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The study of dynamical processes in problems of mesofracture layers exploration seismology by methods of mathematical and physical simulation

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Abstract: **The article is devoted to the study of the propagation of elastic waves in a fractured seismic medium by methods of mathematical modeling. The results obtained during it are compared with the results of physical modeling on similar models. For mathematical modeling, the grid-characteristic method with hybrid schemes of 1-3 orders with approximation on structural rectangular grids is used. The ability to specify inhomogeneities (fractures) of various complex shapes and spatial orientations has been implemented. The description of the developed mathematical models of fractures, which can be used for the numerical solution of exploration seismology problems, is given. The developed models are based on the concept of an infinitely thin fracture, the size of the opening of which does not affect the wave processes in the fracture area. In this model, fractures are represented by boundaries and contact boundaries with different conditions on their surfaces. This approach significantly reduces the need for computational resources by eliminating the need to define a mesh inside the fracture. On the other hand, it allows you to specify in detail the shape of fractures in the integration domain, therefore, using the considered approach, one can observe qualitatively new effects, such as the formation of diffracted waves and a multiphase wavefront due to multiple reflections between the surfaces, which are inaccessible for observation when using effective fracture models actively used in computational seismic. The obtained results of mathematical modeling were verified by physical modeling methods, and a good agreement was obtained.**

Keywords: **mathematical modeling, grid-characteristic method, physical modeling, elastic waves, exploration seismology, fractured media, mesofractures**

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Contents

1. INTRODUCTION

The problem of searching for fractured hydrocarbon reservoirs is one of the primary problems of geophysics, to the solution of which exploration seismology is involved [1,2]. The widespread use of traditional seismic technologies without sufficient justification for their application to unconventional seismic objects in many cases leads to ambiguous geological interpretation of seismic data, false ideas about the geological structure of the target object. The combined use of mathematical and physical modeling can improve the quality of seismic data interpretation.

Papers [3-6] are devoted to different approaches to fracture modeling. According to [7], several types of fractures are distinguished, depending on their size: microfractures, the opening of which is about tens of microns, and the length is several centimeters; mesofractures with an opening of the order of hundreds of microns, with a length of up to several meters, and macrofractures, the opening of which reaches the order of several millimeters or more, and the length – from tens to hundreds of meters.

For modeling microfracturing, the most optimal will be the use of effective models [8,9]. Meso- and macro-fracturing can be considered in more detail with discrete assignment of fractures in the integration domain. Papers [10,11] are devoted to the study of the formation of responses on macrofractures using this approach. This article will consider studies using mathematical and physical modeling of the formation of responses in mesofractures.

2. MATERIALS AND METHODS

2.1. Mathematical model and numerical method

For mathematical modeling, a linear elastic medium model is used. The computation uses a grid-characteristic method with a hybrid scheme of the 2nd order.

Wave processes in an elastic geological medium are described on the basis of the governing equations of the theory of a linearly elastic medium [12]. The state of an infinitely small volume of a medium, according to this model, obeys a system of two equations: a local equation of motion and a rheological relationship connecting stresses and deformations in the medium. They can be reduced to the form:

$$\rho \frac{\partial V_i}{\partial t} = \frac{\partial T_{ji}}{\partial x_j},$$
$$\frac{\partial T_{ij}}{\partial t} = \lambda \left(\sum\nolimits_k \frac{\partial V_k}{\partial x_k} \right) I_{ij} + \mu \left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i} \right). \quad (1)$$

where V_i – velocity components, T_{ji} – components of elastic tensor, ρ – medium density, λ and μ – Lame coefficients, I_{ij} – components of unit vector. Introducing the vector of variables u $\vec{u} = \{V_x, V_y, T_{xx}, T_{yy}, T_{xy}\}$, (1) can be reduced to:

$$\frac{\partial \vec{u}}{\partial t} + \sum\nolimits_{i=1,2} A_i \frac{\partial \vec{u}}{\partial \xi_i} = 0. \quad (2)$$

The numerical solution (2) is found using the grid-characteristic method [13]. We carry out the coordinate-wise splitting and change the variables to reduce the system to a system of independent scalar transport equations in Riemann invariants.

$$\frac{\partial \vec{w}}{\partial t} + \Omega_i \frac{\partial \vec{w}}{\partial \xi_i'} = 0, \quad i = 1, 2. \quad (3)$$

For each transfer equation (3), all nodes of the computational mesh are traversed, and for each node the characteristics are omitted. From the time layer n, the corresponding component of the vector $\vec{w}$ is transferred to the time layer n+1 by the formula

$$w_k^{n+1}(\xi_i') = w_k^n(\xi_i' - \omega_k \tau),$$

where τ is time step.

