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ASSESSMENT OF GROUND SURFACE SUBSIDENCE DURING CHAYANDA FIELD DEVELOPMENT WITH REGARD TO CHANGES IN PETROPHYSICAL PARAMETERS OF OIL AND GAS RESERVOIRS

The geodynamic consequences of long-term mineral mining can involve both extensive ground surface subsidence in the mining area and local activations of fault zones. Estimates of the ground surface subsidence in Chayanda field of hydrocarbons in Eastern Siberia are considered. The nature of changes in the pore space of the Vendian-age Botuoba, Talakh and Khamakin reservoirs was studied by modeling the development of the field up to depletion at the increasing effective pressure from 37.0 to 50.0 MPa. It is revealed that the average value of the porosity coefficient will decrease from 8.976% to 8.916%, the compressibility of the pore space will decrease from 2.844 to 2.616 1/GPa by 0.228 1/GPa or by 8.0% relative to the beginning of development.

Estimates of the possible subsidence values in the modeling of the field development process were made using Kuzmin's genetic model of a deformable reservoir. The parameters of the geomechanical model of productive gas-bearing layers were adopted in accordance with the geological and structural characteristics of the field. The maximum values of possible surface subsidence in the field development modeling are estimated as 33.0 cm and 33.5 cm at the decrease in the reservoir pressure by 5 MPa with and without regard to the dynamics of petrophysical parameters, respectively. When the reservoir pressure decreases by 13 MPa, the maximum subsidence is estimated as 78.0 cm and 83.0 cm with and without regard to the dynamics of petrophysical parameters.

The studies have shown that taking into account the dynamics of petrophysical characteristics of reservoirs during long-term development of hydrocarbon deposits significantly diminishes the values of ground surface subsidence above the field and reduces the level of geodynamic risk of oil and gas facilities.

Keywords: *reservoir, porosity, pore compressibility, reservoir fluid pressure, ground surface subsidence, hydrocarbon field development, geomechanical modeling*
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Introduction

As known, geodynamic (deformation) consequences of long-term development of oil and gas fields can have two forms: extensive subsidence of the entire field and local deformation activation of fault zones [1–6]. It is noteworthy that numerous geodetic measurements carried out in oil and gas-bearing areas, both seismically active and aseismic regions, including shelf fields and underground gas storage facilities, showed identical manifestation forms of anomalous geodynamic activity caused by a decrease (increase) or cyclic change of reservoir pressure [7]. The relevance of the research into recent geodynamics of oil and gas fields is governed by the increased level of the environmental and industrial hazards of infrastructure facilities in the fields being developed.

It is well known that the values of such reservoir characteristics as porosity and pore space compressibility decrease with decreasing reservoir pressure and increasing effective stress in the course of oil and gas field development. This is especially relevant for gas fields which are nearly depleted. It appears that the most contrasting and intense changes in the mentioned poroelastic parameters are experienced by reservoir rocks with fractured porosity [8, 9]. Porosity, compressibility and their changes are among the main parameters of reservoirs, that need to be determined at the stage of the hydrocarbon field development project. On the other hand, it is important to estimate the change in the final estimated amplitude of ground surface subsidence with a decrease in the poroelastic parameters in the mining period, especially the pore space compressibility.

In this paper, in terms of the example of the Chayanda field in Eastern Siberia, based on the core petrophysics studies, geomechanical modeling is carried out and the comparative assessment of the ground surface subsidence amplitude over the period to 2120 is given with and without regard to the changes in the petrophysical properties of reservoir rocks during the whole mining period.

Experimental research procedure and equipment

Experimental studies allow direct measurement of the volume of pore fluid squeezed out of a rock sample with an increase in the confining pressure, and calculating both the change in porosity and the volumetric deformation of the sample. The latter was calculated taking into account the well-known fact that the compressibility of the pore space was several orders of magnitude higher than the compressibility of the rock matrix.

The porosity factor m under conditions simulating reservoir conditions was determined with regard to the volume of fluid displaced from the pore space of the sample from the formula:

$$m = m_{ac} - \Delta V_{por}/V, \quad (1)$$

where m_{ac} is the porosity factor under atmospheric conditions, %; ΔV_{por} is the volume of pore fluid squeezed out of the sample (change in pore volume), cm^3; V is the sample volume, cm^3.

