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The exploration of wave processes in the Arctics geological layers in the presence of the ice field

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Abstract: **The Arctic shelf zone is a very important region in our country due to the huge amounts of hydrocarbons, located there. The exploration of this region is difficult because of the presence of lots of various ice constructions, in particular, ice fields. While carrying out the seismic prospecting works, the reflected waves from the ice field contribute much to the seismograms. It sufficiently complicates the process of further interpretation of the seismograms. Only a few works are devoted to modelling the seismic waves spread through the geological layers of the Arctics in the presence of an ice field as this theme is rather new and needs deeper investigation. In this work we present the results of the investigation of the seismic waves spread in models with an ice field for the 3D case using the grid-characteristic method. The modelling results (wave fields of the velocity distribution and seismograms) allow to identify the reflected waves from the ice field from other waves. In addition, we carried out the comparative analysis of the wave fields and seismograms for the 2D model with an ice field on the surface of the calculated area for the problem description from the work of other authors. The results demonstrate a good qualitative coincidence under different approaches to the solution of the problem.**

Keywords: **seismic prospecting, numerical modelling, grid-characteristic method, ice field.**

UDC 519.63

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Contents

1. INTRODUCTION

Ice and different ice structures (icebergs, ice hummocks) bring in the significant noise into seismograms in the form of additional seismic waves [1,2]. Then, the seismograms are hard to interpret and separate the useful information about the reflected waves from hydrocarbon deposits from the noise, presented by the reflections from ice constructions. Besides, in the ice field additional waves spread along the whole surface of ice, which contribute much to the seismograms in the form of numerous reflections from the borders ice-air and ice-water.

In this work we carry out the research of influence of the ice field on the results of modeling – wave fields of the velocity distribution and seismograms. The ice field in the Arctic shelf zone is characterized by a small layer width in comparison with the length of the spreading waves, which demands the particular approach to the research conduction. The analytical solutions to the problems of the seismic waves spread in the models ice-water do not take into account all types of waves (Rayleigh waves, Scholte waves [3]), which appear in the ice layer in this kind of problems, and it leads to the incorrect or incomplete solution. In this work the solution to the problem of the seismic waves spread from the impulse source, located on the surface of the ice field, is carried out with the use of the direct numerical modeling by the grid-characteristic method of the third order of accuracy.

We conducted the computations of the model from [4] in order to compare the applied approach with the approach of other authors to the exploration of similar problems. The results demonstrated a good qualitative coincidence.

2. THE DETERMINANT EQUATIONS

For describing the seismic waves spread in geological media, we used the linear-elastic system of equations [5]:

$$\begin{aligned} &\rho \frac{\partial \mathbf{v}}{\partial t} = (\nabla \cdot \boldsymbol{\sigma})^{\mathrm{T}}, \\ &\frac{\partial \boldsymbol{\sigma}}{\partial t} = \lambda(\nabla \cdot \mathbf{v})\mathbf{I} + \mu\left((\nabla \times \mathbf{v}) + (\nabla + \mathbf{v})^T\right), \end{aligned} \tag{1}$$

where υ is the velocity of the seismic waves spread in the medium, σ is the Caushy stress tensor, t is the time, ϱ is the medium density, λ and μ are the Lame parameters, determining the elastic properties of the material.

3. NUMERICAL METHOD

The system of equations (1) was solved using the grid-characteristic method of the third order of accuracy [6,7]. We present the system (1) in the form:

$$\frac{\partial \mathbf{q}}{\partial t} + \mathbf{A}_x \frac{\partial \mathbf{q}}{\partial t} + \mathbf{A}_y \frac{\partial \mathbf{q}}{\partial t} = 0. \tag{2}$$

where matrixes $\mathbf{A}_x$ and $\mathbf{A}_y$ are made out of the coefficients of the system (1), the vector $\mathbf{q}$ consists of three components of the Caushy stress tensor and two components of the velocity vector: $q = \{\sigma_{xx}, \sigma_{yy}, \sigma_{xy}, \nu_x, \nu_y\}.$.