After all the values have been transferred, there is a reverse transition to the vector of the desired values $\vec{u}$.

The grid-characteristic method makes it possible to apply the most correct algorithms at the boundaries and contact boundaries of the integration domain [14,15].

The boundary condition can be written in general form as:

$$\boldsymbol{D}\vec{u}(\xi_1, \xi_2, \mathrm{t}+\tau) = \vec{\mathrm{d}},$$

where D – some matrix of size 9×3 in 3D-case (5×2 in 2D-case), $\vec{d}$ – some vector, u $\vec{u}(\xi_1, \xi_2, \mathrm{t}+\tau)$ – the value of the sought values of the velocity and the stress tensor components at the boundary point at the next time step.

2.2. Mathematical models of fractures

In real problems of exploration seismology, one has to deal with the inhomogeneity of the nature of the interaction of elastic waves with the surface of the fracture when passing through it. A fracture is a complex heterogeneous structure [7,16]. In some places, the flaps of the fractures are located at some distance and are separated by a saturating fluid or void [7], in some places adhesion is observed, when, under the action of pressure forces, the walls are close to each other [17]. In addition, fractures can be classified according to the nature of saturation: fluid or gas [7,17].

In the problem under consideration, discrete fracture models were used based on the concept of an infinitely thin fracture. The fracture was specified as a boundary or a contact boundary with a specific boundary condition.

a) Gas-saturated fracture

The gas-saturated fracture model well simulates the behavior of fractures filled with air or gas at shallow depths up to 100-150 m [17]. At great depths, under the influence of pressure, fractures with air are closed, and the gas acquires the properties of a liquid.

The fracture is specified as the boundary condition of free reflection on the fracture flaps:

$$\boldsymbol{T}\vec{n} = 0.$$

This model is applicable to the described situation. The speed of propagation of longitudinal elastic waves in the geological environment (1500 – 7000 m/s) is much higher than the sound speed in air (330 m/s) or natural gas (430 m/s) at low pressures. The speed of propagation of transverse waves in air is zero. Similarly, with densities (1000-3000 kg/m^3 versus 1.2 kg/m^3). Therefore, the reflection coefficient is approximately equal to unity.

Thus, a fracture filled with gas under a pressure close to normal can be considered empty and the boundary condition for a free boundary can be set, which gives a complete reflection of the incident wave.

b) Fluid-filled fracture

In most of the problems solved in practice, the fractures are filled with a fluid: water, oil, liquefied gas, etc. [7,11,17] Therefore, it was advisable to develop a model to describe such a situation.

A fluid-filled fracture is specified as a contact boundary with the condition of free sliding [11]:

$$\vec{v}_a \cdot \vec{n} = \vec{v}_b \cdot \vec{n},\ \vec{f}_n^{\,a} = -\vec{f}_n^{\,b},\ \vec{f}_\tau^{\,a} = \vec{f}_\tau^{\,b} = 0.$$

Such a contact boundary completely transmits longitudinal vibrations without reflection and completely reflects shear waves. This picture corresponds to a real situation: the values of the velocities of propagation of longitudinal waves in liquids and densities are comparable to the values of the velocities and densities of geological media; while the velocities of transverse vibrations in liquids are close to zero.

c) **Glued fracture**

At great depths, under the action of pressure, it happens that the flaps of the fractures touch so that the elastic waves almost completely pass through the fracture. In this case, it will be optimal to use the contact condition of complete adhesion [11]:

$$\vec{v}_a = \vec{v}_b, \ \vec{f}_a = -\vec{f}_b.$$

where $\vec{v}$ – the velocities of contacted points of contact boundaries, $\vec{f}$ – the force acting to the boundary. *a* – first, and *b* – second flap of fracture.

d) **Partially-glued fracture**

In real exploration seismology, there are partially stuck together fractures [11,17], in which part of the valve surface is stuck together, and part is separated by fluid or gas. Such fractures show partial transmission of the elastic wave front, which affects the amplitudes of the response waves on the seismograms.

A fracture model was developed, where gas saturation (fluid filling) and complete adhesion conditions were randomly set at different points of the valves. The number of certain points was regulated by a weighting coefficient – the gluing coefficient. Such a model made it possible to define gas-saturated and fluid-filled fractures with a percentage of glued points from 0 to 100%.

Since at some points the fracture reflects the wave front, and at others it passes, the superposition of scattered waves formed during interaction with all points is a response of a gas-saturated (fluid-filled) fracture with a lower amplitude.