The pore space compressibility C_{por} was found from the formula:

$$C_{por} = (\Delta V_{por}/V_{por})/\Delta P_{eff}, \quad (2)$$

where ΔV_{por} is the change in the pore space volume, cm^3 (volume of pore fluid squeezed out of the sample); V_{por} is the volume of the pore space in the sample, cm^3; ΔP_{eff} is the change in effective pressure, GPa.

The effective pressure in the reservoir is taken as the difference between the lithostatic (confining) pressure due to the overlying rock weight and the pressure of fluid (in our case, gas) in the reservoir.

Using the high-pressure equipment, the effective pressure was increased by steps, with an increase in the confining pressure and with the pore pressure unchanged. At each step of the effective pressure, the volume of pore fluid squeezed out of the sample was measured and the porosity and pore space compressibility were calculated using formulas (1) and (2).

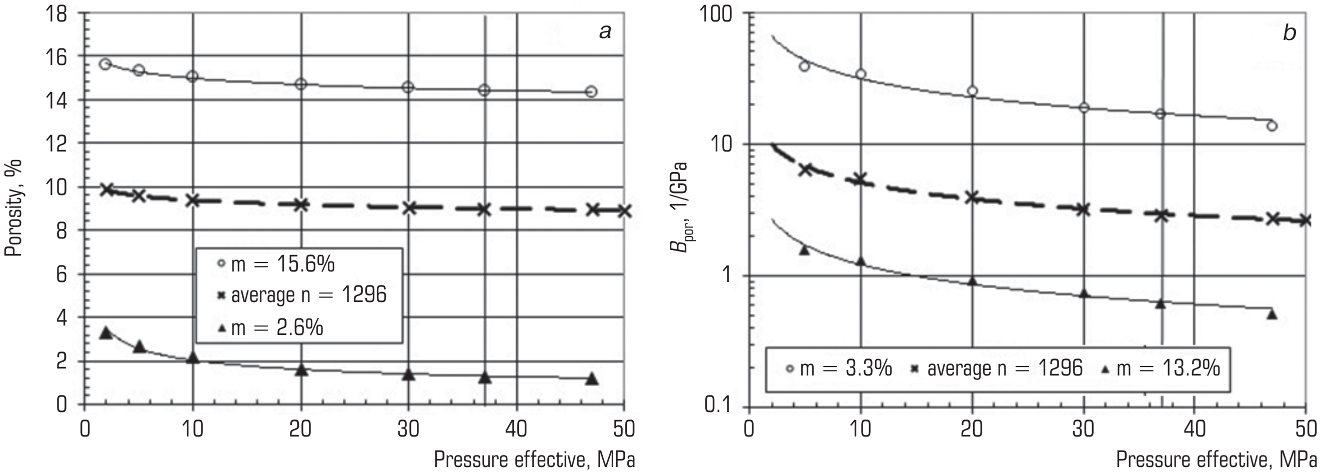

Fig. 1. Changes in (*a*) porosity and (*b*) pore space compressibility versus effective pressure

Results

Change in porosity. The results of the experimental studies have shown that the dependence of the average porosity factor m on the effective pressure P_{eff} (**Fig. 1a**) can be described at high confidence ($R^2 = 0.99$) by the relation:

$$m = 10.067 \cdot P_{eff}^{-0.031}. \quad (3)$$

When developing a reservoir, the reservoir pressure reduction by 10 MPa (the increase in the effective pressure by 10 MPa) will result in a decrease in porosity in absolute percentages from 8.976% to 8.933% or by 0.043%. Taking the porosity value of 8.976% at the beginning of mining (at P_{eff} of 37 MPa) as 100% and comparing it with the porosity at the effective pressure of 47 MPa (8.933%), it turns out that it decreases by 0.48%. By the end of the mining period, the increase in the effective pressure can reach 13.0 MPa, and the porosity will decrease to 8.916% (absolute) or 0.061% relative to the beginning of mining operations.

Change in pore space compressibility. It is found that the dependence of the average value of the compressibility on the effective pressure (**Fig. 1b**) at high confidence ($R^2 = 0.97$) is described by the power equation:

$$B_{por} = 13.282 \cdot P_{eff}^{-0.415}. \quad (4)$$

The increase in the effective pressure during the reservoir development by 10.0 MPa will reduce the average value of the pore space compressibility from 2.844 1/GPa (at P_{eff} 37 MPa) to 2.685 1/GPa (at P_{eff} 47 MPa) or 0.160 1/GPa, which means its decrease by 5.62% relative to its value at the beginning of mining. At the final stage of development, the increase in the effective pressure may reach 13.0 MPa, and the pore space compressibility will decrease to 2.616 1/GPa or 0.228 1/GPa (8.01%) relative to the beginning of mining.