Then, we apply the method of splitting by the space coordinates and obtain two $1D$ systems of equations:

$$\frac{\partial \mathbf{q}}{\partial t} + \mathbf{A}_i \frac{\partial \mathbf{q}}{\partial i} = 0,\ i \in \{x, y\}. \tag{3}$$

Now we examine the system (3), for example, for the x coordinate:

$$\frac{\partial \mathbf{q}}{\partial t} + \mathbf{A}_x \frac{\partial \mathbf{q}}{\partial x} = 0. \tag{4}$$

The system (4) is hyperbolic, then it can be presented in the form:

$$\frac{\partial \mathbf{q}}{\partial t} + \mathbf{\Omega}_x \mathbf{\Lambda}_x \mathbf{\Omega}_x^{-1} \frac{\partial \mathbf{q}}{\partial x} = 0. \tag{5}$$

In (5) $\mathbf{\Omega}_x$ is the matrix, made out of the eigen vectors of the matrix $\mathbf{A}_x$, $\mathbf{\Lambda}_x$ is the diagonal matrix with the eigen values $\{-c_p, c_p, -c_s, c_s, 0\}$ on the diagonal, c_p and c_s are the longitudinal and the transverse sound velocities, correspondingly:

$$c_p = \sqrt{(\lambda + 2\mu)/\rho},\ \ c_s = \sqrt{\mu/\rho}. \tag{6}$$

The similar transformations can be made for the system (3) for the coordinate y.

After the variable change $\omega = \Omega_x^{-1} q$, the system (5) will look as:

$$\frac{\partial \omega}{\partial t} + \Lambda_x \frac{\partial \omega}{\partial x} = 0. \tag{7}$$

The system (7) consists of five equations, each of which can be solved by any finite-difference scheme. In this work we solved the system (7) with the help of the Rusanov scheme of the third order of accuracy [8]:

$$
\begin{aligned}
(p_i)_m^{n+1} &= (p_i)_m^n + \\
&+\lambda_i\tau\frac{6(p_i)_{m-1}^n - 3(p_i)_m^n - 2(p_i)_{m+1}^n - (p_i)_{m-2}^n}{6h} + \\
&+\frac{(\lambda_i\tau)^2}{2}\frac{(p_i)_{m+1}^n - 2(p_i)_m^n + (p_i)_{m-1}^n}{h^2} + \\
&+\frac{(\lambda_i\tau)^3}{6}\frac{(p_i)_{m-2}^n - 3(p_i)_{m-1}^n + 3(p_i)_m^n - (p_i)_{m+1}^n}{h^3}.
\end{aligned}
\tag{8}
$$

The system (8) is represented for the positive eigen values.

4. THE BORDER AND CONTACT CONDITIONS

On the side and low borders of the model we established the non-reflective boundary condition. On the upper contact border between ice and air the free boundary condition was used [9, 10].

Between the ice layer and the water layer the free slip contact condition was established.

$$v_n^1 = v_n^2 = V_n. \tag{9}$$

$$f_n^1 = -f_n^2. \tag{10}$$

$$f_\tau^1 = -f_\tau^2 = 0. \tag{11}$$

The condition (9) means the equality of the normal components of the velocity on the contact border between the layers 1, 2. The condition (10) means the equality of the normal components of stress tensor on the border, the condition (11) means the equality of the tangential components of stress tensor to zero on the border.

5. RESULTS

We examined the model of a heterogeneous medium with an ice field. The model consisted of the water layer 200 m high and the ice layer 3 m high. We computed the spread of the seismic waves from the impulse source, located on the surface of ice in the center of the calculated area. The central frequency of the impulse source was equal to 30 Hz.

