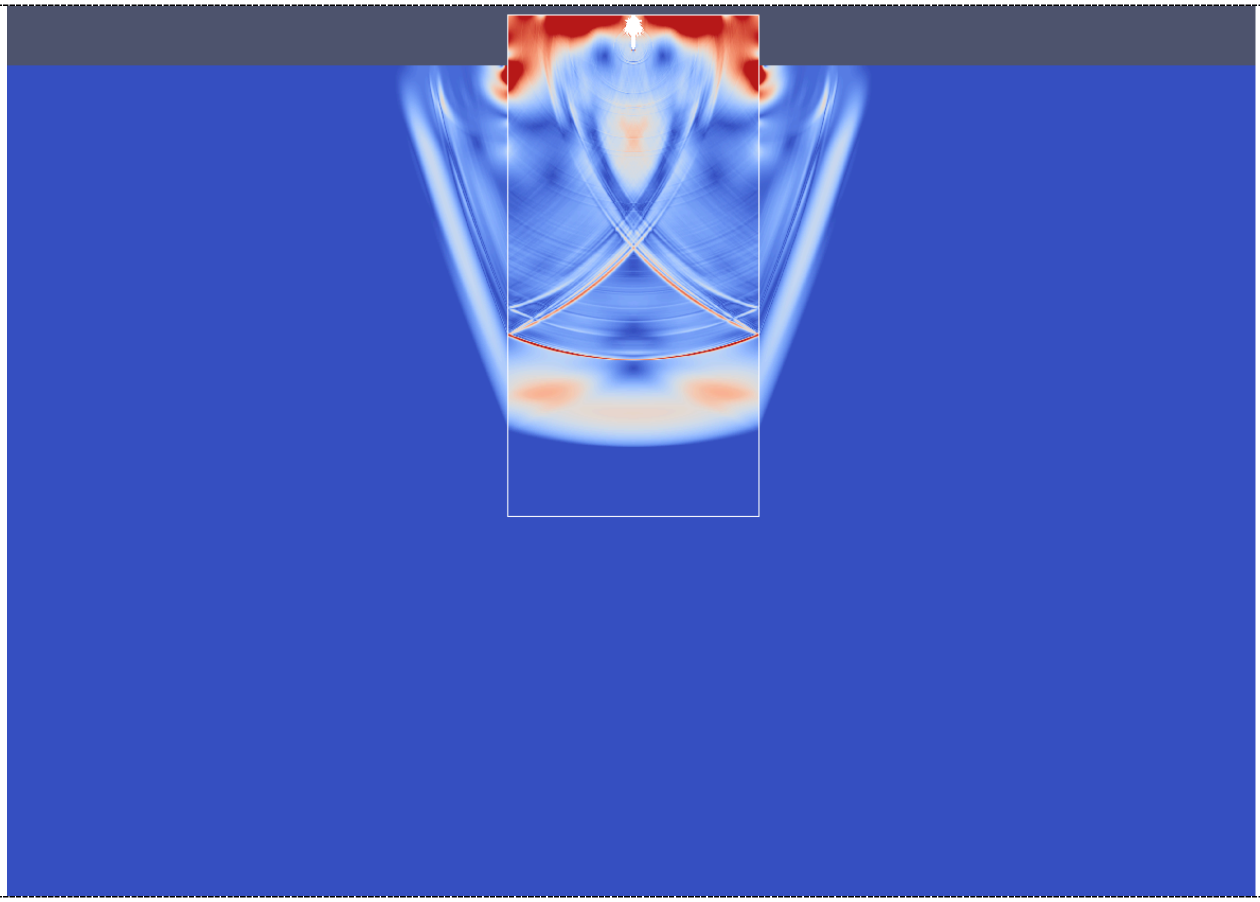

Figure 2. Impact on the iceberg. Wave pattern.

Figure 3 shows the computational grid and the wave pattern that occurs during the collision between the iceberg and fixed oil platform. The calculation was performed using a discontinuous Galerkin method [14-17,40], color shows the module of velocity, the scale is shown at figure 3.