Reservoir models

Hydrocarbon reservoirs in the test field are confined to productive terrigenous, slightly tilted horizons of the Vendian age at the occurrence depth of 1420–2020 m [10]. The reservoirs were modeled by prismatic bodies of a certain length, width and thickness, separately for each productive horizon: Botuoba, Khamakin and Talakh, and together as a single formation (**Fig. 2**).

The development period of these productive formations is assumed to be equal to 100 years: 2020–2120. Development is carried out in gas mode, that is, up to depletion. The combined geomechanical model of the productive Botuoba, Khamakin and Talakh horizons can, as a first approximation (see Fig. 2), be a prism with an average thickness of 42.7 m at a depth of 1710 m (absolute elevation of 1270 m).

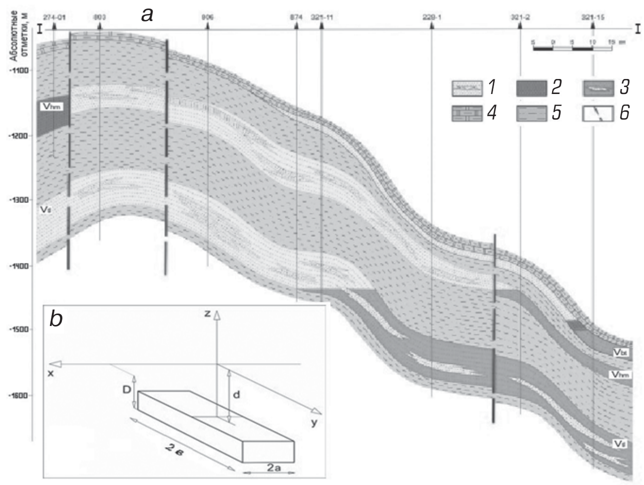

Fig. 2. Schematic profile section of Chayanda oil and gas horizons according to [10] (a) and prismatic model of each productive layers (b):

1 – gas-bearing sandstones; *2* – oil-bearing sandstones; *3* – water-bearing sandstones; *4* – mudstones; *5* – clayey dolomites; *6* – tectonic faults

The productive reservoirs were modeled by rectangular prisms with geometric characteristics: width 2a, length 2b, occurrence depth of the upper d and lower D boundary of the effective gas-bearing part of the reservoirs and the average reservoir depth H (see Fig. 2b). For the calculation, the following parameters of productive gas-bearing formations were used to simulate geological and structural characteristics of the Chayanda field. Botuoba reservoir (V bt): $2a = 40$ km, $2b = 80$ km, $D\text{-}d = 7.1$ m, $H = 1.71$ km. Khamakin reservoir (V hm): $2a = 60$ km, $2b = 115$ km, $D\text{-}d = 12.2$ m, $H = 1.70$ km. Talakh reservoir (V tl): $2a = 60$ km, $2b = 85$ km, $D\text{-}d = 23.4$ m, $H = 1.75$ km.

Modeling reservoir pressure dynamics

The reservoir pressures in the Chayanda field vary from 11.9 to 13.4 MPa, i.e. from conditionally hydrostatic to abnormally low [11]. The field development project involves regulation of gas extraction from individual blocks of the field to ensure a balanced composition of the produced gas. Horizontal and sub-horizontal wells are used for gas production. The wells are located in areas of maximum density of reserves and are clustered to be off river channels, mountain ranges and specially protected natural areas. The geological structure of the field, the patterns of the well clusters and the well profiles are continuously updated based on the new drilling data [12].

For reliable prediction of fluid reservoir pressure in the course of mining, it is necessary to set gas production and well production rates taking into account a large number of factors. As a first approximation, it can be assumed that the fluid reservoir pressure will decrease from 13.1 MPa to 8.1 MPa by 2030 and to 3.1 MPa by 2060.

Modeling ground surface subsidence during productive reservoir development

To date, there exist some models of ground surface subsidence, which can be conditionally divided into 3 groups. ***The first group*** includes semi-analytical (engineering) models. J. Geertsma in the well-known article [13] first used this approach. It involved the empirical compaction coefficient which was obtained from the numerous test data of core material under uniaxial compression. The value of this empirical coefficient is chosen depending on the porosity and mineralogical composition of rocks. In the model, it is assumed that the ground surface subsidence takes place due to compressibility of the reservoir. Then, the same ideas were used in the works [14–16]. However, in reality, deformation embraces the reservoir under development and the surrounding rock mass, including the overlying strata.

