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Direct seismic modeling: day surface topography and shallow subsurface anisotropy

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Abstract

Introduction. The article is devoted to one of the problems in the oil and gas fields development — the correct geological models construction of the subsurface space. Researchers from various scientific groups around the world have proposed various ways to improve the accuracy of the computer simulations used in this process. The purpose of this study is to assess the degree of the day surface relief and the anisotropy of the geological section upper part influence on the recorded seismic signal using a realistic model of the Orenburg field as an example.

Materials and methods. The seismogeological model describing the Orenburg geological section Lower Permian interval is considered. The elastic properties of geological formations were estimated according to well data: density and propagation velocities of longitudinal and transverse waves. There is a high contrast of P-wave velocities estimated from sonic logs. The reservoir is confined to the lower layers in this model. It is composed of sulfate-carbonate media, uniform in density and acoustic properties. Using the grid-characteristic method, zero-offset synthetic seismograms were calculated. The choice of structural curvilinear computational grids made it possible to correctly consider the relief of the day surface.

Research results. Two different models were compared in this work. The first model included the anisotropy of the section's upper part and the day surface topography. In the second model, the upper boundary of the computational domain was flat, and the entire medium was considered within the framework of an isotropic linear elastic model. The analysis of synthetic seismograms showed that the anisotropy inherent in this model does not significantly affect the recorded seismic wave field. However, considering the relief of the day surface significantly shifts the times of arrival of reflected waves.

Discussion and conclusion. The algorithm presented in the paper can be used to verify the field data processing graph, since the assessment of the anisotropy of the medium is a standard step in building a velocity model. The presented approach can be extended to 3D realistic dimensions models.

Keywords: mathematical modeling, seismic exploration, grid-characteristic numerical method, anisotropic media, day surface topography.

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Научная статья

Прямое численное моделирование: топография дневной поверхности и анизотропия верхней части разреза

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Аннотация

Введение. Одной из проблем разработки нефтегазовых месторождений является построение корректных геологических моделей подповерхностного пространства. Исследователями из различных научных групп во всем мире предложены различные способы повышения точности компьютерного моделирования, используемого в этом процессе. Цель настоящего исследования — оценка степени влияния рельефа дневной поверхности и анизотропии верхней части геологического разреза на регистрируемый сейсмический сигнал на примере реалистичной модели Оренбургского месторождения.

Материалы и методы. Рассмотрена сейсмогеологическая модель, описывающая нижнепермский интервал Оренбургского геологического разреза. По скважинным данным оценены упругие свойства геологических пластов: плотность и скорости распространения продольных и поперечных волн. Отмечается высокий контраст скоростей продольных волн, оцененных по диаграммам акустического каротажа. Резервуар в этой модели приурочен к нижним пластам. Он сложен сульфатно-карбонатными средами, однородными по плотности и акустическим свойствам. С использованием сеточно-характеристического метода были рассчитаны синтетические сейсмограммы нулевых удалений. Выбор структурных криволинейных расчетных сеток позволил корректно провести учет рельефа дневной поверхности.

Результаты исследования. В работе было проведено сопоставление двух различных моделей. В первую модель была включена анизотропия верхней части разреза и топография дневной поверхности. Во второй модели верхняя граница расчетной области была плоской, и вся среда рассматривалась в рамках изотропной линейно упругой модели. Анализ синтетических сейсмограмм показал, что анизотропия, присущая этой модели, не оказывает существенного влияния на регистрируемое сейсмическое волновое поле. Однако учет рельефа дневной поверхности заметно сдвигает времена прихода отраженных волн.

Обсуждение и заключение. Представленный в работе алгоритм может быть использован для верификации графа обработки полевых данных, поскольку оценка анизотропии среды является стандартным шагом при построении скоростной модели. Представленный подход может быть расширен на трехмерные модели реалистичных размеров.

Ключевые слова: математическое моделирование, сейсмическая разведка, сеточно-характеристический численный метод, анизотропные среды, топография дневной поверхности

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Introduction. The problem of considering the surface topography during seismic survey simulations attracts the attention of many researchers. The trivial approach is based on the stair-step approximation of the top domain boundary and finite-difference schemes [1] on rectangular grids. However, it leads to the appearance of additional source artifacts due to diffraction. The rotated staggered-grid modification was proposed to align the grid to the boundary interface. [2]. The use of finite-difference schemes on deformed grids does not allow describing very steep slopes in relief [3]. In [4], a pseudospectral method was proposed with the mapping of rectangular grids onto a curved surface, which also turned out to be unstable near strongly inclined boundaries. Apparently, an acceptable solution is to use finite element methods on nonstructural grids [5]. The disadvantage of this approach is a significant increase in the computational complexity of the task and the required RAM. In [6] an approach based on the combination of the discontinuous Galerkin with the finite difference method was developed. It allows to cover only the thin subsurface layer with an unstructured grid, while using the rectangular one in the rest of the geological model.