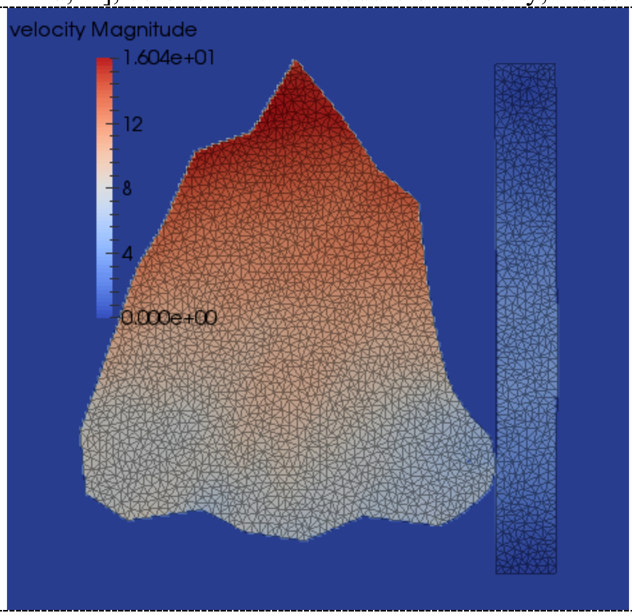

Figure 3. Collision between the iceberg and the fixed oil platform.

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Figure 4 represented the wave patterns resulting from the numerical solution of problems of seismic exploration in the Arctic shelf. The colors shows the module of velocity. The red color corresponds to the maximum value, and blue color corresponds to the zero value. Figures 4, 5 demonstrates the source located in the ice, figures 6, 7 demonstrates the source located at the sea bed. Figures 5, 7 demonstrates the case without carbon reservoir. We consider the complex system composed from ice, water, soil and carbon reservoir and use grid-characteristic method [40-52].

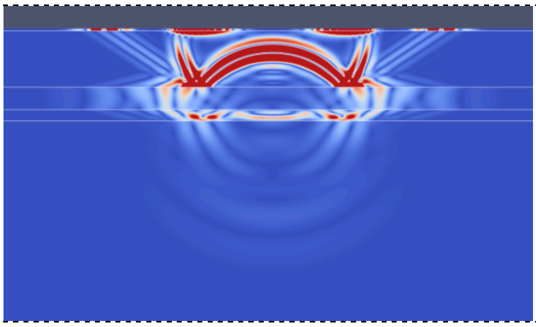

Figure 4. Wave pattern. Source in the ice. With reservoir.

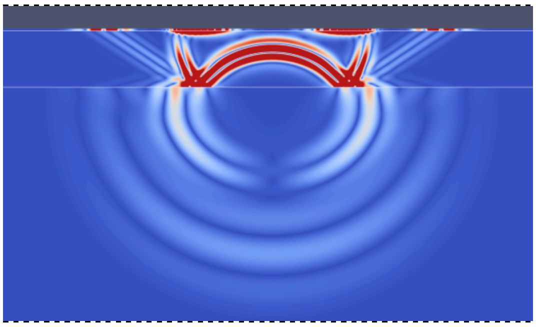

Figure 5. Wave pattern. Source in the ice. Without reservoir.

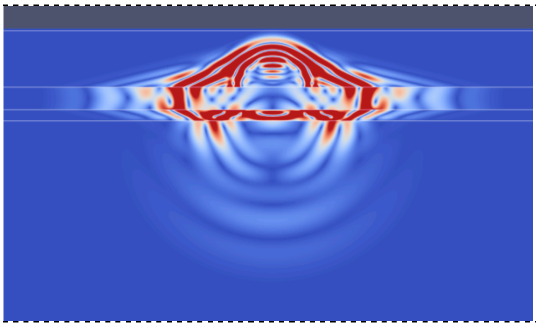

Figure 6. Wave pattern. Source at the sea bed. With reservoir.

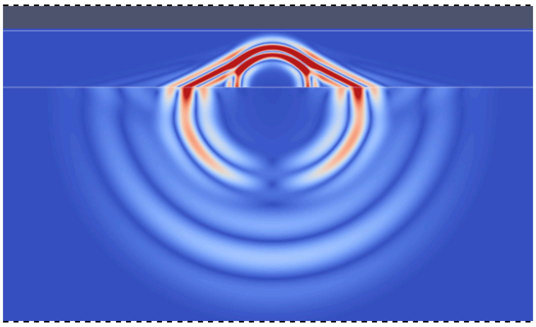

Figure 7. Wave pattern. Source at the sea bed. Without reservoir.

Figure 5 shows the seismograms corresponding to all the cases considered above, recorded on a receivers located on the ice and measuring the vertical component of velocity.