The second group is analytical models which assess deformation of the whole rock stratum, including the vicinity of the reservoir. Even J. Geertsma used the well-known mathematical formalism of "deformation nuclei" based on Green's functions [17]. The author obtained formulas for the distribution of vertical and horizontal displacements of ground surface above a disk-shaped reservoir. Later on, using the concept of fluid diffusion in the framework of the Rice–Clery poroelastic theory, P. Segall constructed the closed analytical solutions [18, 19] linking the production parameters with the change in the stress–strain behavior in neighborhood of the reservoir for the conditions of a plane problem. The further development of these concepts [20–23] was based on the adjustment of the development modes and rheological parameters of rocks. Note that all models–analogues of the layers being mined were axisymmetric (sphere, disk, ellipsoid of rotation), and were placed in the elastic weightless half-space.

In the Russian Federation, the most widespread analytical model is the deformable prismatic body by Kuzmin–Chernykh [2, 24]. The model produced formulas for the horizontal and vertical displacements of the surface of the elastic half-space inside which an object of regular geometric shape (rectangular parallelepiped) was placed. The difference of the approach implemented in [2] consists in taking into account the weight of the medium and the genesis of the formation of a reservoir. Estimates have shown that additional subsidence, due to the influence of the weight of the formation, reaches 15–20%. In addition, the genetic component was taken into account. As a rule, mineral deposits are structures of the anticlinal type, i. e. bending of the rock stratum overlying the reservoir.

The genetic correction accounts for the force that formed the reservoir itself. There is a balance of three factors that form the final subsidence: the drop in reservoir pressure, which reduces the volume of the reservoir and leads to subsidence of the surface, the weight of the overlying strata above the reservoir, which adds subsidence, and the genetic factor, i.e., the upward forces that form the anticlinal uplift and reduce subsidence. The competition of these three forces leads to the formation of the final amplitude of ground surface subsidence during field development. It is important to note here that analytical modeling makes it possible to create hybrid (numerical-and-analytical) models, when, using the principle of superposition of solutions from prismatic elements of various sizes, it is possible to simulate reservoir conditions with a complex geological structure.

The third group includes a number of numerical and laboratory models, which, unlike analytical models, can, using the finite or boundary element methods, take into account the more complex geometry of the reservoir, thereby dividing it into separate elements [25–27]. At the same time, it should be noted that when dividing the productive formation and the enclosing rock strata into a large number of "cubes", in view of the lack of initial geological and field information, it is necessary to use a certain average value of porosity, compressibility, etc. as the filling of these cubes. This fact is a significant limitation of numerical models when used to analyze vertical and horizontal displacements of the surface and their attenuation with distance. Particularly acute issue is the lack of data to determine the pore space compressibility. This indicator is obtained from the petrophysical analysis of cores taken in wells. As a rule, such wells are very few in number even in large oil and gas fields.

Approach suggested by the authors. The compressibility of the pore (intergranular and fractured) space is one of the key parameters for assessing ground surface subsidence, and, a researcher using the finite element methods, despite the detailed geometry of the reservoir, comes to a geomechanical model of a productive reservoir field which has a heterogeneous structure but homogeneous deformation properties. It is important to note that, for example, displacement gradients in this model have to be calculated in each specific finite element, and then summed over the entire reservoir, which is also not a completely correct procedure.

Therefore, when it is necessary to analyze mechanisms of ground surface subsidence and, especially, distribution of displacement gradients, it is advisable to use the genetic model of a deformable reservoir. This model has been repeatedly tested in a number of fields (including offshore deposits) and underground gas storage facilities, where the calculated displacements are directly compared with the results of mine surveying and geodetic monitoring [7, 28].

To calculate the subsidence, the genetic model of a deformable reservoir was used [2]. The formula of the vertical ground surface displacements (Uz) is of the product of two factors:

$$Uz = F \cdot G. \quad (5)$$

The physical factor F includes such parameters as the porosity m, the pore space compressibility B_{por}, as well as the change in the reservoir pressure ΔP_{por}. The ground surface subsidence which can be expected ion the long-term development of productive strata was modeled for three intervals of time: from 2020 to 2030, from 2020 to 2080 and from 2020 to 2120 (**Figs. 3 and 4**).

The geometric factor G in formula (5) takes into account the length of the reservoir ($2a$), the width ($2b$), the depths of the upper edge (d) and lower edge (D), the thickness of the reservoir (D-d) (see Fig. 2), as well as the average depth of the reservoir (H). These geometrical dimensions of the reservoir were taken on the basis of geological profiles along and across the strike of the field [10].