In elastic media with sharp variations of physical properties the grid-characteristic method can be effectively used [7, 8]. The method of superimposed grids was combined with it, which makes it possible to correctly describe curved boundaries [9]. This study uses a different approach. A separate curved grid is used to cover each geological layer, together with the explicit statement of contact conditions between the individual layers. This method preserves the advantages of the grid-characteristic method without leading to an excessive increase in the computational complexity of the problem. The paper takes into account the thin-layering of the upper part of the geological section using the widely used vertical transverse isotropic (VTI) model of the medium [10, 11].

The purpose of this work is to assess the degree of the daytime surface relief and the anisotropy of the upper part of the geological section influence on the recorded seismic signal using the example of the Orenburg field's realistic model.

Materials and methods. A significant amount of seismic survey is related to the investigation of oil and gas basins. These territories, being composed of sedimentary rocks, are thick strata of a thin layer interbedding. The formation conditions of sedimentary rocks determine the difference in physical properties of each layer. The geological history of each region determines the current position of the formed rock strata. Therefore, a characteristic feature is the presence of layers, laterally extended, but thin related to used seismic wavelengths. It provides the possibility to describe this geological medium by the VTI model. This model was formulated due to the registration of different velocities for vertical and inclined seismic rays in 1930-th. In this work, the seismic-geological model describing the Lower Permian interval of the Orenburg geological section was considered. The physical properties were evaluated based on borehole data from the Orenburg oil and gas condensate deposit (Fig. 1 *a*). Two main parts of the model were distinguished: (1) the thin-bedded upper interval corresponded to the Kungurian stage and (2) the lower one describing the Filippovsky horizon and the Artinsk stage. The first one was represented by pure salts and the interbedding of rock salt, anhydrites, and dolomites. A high contrast was noted in compressional wave velocities estimated by acoustic logging diagrams. The typical value for rock salt was 4500 *m/s*, for anhydrites — 6300 *m/s*, and for dolomites — in the range from 4500 *m/s* to 6500 *m/s* (Fig. 1 *b*). This interval affects kinematic characteristics of the wavefield and causes the anisotropy.

Figure 2 shows the field seismic data. The alternation of dolomite, salt and anhydrite layers induces dynamically pronounced reflections. The section shows a complex geometry of the reflecting boundaries of the upper interval and halokinesis processes, accompanied by the salt penetration into the overlying terrigenous strata. It can be assumed, that in areas of the contrast subhorizotal layer location, the anisotropy parameters will be different from the ones of salt diapirs. The reservoir in this model is confined to the lower strata. It is composed of sulfate-carbonate media, homogeneous in its density and acoustic properties. The reflective boundaries in this interval have low contrast. This fact is explained by the absence of acoustically rigid boundaries. According to the well logging, the interval is relatively homogeneous (Fig. 1 *a*). Based on the above description, an elastic two-dimensional model was developed. A thin-layered interval was described by the VTI model to achieve the desired accuracy.