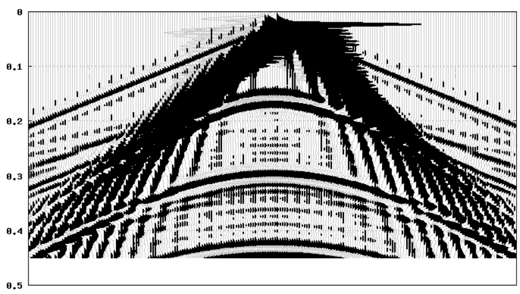

Figure 8. Seismogram. Source in the ice. With reservoir.

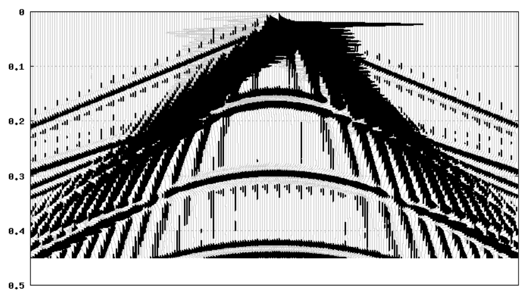

Figure 9. Seismogram. Source in the ice. Without reservoir.

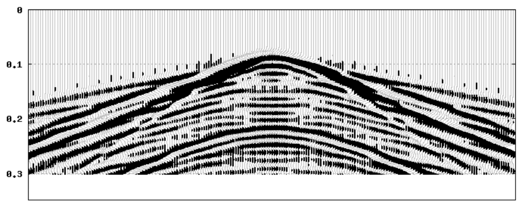

Figure 10. Seismogram. Source at the sea bed. With reservoir.

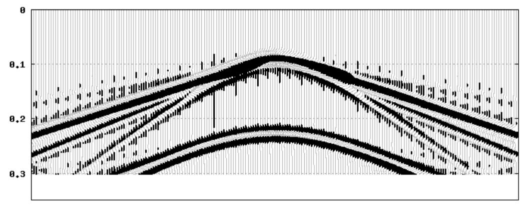

Figure 11. Seismogram. Source at the sea bed. Without reservoir.

Figure 12 shows the seismic and acoustic waves from a series of point sources in the complex system "water-soil-carbon reservoir”. Grayscale shows the module of velocity. We use grid-characteristic method [40-52].

Figure 12. The wave pattern in the system "water-soil-carbon reservoir". Several sources.

3. Conclusions

In this article we discussed several kinds of Arctic problems, several kinds of numerical methods for computer study of these problems and several examples representing results of numerical solutions of these problems using grid-characteristic method [40-52] and discontinues Galerkin method [14-17,40].

The study was funded by Ministry of Education and Science of the Russian Federation under grant agreement No. 14.575.21.0084 on October 20, 2014 (the unique identifier PNI: RFMEFI57514X0084) in the Moscow Institute of Physics and Technology (State University).

I express my gratitude to my students adopted up-to-date numerical methods to solve these problems and obtained the numerical solution of these problems: Favorskaya A.V., Khokhlov N.I, Sannikov A.V., Miryaha V.A., and Petrov D.I.

4. References

[1] Gagnon R E and Wang J 2012 Numerical simulations of a tanker collision with a bergy bit incorporating hydrodynamics, a validated ice model and damage to the vessel *Cold regions. Science and Technology*

[2] Lee S G, Lun S H and Kong G Y 2013 Modeling and simulation system for marine accident cause investigation *Collision and Graunding of Ships and Offsore Structure* ed Amdahl, Ehlers and Leira (Taylor and France Group, London) pp 39–47

[3] Bekker A T, Sabobash O A, Seliverstov V I, Koff G I and Pipko E N 2009 Estimation of Lomit Loads on Engeneering Offshore Structures Proceeding of the Nineteenth *International Offshore and Polar Engeneering Conference* (Osaka, Japan) pp 574–579

[4] Weiss J 2013 Drift, Deformation and Fracture of Sea Ise. A perspective Across Scales. *Springer* p 83

Journal of Physics: Conference Series **681** (2016) 012026 doi:10.1088/1742-6596/681/1/012026