With regard to the close values of the average porosity in all three productive reservoirs, as the initial, we used the average values of porosity and pore space compressibility at the reservoir pressure of 13.1 MPa at the beginning of field development in 2020: $m = 8.976\%$; $B_{por} = 2.844$ 1/GPa.

Influence of change of petrophysical parameters on final assessment of subsidence

When carrying out model estimates, a situation arises when detailed calculations are based on a limited number of experimental data on the mechanical parameters of the simulated medium: the value of Young's modulus, Poisson's ratio, rock compressibility and pore volume compressibility.

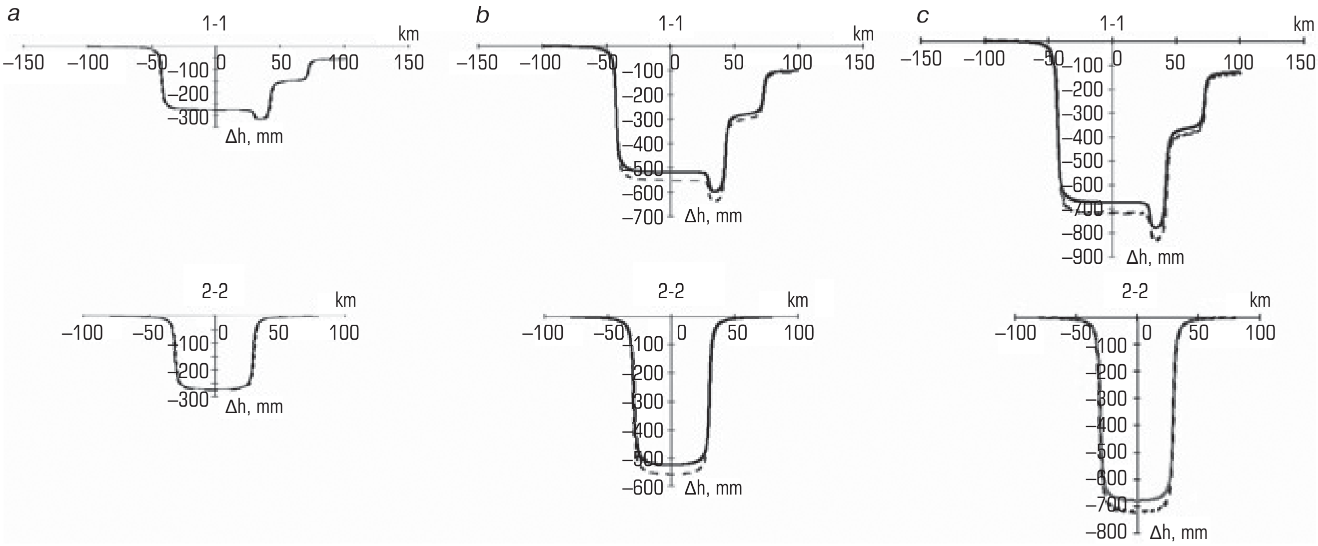

Fig. 3. Modeling of vertical displacements in profiles along (1-1) and across (2-2) of the field during development:
a – at P_{por} = 8.1 MPa, 2030; *b* – at P_{por} = 3.1 MPa, 2060; *c* – at P_{por} = 0.1 MPa, 2120