2.3. Installation for physical modeling

To conduct research on physical models within the framework of this topic, an installation for ultrasonic seismic modeling (IUSM) is used. The installation is made according to a single-channel scheme and includes:

- a source of elastic vibrations from piezoceramics;
- receiver of elastic vibrations from piezoceramics;
- generator of exciting electrical impulses;

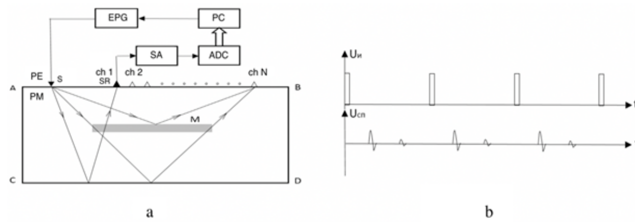

Fig. 1. *Functional scheme (a) and timing diagrams (b) of the setup for ultrasonic seismic modeling of the IUSM.*

- seismic amplifier;
- analog-to-digital converter;
- personal computer - a controller that controls all system nodes and stores simulation results.

The functional scheme of the IUSM is shown in **Fig. 1**.

An exciting pulse generator (EPG) generates voltage in the form of a sequence of short pulses. The source of seismic waves (*S*), connected to the EPG output, emits elastic vibrations - seismic waves - into the medium of the physical model (PM). Seismic waves of various types propagating in the medium are recorded by a seismic receiver (SR), which sequentially moves along the points (ch 1 - ch N) of the seismic profile. The signal from the seismic receiver (SR) output is amplified by the seismic amplifier (SA) to the required level and converted by an analog-to-digital converter (ADC) into digital form. Registration, processing of digital signals, recording in the standard seismic SEG-Y format and control of the system as a whole are performed using a personal computer (PC).

By moving the source and the seismic receiver along the given points of the seismic profile, it is possible to form a given observation system. The data is accumulated in the form of n-channel seismograms and can be processed according to the standard processing graphs used in exploration seismology.

2.4. Fractured layer physical modeling technology

The physical model was made from a sheet of plexiglass with dimensions of 1640×800×4 mm and simulates a homogeneous environment in which the investigated mesofractured layer of a given shape and given physical parameters is located. With the coefficient of geometric similarity K = 4000, it is possible to simulate a geological section with a size of 6560×3200 m. The IUSM installation uses signals with a signal frequency of the order of 40-50 kHz. Seismic waves propagate in a medium with velocities of longitudinal and shear waves V_p = 2200-2400 m/s и V_s = 1200-1300 m/s. Accordingly, seismic waves with a wavelength of λ = 5-6 cm.

In Fig. 1*a*, the side of the sheet AB corresponds to the surface, and the side AC corresponds to the depth. The CD side ("bottom" of the model) can be used as a very contrasting reference horizon. Taking into account the similarity coefficient K = 4000, the ultrasonic frequency signals are transformed into the low-frequency region with prevailing frequencies of the order of 10-12 Hz.

2.5. Methodology for comparing the results of mathematical and physical modeling

Both mathematical and physical simulation results are saved in the standard seismic SEG-Y format. The obtained data are processed in order to quantitatively compare the results. For a qualitative comparison of the results, visualization is performed in the form of seismograms in the SeiSee program.

3. RESULTS

3.1. Formulation of the problem

The problem of studying wave responses from a system of uniformly oriented mesofractures located at a depth of 1640 m is considered. The horizontal length of the formation is 2800 m, the vertical length is 120 m. The fractures are evenly distributed in the formation. The height of the fractures is 12 m, the distance between them is 12 m, the angle of inclination is 5 degrees. The observation scheme is shown in **Fig. 2.**

An excitation point is used, located on the day surface, its horizontal position coincides with

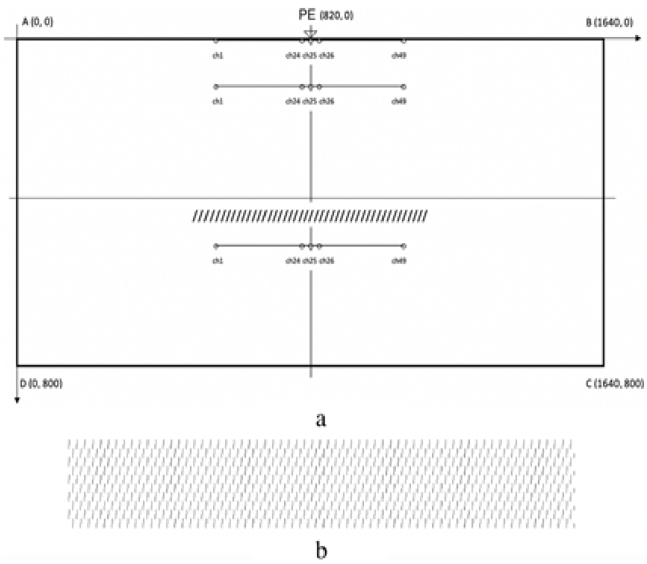

Fig. 2. *Observation scheme (a), detailing the picture of the location of fractures in the reservoir (b).*

the center of the fracture layer. The frequency of the excited seismic pulse is 10 Hz.