[5] Pavlov V, Pavlova O and Korsnes R 2004 Sea ice fluxes and drift trajectories from potential pollution sources, computed with a statistical sea ice model of the Arctic Ocean *Journal of marine Systems* **48** pp 133–157
[6] Eik K 2009 Iseberg drift modeling and validation of applied metocean hindcust data *Cold Region Science and Technologhy* **57** pp. 67–90
[7] Garbrecht T, Luphes C, Augstein E and Wamser C 1999 Influence of a sea ice ridge on low-level airflow *J. Geophysics. Res.* **104** pp 2449–24507
[8] Shinohara Y 1999 A redistribution function applicable to a dynamic sea ice model *J. Geophysics. Res.* **95** pp 13423–13431
[9] Marchenko A 2008 Thermodynamic consolidation and melting of sea ice ridges *Cold regions. Science and Technology* **52 (3)**
[10] Shinohara Y 1990 A redistribution foundation ice model. *J. Geophysics. Res.* **95** pp 13423–14431
[11] Gray J and Killworth P D 1996 Sea ice ridging schemes *J. Physics. Oceanogr.* **26** pp 2420–2428
[12] Julev S K and Belyaev K 2012 Probility distribution characteristics for surface ari-sea turbulent heat Aluxes over the global ocean *Journal of Climate* **25 (1)** pp 184–206
[13] Belyaev K P, Tuchkova N P and Cubash U 2010 Response of a coupled ocean ice atmosphere model to data assimilation in the tropical zone of the tropical zone of the Pacific ocean *Oceanology* **50(3)**
[14] Käser M and Dumbser M 2006 An arbitrary high-order discontinuous Galerkin method for elastic waves on unstructured meshes – I. The two-dimensional isotropic case with external source terms *Geophys. J. Int.* **166(2)** pp 855–877
[15] Käser M and Dumbser M 2006 An arbitrary high-order discontinuous Galerkin method for elastic waves on unstructured meshes – II. The three-dimensional isotropic case *Geophys. J. Int.* 167(1) pp 319–336
[16] Käzer M and Dumbser M 2008 A highly accurate discontinuous Galerkin method for complex interfaces between solids and moving fluids *Geophysics* **73(3)** pp T723–T725
[17] Käser M and Igel H 2001 Numerical simulation of 2D wave propagation on unstructured grids using explicit differential operators *Geophysical Prospecting* 49(5) pp 607–619
[18] Zhdanov M S 2002 *Geophysical Inverse Theory and Regularization Problems* Elsevier
[19] Zhdanov M S 2015 *Inverse Theory and Applications in Geophysics* Elsevier
[20] Landau L D and Lifshitz E M 1959 *Fluid mechanics* (Pergamon Press)
[21] LeVeque R 2002 *Finite volume methods for hyperbolic problems* Cambridge University Press
[22] Aki K and Richards P G 2002 *Quantitative seismology, theory and methods*, second edition, University Science Books, Sausalito, California
[23] Bording R P and Lines L R 1997 Seismic Modeling and Imaging with the Complete Wave Equation *SEG proceedings*
[24] Carcione J M, Herman G C and Kroode A P E 2002 Seismic modeling *Geophysics* **67(4)** pp 1304−1325.
[25] Chapman C 2004 Fundamentals of Seismic Wave Propagation *Cambridge University Press*
[26] Di Bartolo L, Dors C and Mansur W J 2012 A new family of finite-difference schemes to solve the heterogeneous acoustic wave equation *Geophysics* **77(5)** pp T187−T199
[27] Etgen J T and O'Brien M J 2007 Computational methods for large-scale 3D acoustic finite-difference modeling: A tutorial *Geophysics* **72(5)** pp SM223−SM230
[28] Hestholm S 2009 Acoustic VTI modeling using high-order finite differences *Geophysics* **74(5)** pp T67−T73
[29] Hobro J W D, Chapman C H and Robertsson J O A 2014 A method for correcting acoustic finite-difference amplitudes for elastic effects *Geophysics* **79(4)** pp T243−T255

[30] Jianfeng Z 1997 Quadrangle-grid velocity-stress finite-difference method for elastic-wave-propagation simulation *Geophys. J. Int.* **131(1)** pp 127–134

[31] Levander A. 1988 Fourth-order finite-difference P-SV seismograms *Geophysics* **53(11)** pp 1425–1436.

[32] Peter D, Komatitsch D, Luo Y, Martin R, Le Goff N, Casarotti E, Le Loher P, Magnoni F, Liu Q, Blitz C, Nissen-Meyer T, Basini P. and Tromp J 2011 Forward and adjoint simulations of seismic wave propagation on fully unstructured hexahedral meshes *Geophys. J. Int.* **186(2)** pp 721–739.

[33] Sanyi Y, Shangxu W, Wenju S, Lina M and Zhenhua L 2014 Perfectly matched layer on curvilinear grid for the second-order seismic acoustic wave equation *Exploration Geophysics* **45(2)** pp 94−104

[34] Seriani G, Priolo E, Carcione J M and Padovani E 1992 High-order spectral element method for elastic wave modeling, *62nd Annual International Meeting and Exposition, SEG, Extended Abstracts* pp 1285–1288.