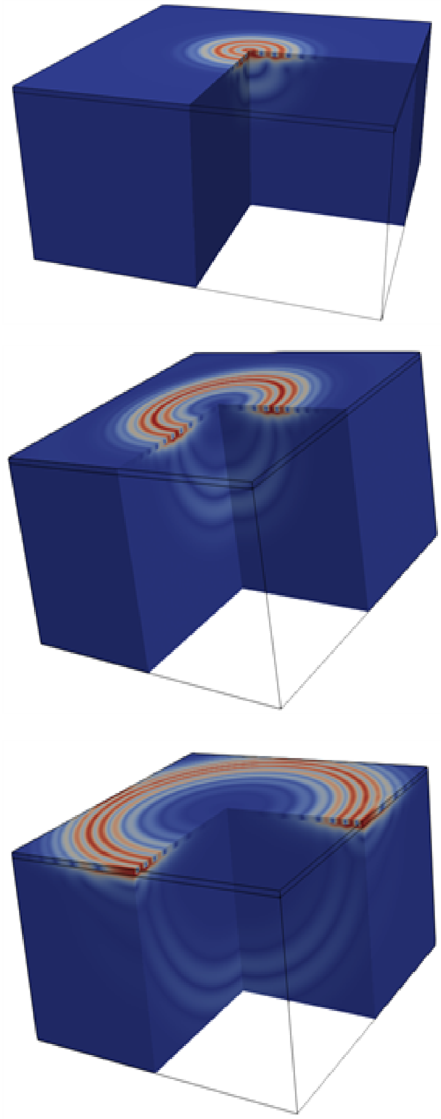

Fig. 1. *The wave fields of distribution of the velocity module for the model with an ice field at time moments 0.05 s, 0.07 s, 0.1 s.*

Fig. 1 presents the wave fields of the velocity module distribution for the model with an ice field. The wave fields give the opportunity to watch the consistent wave spread from the impulse source deep into the water layer. In the ice field the so-called multiple waves appear, which are obtained as a result of numerous reflections from the contact border ice-water and from the free border ice-air.

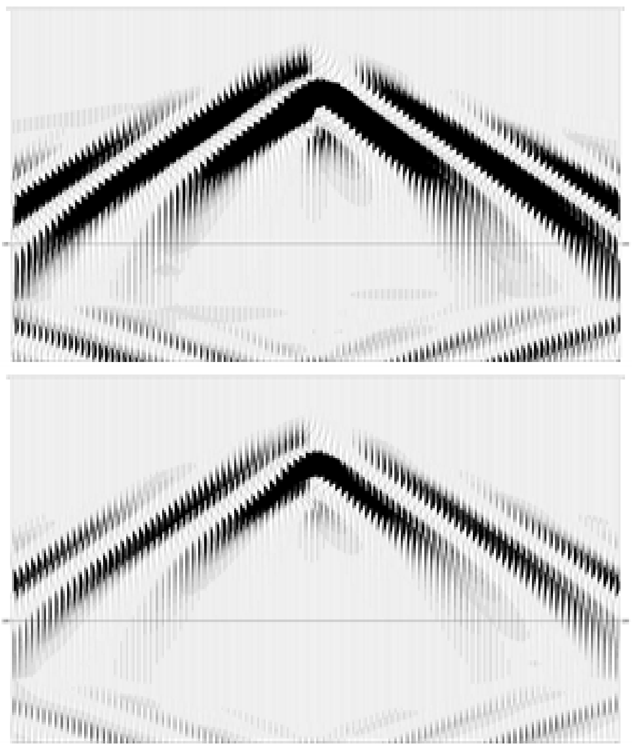

Fig. 2. *The seismograms of the recordings on the receivers for the velocity components V_x, V_z.*

On the surface of ice a row of seismic receivers was established for the registration of the reflected waves. The seismograms of the collected data on the receivers for the velocity components V_x, V_z are presented in **Fig. 2**. The number of the receiver (0-200) is depicted along the *x*-axis, the time of the arriving signal at the receiver is depicted along the y-axis. It follows from the seismograms that the spreading waves in the ice field contribute little to the result field of the reflected waves for the model, which further will allow to identify the reflected waves from oil, gas and other hydrocarbon deposits.

Next, we examined the model of a heterogeneous medium with the ice layer, the water layer and the soil layer, similar to the model from the work [4]. The density of ice was 931 kg/m^3, the density of water was 1004 kg/m^3, the soil density was 2700 kg/m^3. The longitudinal sound speed in ice was 3289 m/s, the longitudinal sound speed in water was 1448 m/s, and in soil it was equal to 1800 m/s. The transverse sound velocity in ice was 1657 m/s, and in soil it was equal to 1040 m/s. The height of the ice layer was 0.75 m, the height of the water layer was 22 m, the soil height was equal to 50 m.

The parameters of calculations were the following. The space step was 5 cm in order to consider the small height of the ice layer in the model correctly. The width of the model was equal to 800 m in order to avoid the reflections from the side borders of the model.

The seismic source of impulse with 100 Hz central frequency was located in the center of the calculated area on the surface of ice. 120 receivers of the reflected signals were located on the left from the impulse source with the distance of 3.125 m between them.