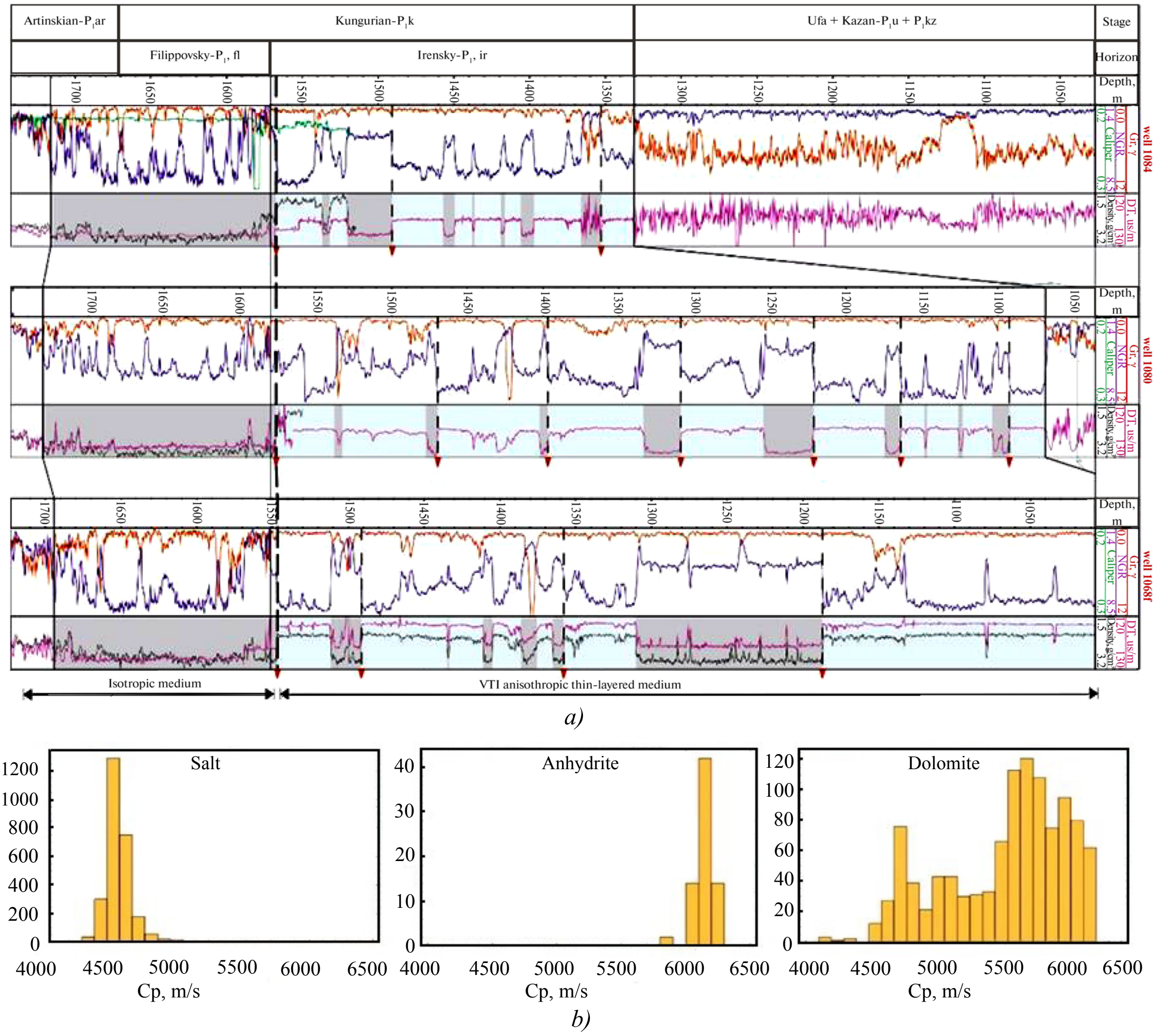

Fig. 1. The field measurements' results: *a* — Borehole data from the Orenburg oil and gas condensate deposit (by TNG-Group); *b* — P-wave velocity histograms based on sonic data

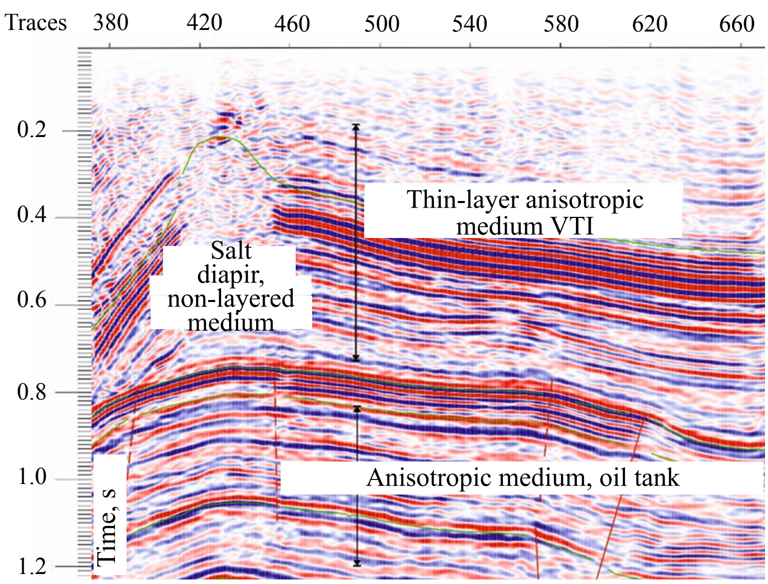

Fig. 2. The seismic section of the Orenburg deposit

The hyperbolic system of governing PDEs can be written in the canonical form:

$$\vec{q}_t + A_1\vec{q}_x + A_2\vec{q}_y = \vec{f},$$

where the vector $\vec{q}$ consists of all unknowns (velocity vector components and symmetrical stress tensor components). The space-dependent matrices A_1, A_2, are defined by the material parameters. In order to solve system (1) $\vec{q}_t + A_1\vec{q}_x = \vec{0}$, we apply the splitting technique to this 2D equation system: $\vec{q}_t + A_2\vec{q}_y = \vec{0}$ solve, firstly , secondly, solve and, finally, solve $\vec{q}_t = \vec{f}$. Thus, the multidimensional problem is reduced to a sequence of one-dimensional ones. The final step with the right-hand side can be easily and efficiently done, since it solves an ODE in each grid point. Each one-dimensional equation has the following form:

