The numerical solution of the problem of the contact interaction in models with gas pockets

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Abstract. We present the solution to the problem of detecting the gas layers in the Arctic conditions through the numerical modelling of the seismic waves spread in the heterogeneous media. The grid-characteristic method of the third order of accuracy is used in all the computations. We build the models with the different numbers of the gas layers and analyze the full wave fields in the heterogeneous media and the anomalous fields, excluding the seismic reflections from all the geological layers except for the gas layers. The results demonstrate the possibility of applying the grid-characteristic method to solving these problems. The result seismograms allow us to determine the location of the gas layers through collecting the time moments of the coming reflections from the gas layers to the seismic receivers.

1. Introduction
The exploration of problems concerning the Arctic region is rather actual today due to the active development of the hydrocarbon deposits of the North areas in our country [1]. The hydrocarbons are usually situated very deep in the ground, which makes it difficult for the explorers to detect and, later on, extract them from there. One of the effective ways of detecting the hydrocarbons is the seismic prospecting of the geological areas [2]. During the seismic exploration of the territory, geologists establish the signal source and the signal receivers on the surface of the explored area. The impulse source sends the seismic waves into the depth of the geological area, and the receivers pick up the reflected waves from different inhomogeneities, recording the velocity of the returned waves. As a result, the seismograms are got on the receivers, that later are to be analyzed. The process of the real seismic works in the area is rather difficult and not always effective because of the variety of the seismograms interpretation. Therefore, the numerical modelling of the already investigated area (or which will be investigated in future) is carried out. There are two ways of solving the mentioned problem numerically. In the first one, scientists solve the inverse problem or the incorrect problem of calculating the media characteristics using the seismograms, collected earlier. In the second case, scientists solve the direct problem of calculating the velocities in the geological area, including the meanings on the surface, imitating the signal receivers. The second problem formulation is easier to solve, though it demands numbers of calculations in order to observe different cases of the media characteristics. In this paper we investigate the problem of detecting the so-called gas pockets in the Arctic conditions through the numerical modelling of the seismic waves spread in the heterogeneous media. Gas layers, closed from outside and, therefore, with great pressure inside,
are usually situated at depths of 900 - 1500 m under the surface and can be of great danger in case of their unintended opening [3]. Gas spreads all over the area and erupts into the surface, that can lead to the breakage of drilling rigs and even human deaths. That is why it is very important to explore the researched area carefully before starting any works.

In our previous work [4], we investigated the models with gas layers by applying the transparent method in the calculations. This method does not take into account the contact conditions between the geological layers, then, we lose the useful information about the seismic reflections between the layers. In addition, the order of accuracy on the contact borders between the layers, speeds to the first. In this work, we introduce the solution to the problem of the contact interaction between the homogeneous media in models with gas layers using the grid-characteristic method of the third order of accuracy [5, 6]. We describe the numerical method, used in all the calculations, and the equations, applied to the calculation of the meanings on the contact boundaries between the layers, in the first Section of the paper. In the second Section we introduce the results of the numerical modelling of the seismic waves spread through the heterogeneous medium with gas layers: wave fields and seismograms. Then, we conclude the paper in the last Section.

2. Numerical method

We used the system of equations, describing the waves spread in the linear-elastic medium [7]:

\[ \rho \frac{\partial}{\partial t} \vec{v} = (\nabla \cdot \sigma)^T \]  

\[ \frac{\partial}{\partial t} \sigma = \lambda (\nabla \cdot \vec{v}) I + \mu (\nabla \otimes \vec{v} + (\nabla \otimes \vec{v})^T) \]  

where \( \rho \) is the medium density, \( \vec{v} \) is the velocity, \( \sigma \) is the Cauchy stress tensor, \( \lambda, \mu \) are the Lame parameters, determining the elastic medium characteristics.