Three observation profiles are used, on which wave responses are recorded in the form of seismograms:

1) Reception points ch-1 – ch-49 are located on the day surface with an interval of 40 m to the right and left of the source, 24 sensors each. ch-1 – ch-49 sensors are located from left to right. ch-25 is combined with the excitation point.

2) Reception points ch-1 – ch-49 are located at a depth of 400 m with an interval of 40 m to the right and left of the source with 24 sensors each. ch-1 – ch-49 sensors are located from left to right. ch-25 is under the excitation point.

3) Reception points ch-1 – ch-49 are located at a depth of 2000 m with an interval of 40 m to the right and left of the source, 24 sensors each. ch-1 – ch-49 sensors are located from left to right. ch-25 is under the excitation point.

3.2. Results of mathematical and physical simulation

The solution to the problem was carried out jointly by the methods of mathematical and physical modeling. The results are shown in the figures – for mathematical modeling on the left, for physical – on the right. A fairly good agreement is seen.

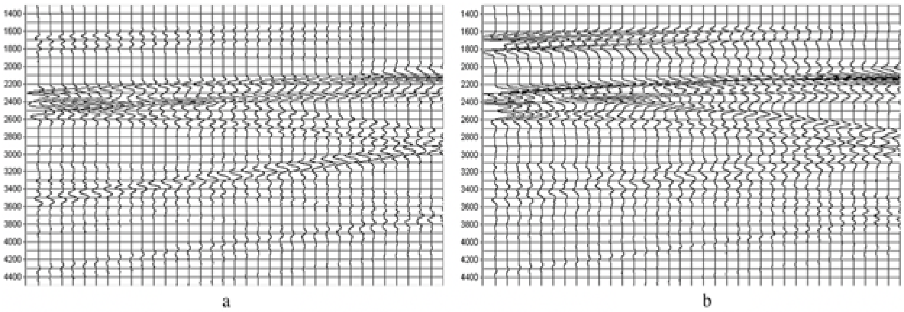

Fig. 3. *Results in the form of seismograms for the horizontal component, obtained using mathematical (a) and physical (b) modeling for the profile located on the surface.*

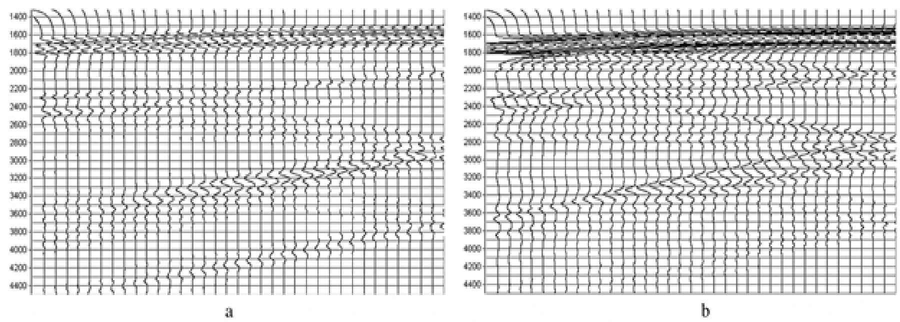

Fig. 4. *Results in the form of seismograms for the vertical component, obtained using mathematical (a) and physical (b) simulations for the profile located on the surface.*

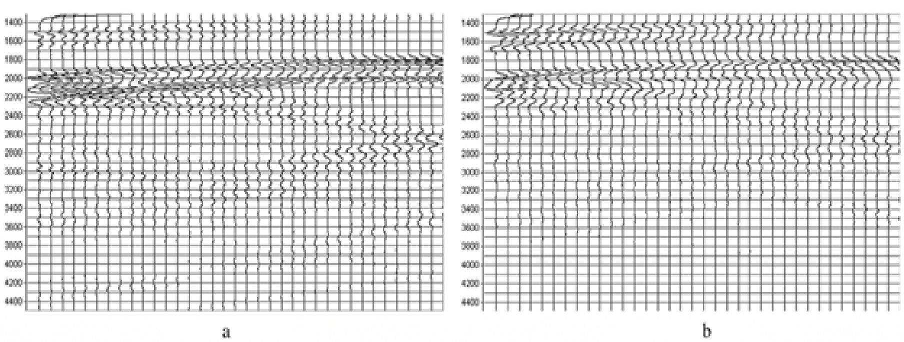

Fig. 5. *Results in the form of seismograms for the horizontal component obtained using mathematical (a) and physical (b) modeling for a profile at a depth of 400 m.*