$$\vec{q}_t + A\vec{q}_\xi = \vec{0}.$$

The hyperbolicity of (1) ensures that matrix A has a full set of eigenvectors and can be represented as:

$$A = \Omega^{-1}\Lambda\Omega,$$

where matrix Λ is diagonal. The matrix A consists of eigenvectors of. Introducing the transformation to the Riemann invariants, a set of independent transport equations is obtained: $\vec{w} = \Omega\vec{q}$. The following relation is used for each equation: $\vec{w}_t + \Lambda\vec{w}_\xi = \vec{0}$, where the subscript I mark components of the vector:

$$w_i(x, t + \tau) = w_i(x - \lambda_i\tau, t),$$

After each one-dimensional step we return back to the original unknowns by: $\vec{q} = \Omega^{-1}\vec{w}$.

The critical difference between implementations of this method on rectangular grids and on structured curvilinear grids is that in the first case there are only two fixed directions along which the matrices **Ω** have a simple form and can be written analytically (even in case of space-dependent coefficients and matrices). In the case of the curvilinear mesh each point has a local coordinate system (ξ, η) along grid lines and matrix **Ω** and its inverse have to be found numerically (by an iterative procedure).

Research results. The wavefield in the described geological model was successfully simulated. The deformed grid was generated by the UNAMALLA software (Barrera et al. (2009)) and covered the region of 10 km × 5 km. The solution of one-dimensional transport equations was done by the Rusanov numerical scheme. The spatial time step was approximately 2 m. The time step was chosen to satisfy the CFL stability condition. Two different cases — with the anisotropy and topography and without both of them — were compared (Fig. 3). The careful synthetic data analysis reveals that the anisotropy inherent in this model doesn't influence the seismic wavefield significantly. On the contrary, the topography shifts noticeably arrival times of reflected waves.

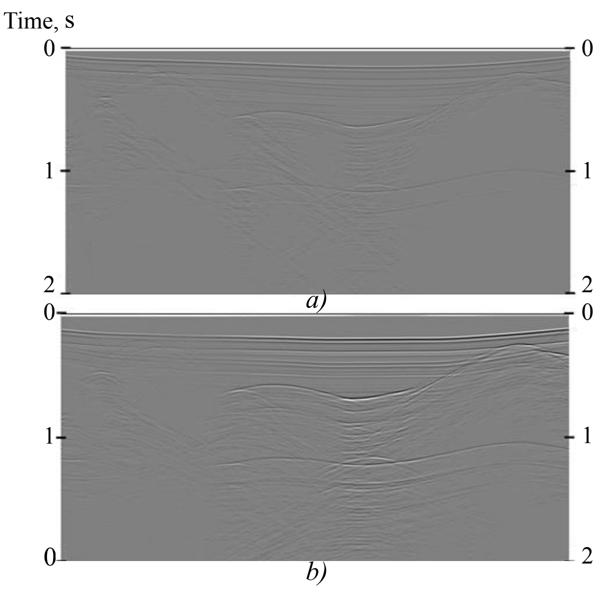

Fig. 3. Seismograms for the isotropic model with the flat day surface (*a*) and for the VTI model with the proper topography (*b*)

Discussion and conclusions. In this work the importance of the day surface topography and the shallow subsurface anisotropy influence on seismic survey data was discussed. The real Orenburg oil and gas condensate deposit was considered for the sake of clarity. The grid-characteristic method on structured grids was successfully applied to take into account anisotropy and topography of the model. The calculated wavefields reproduce the main features of the original seismic section, which indicates the model adequacy. The numerical simulations results represent a sufficient influence of considered facts on the day surface signal.

The presented algorithm can be used for the real data processing graph verification, since the VTI anisotropy estimation is a standard step while building a depth-velocity model [13]. The presented approach can be directly extended for real-scale three-dimensional problems.

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Claimed contributorship

V. I. Golubev: statement of the purpose and objectives of the study, preparation of the text, formulation of conclusions. A.V. Shevchenko: carrying out numerical calculations on an isotropic model without relief. A.V. Ekimenko: construction of a geological model, analysis of the results of numerical calculations. V. Yu. Petrukhin: carrying out calculations on an anisotropic model with relief.

Conflict of interest statement

The authors declare that there is no conflict of interest.

All authors have read and approved the final version of the manuscript.