For solving the system (1), (2) we split the system in coordinates x, y and then applied the grid-characteristic method of the third order of accuracy:

\[ \frac{\partial \vec{q}}{\partial t} + \vec{\Omega}_x \vec{A}_x \vec{\Omega}_x^{-1} \frac{\partial \vec{q}}{\partial x} = 0 \]  

where \( q = (\sigma_{xx}, \sigma_{yy}, \sigma_{xy}, \nu_x, \nu_y) \), \( \vec{\Omega}_x \) is the matrix, constructed of the eigenvectors of the matrix, made of the coefficients of the system (1), (2) \( \vec{A}_x \) is the matrix, constructed of the eigenvalues of the matrix, made of the coefficients of the system (1), (2). The method for the y-coordinate can be written analogically.

The full adhesion contact conditions were established between different layers [8]:

\[ \vec{v}_l = \vec{v}_r = \vec{V} \]  

\[ \vec{\sigma}_l = -\vec{\sigma}_r \]  

On all the boundaries of the model we established the non-reflecting boundary conditions.
3. Results of the numerical modelling

We carried out the numerical modelling of the seismic waves spread through the heterogeneous medium, containing gas layers, with time. The medium consisted of nine layers, three of which contained the fluid-saturated sand. This layer of sand can slow down the process of gas spread, which allows geologists to detect it. The other layers, of which consisted the model, were supposed to let the gas go through them. Four models with the different number of gas layers, imitating the spread of gas with time, were calculated. The first model contained no gas, the second one - one gas layer, the third one - two gas layers, the fourth one - 3 gas layers. The first model is presented in fig. 1, where numbers 3, 5, 7 depict the gas-containing layers for the other three models. Two hundred receivers were established on the surface of the models, aiming to detect the seismic reflections from the contacts between the geological media and from the gas layers. As a result, we got the wave fields and the seismograms of the seismic velocities at different time moments.

The wave field for the first model without any gas layers is presented in fig. 1a. A great amount of seismic reflections can be seen in the figure, which are hardly differed. The wave field for the second model with one gas layer is depicted in fig.1b. The differences between these two models are hardly seen. Therefore, we analyzed the seismograms for the models, presented below.

![Wave field for the first model without gas layers.](image1)

![Wave field for the second model with one gas layer.](image2)

**Figure 1.** The wave fields for the models at time 0.7 sec.

The seismograms of the X-components of the velocity are presented in Fig. 2a, 2b, 2c, 2d. Fig. 2a depicts the seismogram for the first model without any gas layers, fig. 2b - the seismogram for the second model with one gas layer, fig. 2c - the seismogram for the third model with two gas layers, fig. 2d - the seismogram for the fourth model with three gas layers. The differences between the model with no gas layers and with the presence of gas layers can be seen in the centres of the seismograms at time 1 sec. for the second and first models (fig. 2a, 2b), at time 0.7 sec. for the third and first models (fig. 2a, 2c), at time 0.35 sec. for the fourth and first models (fig. 2a, 2d). These meanings of time correspond to the time, essential for the seismic impulse to go through the heterogeneous medium towards the upper gas layer and backwards if calculate. The seismograms of the anomalous fields for the models are presented in fig. 3a, 3b, 3c. The seismograms depict the X-component of the velocity, demonstrating only the reflections from the gas layers, if compare with the seismogram of the first model in fig. 2a. These graphs are easier to analyze if compare with the full fields, presented in fig.2b, 2c, 2d.
Figure 2. Seismograms for the four models.
4. Conclusions

In this paper, we presented the solution to the problem of the contact interaction between the homogeneous media in models with gas layers using the grid-characteristic method of the third order of accuracy. The numerical method and the contact conditions between the layers were described. The results of the computed models with the different number of gas layers demonstrated the effectiveness of the application of the grid-characteristic method to solving the problem of the correct calculation of the points on the contact boundaries between the different geological layers.

The seismograms with the full wave fields demonstrated the possibility of detecting the gas layers if we know the geological characteristics of the surrounding area. The anomalous fields on the seismograms (if distract the field with no gas layers) allowed us to learn the time moments of the seismic reflections, coming from the gas layers, and, therefore, calculate the location of gas layers.

Later on, this work can be used for solving the indirect problem of the gas layers detection by the seismograms, collected from the area. Numbers of models are to be built according to the real seismograms, and then, the computed seismograms are to be compared with the real ones in order to find the closest, and, as a result, determine the gas layers location.

Acknowledgments

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5. References

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