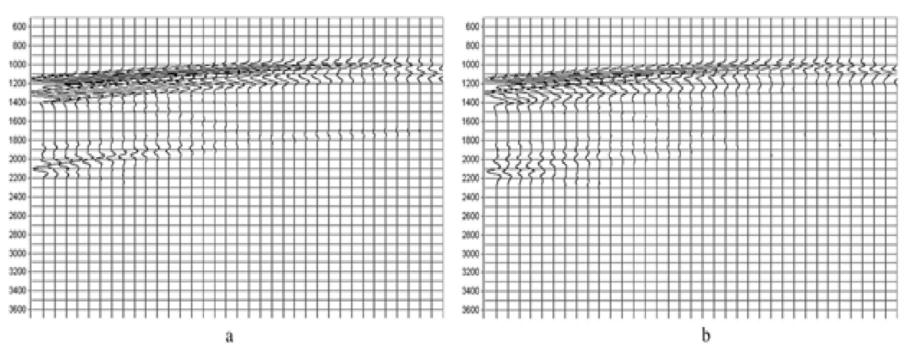

Fig. 6. *Results in the form of seismograms for the vertical component obtained using mathematical (a) and physical (b) modeling for a profile at a depth of 400 m.*

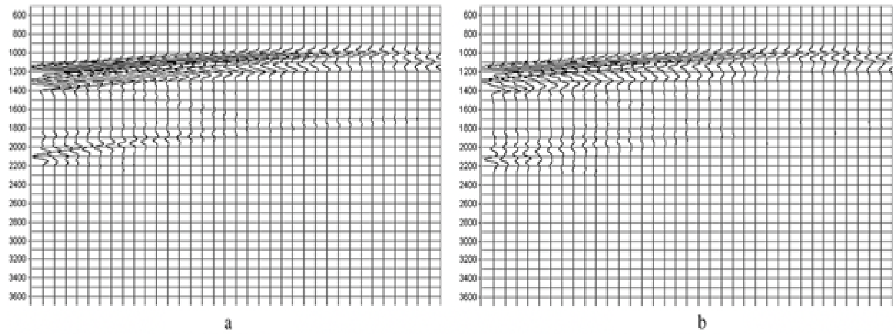

Fig. 7. *Results in the form of seismograms for the horizontal component obtained using mathematical (a) and physical (b) modeling for a profile at a depth of 2000 m.*

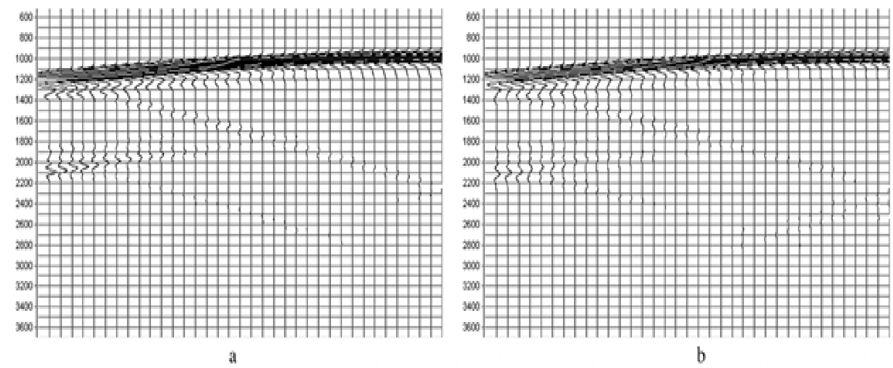

Fig. 8. *Results in the form of seismograms for the vertical component obtained using mathematical (a) and physical (b) modeling for a profile at a depth of 2000 m.*

4. CONCLUSION

The developed technique, based on the grid-characteristic method, makes it possible to carry out mathematical modeling for seismic exploration problems in layers of uniformly oriented mesofractures. Several fracture models based on the concept of an infinitely thin fracture have been developed to simulate heterogeneities with different types of saturation: gas-saturated, fluid-saturated, glued and partially glued gas-saturated and fluid-saturated fractures.

Numerical modeling of the problem of seismic prospecting of a layer of mesofractures in a formulation close to the real one with registration of wave responses in three receiver profiles is carried out. A similar problem was solved using physical modeling, the results of which verified the results of mathematical modeling.

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