The wave field of the distribution of the velocity component V_x at 0.1 s time momemt for the described model is presented in the upper picture of **Fig. 3**, the wave field of the distribution of the velocity component V_y at the same time momemt is presented in the lower picture of Fig. 3.

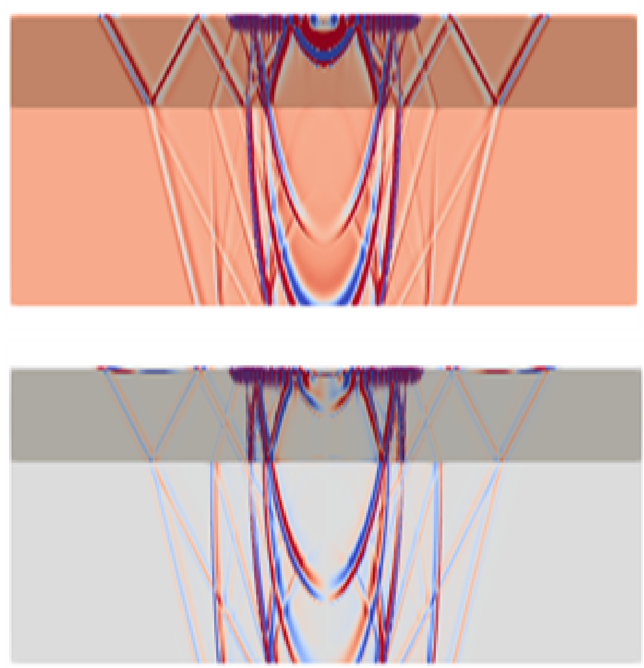

Fig. 3. *The wave fields of distribution of the velocity components V_x, V_y for the model with an ice field at time moment 0.1 s.*

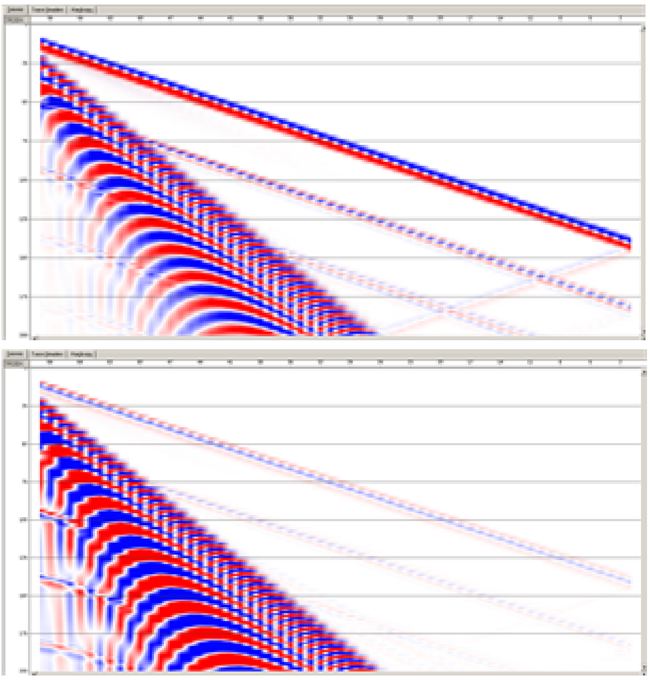

Fig. 4. *The seismograms of the recordings on the receivers for the velocity components V_x, V_y.*

The seismograms of the recordings on the receivers for the velocity components V_x, V_y for the model are presented in the upper and lower pictures of **Fig. 4**, accordingly.

The wave fields, presented in Fig. 3, and seismograms in Fig. 4 have a good qualitative coincidence with the similar modeling results from [4]. In the wave fields, different types of waves, spreading in the ice layer and in the water layer (flexural wave, longitudinal wave, Rayleigh wave and Sholte wave in the ice layer) can be detected.

6. CONCLUSION

In this work we presented the results of exploration of the seismic waves spread in the models with geological media in the presence of the ice field on the surface. The results of modeling, using the grid-characteristic method, showed the opportunity of identification of the reflected waves in the ice field from other reflected waves. We calculated the model with an ice field with the characteristics of the model from the work by other authors. The analysis of the modeling results showed a good qualitative coincidence of the results — wave fields of the velocity module distribution and seismograms. Further, we are going to carry out the research of models with other ice formations — icebergs, ice hummocks.

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