[35] Tong P, Yang D and Hua B 2011 High accuracy wave simulation revised derivation, numerical analysis and testing of a nearly analytic integration discrete method for solving acoustic wave equation, International Journal of Solids and Structures **48** pp 56–70

[36] Van Vossen R, Robertsson J O A and Chapman C H 2002 Finite-difference modeling of wave propagation in a fluid-solid configuration *Geophysics* **67(2)** pp 618−624

[37] Wang X and Liu X 2007 3-D acoustic wave equation forward modeling with topography *Appl. Geophys.* **4** pp 8–15

[38] Zeng Y Q and Liu Q H 2004 A multidomain PSTD method for 3D elastic wave equations *Bull. seism. Soc. Am.* **94** pp 1002–1015

[39] Zhang W, Zhang Z and Chen X 2012 Three-dimensional elastic wave numerical modelling in the presence of surface topography by a collocated-grid finite-difference method on curvilinear grids *Geophys. J. Int.* **190(1)** pp 358–378

[40] Favorskaya A V, Petrov I B, Khokhlov N I, Miryakha V A, Sannikov A V, Golubev V I 2015 Monitoring the State of the Moving Train by Use of High Performance Systems and Modern Computation Methods *Mathematical Models and Computer Simulations* **7(1)** pp 50–60

[41] Muratov M V and Petrov I B 2013 Estimation of wave responses from subvertical macrofracture systems using a grid characteristic method *Mathematical Models and Computer Simulations* 2013 **5(5)** pp 479-491

[42] Golubev V I, Petrov I B and Khokhlov N I 2013 Numerical simulation of seismic activity by the grid-characteristic method *Computational Mathematics and Mathematical Physics* **53(10)** pp 1523−1533.

[43] Magomedov K M and Kholodov A S 1988 *Grid characteristic methods* Nauka, Moscow

[44] Kholodov A S, Kholodov Ya A 2006 Monotonicity criteria for difference schemes designed for hyperbolic equations *Computational Mathematics and Mathematical Physics* **46(9)** pp 1560-1588

[45] Kvasov I E and Petrov I B 2012 High-performance computer simulation of wave processes in geological media in seismic exploration *Computational Mathematics and Mathematical Physics* **52(2)** pp 302−313

[46] Favorskaya A V, Petrov I B, Muratov M V and Sannikov A V 2014 Grid Characteristic Method on Unstructured Tetrahedral Meshes *Computational Mathematics and Mathematical Physics* . 54(5) pp 837–847

[47] Favorskaya A V, Petrov I B, Shevtsov A V, Vasyukov A V, Potapov A P, Ermakov A S 2014 Combined Grid Characteristic Method for the Numerical Solution of ThreeDimensional Dynamical Elastoplastic Problems *Computational Mathematics and Mathematical Physics* **54(7)** pp 1176 – 1189

[48] Favorskaya A V, Petrov I B, Muratov M V, Biryukov V A, Sannikov A V 2014 Grid-Characteristic Method on Unstructured Tetrahedral Grids *Doklady Mathematics* **90(3)** pp 781 – 783
[49] Favorskaya A V, Petrov I B, Shevtsov A V, Vasyukov A V, Potapov A P, Ermakov A S 2015 Combined Method for the Numerical Solution of Dynamic Three-Dimensional Elastoplastic Problems *Doklady Mathematics* **91(1)** pp 111–113
[50] Favorskaya A V, Petrov I B, Vasyukov A V, Ermakov A S, Beklemysheva K A, Kazakov A O, Novikov A V 2014 Numerical Simulation of Wave Propagation in Anisotropic Media *Doklady Mathematics* **90(3)** pp 778–780
[51] Petrov I B, Favorskaya A V, Sannikov A V, Kvasov I E 2013 Grid-Characteristic Method Using High Order Interpolation on Tetrahedral Hierarchical Meshes with a Multiple Time Step Mathematical *Models and Computer Simulations* 5(5) pp 409–415
[52] Petrov I B, Favorskaya A V, Beklemysheva K A. Numerical Simulation of Processes in Solid Deformable Media in the Presence of Dynamic Contacts Using the Grid-Characteristic Method *Mathematical Models and Computer Simulations* 2014 **6(3)** pp 294–304
[53] Bathe K-J *Finite Element Procedures* (Prentice Hall, Upper Saddle River, New Jersey)