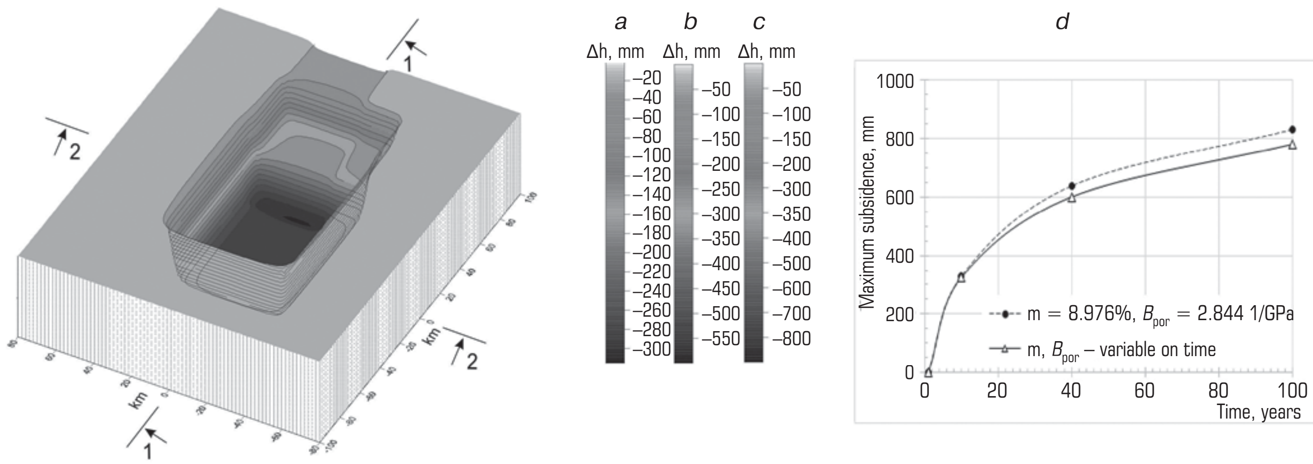

Fig. 4. Volumetric distribution model:
a – scale at P_{por} = 8.1 MPa, 2030; *b* – scale at P_{por} = 3.1 MPa, 2060; *c* – scale at P_{por} = 0.1 MPa, 2120; *d* – summary graph of maximum subsidence at constant porosity values (m = 8.964%) and pore space compressibility (B_{por} = 2.844 1/GPa) and with regard to their changes over time during field development

Researchers often neglect the fact that in the course of field development with the decrease in fluid pressure in the reservoir over time, the mechanical parameters of the reservoir rocks can also change [8, 29–32] and significantly affect the calculated (predicted) value of subsidence. For a more accurate prediction, when calculating subsidence, changes in the porosity coefficient (see Fig. 1a) and the pore space compressibility (see Fig. 1b), accompanying an increase in the effective pressure during field development, were taken into account. To this effect, the results of laboratory studies of the petrophysical parameters of rocks sampled at the depths studied by us were analyzed.

Vertical displacements were plotted with regard to the changes in porosity and pore space compressibility during field development at P_{por} of 8.1 MPa and 3.1 MPa (see Figs. 3 and 4). Moreover, for the visual illustration and comparison, displacement curves obtained without regard to the changes in porosity and compressibility of productive rocks were given.

Discussion

In the first case, at the decrease in the reservoir fluid pressure from 13.1 MPa in 2020 to 8.1 MPa in 2030, that is, 10 years after the start of the field development, the vertical displacements of the maximum amplitudes of 330 and 325 mm were obtained (Figs. 3a and 4a). In the second case, the assessment of the vertical displacements at the reservoir pressure of 3.1 MPa gives the values of 638 and 600 mm in 2060, i.e. after 40 years (Figs. 3b and 4b). Thus, it is shown that taking into account the change in the porosity and the pore compressibility significantly reduces the displacements amplitudes and has a cumulative character over time. If in 2030 the difference in the value of the vertical displacements will be only 5 mm, then by 2060 the discrepancy will be 35 mm.

This means that when calculating vertical displacements (subsidence) in reservoir fields, it is important to take into account the changes in the porosity over time and especially the compressibility of the pore space. Otherwise, the geodynamic risk of industrial safety will be significantly overestimated. The geodynamic hazard assessment is based on the gradients of displacements [2]. That is why, when modeling ground surface subsidence, it is necessary to take into account all varied factors in the process of field development in order to obtain a more accurate final result.

Conclusions

The analysis of changes in petrophysical parameters of gas-bearing reservoirs of Botuoba, Talakh and Khamakin horizons of the Vendian age during physical modeling of development of the Chayanda hydrocarbon field to depletion at the decrease in the reservoir fluid pressure by 10 MPa has shown that the decrease in the porosity coefficient will be 0.060 absolute percent. The pore space compressibility decreases by 0.228 1/GPa.

The maximum values of possible ground surface subsidence at the initial stage of the field development at the decrease in the reservoir pressure by 5 MPa are estimated as 33.0 cm and 33.5 cm with and without regard to the dynamics of petrophysical parameters, respectively. At the decrease in the reservoir pressure by 10 MPa, the maximum drawdown is already estimated at 60.0 cm and 65.0 cm with and without regard to the dynamics of petrophysical parameters.

The implemented studies have convincingly demonstrated that taking into account the dynamics of petrophysical characteristics caused by the long-term development of hydrocarbon fields significantly changes the intensity of deformation state of rock mass and ground surface above the fields, which, accordingly, amends the perception of the level of geodynamic risk at oil and gas facilities.

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