Modeling of the stress-strain state at the Shtokman gas condensate field accounting its block structure

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Abstract. The stress-strain state of the Shtokman gas condensate field has been studied using mathematical modeling and accounting its block structure. It is assumed that the rock mass’s structure has a vertical block structure, which is under the influence of gravity and tectonic force fields. It has been revealed that the stress-strain state of the rocks depends essentially on relationships of initial operating efforts and in-situ gas pressure, which magnitude varies with its production; direction of the maximum forces and dip of angles of fault zones; and elastic characteristics of the main rock mass and fault zones. It has been established that the change in the dip of angle of fault zones and reducing the rocks’ stiffness increases tensile stress in the roof of a horizontal seam and near the sea bottom. A forecast assessment has been performed of the vertical displacement of a rock block contoured with faults relatively to the main rock mass.

1. Introduction
As is known, the implementation of the Shtokman project had been postponed due to economic conditions having been changed. However, nowadays the active discussions are being held on development of mineral resources in the Arctic, including oil and gas fields at the shelf of the Barents and Kara Seas [1, 2]. Therefore, the modeling of geomechanical conditions which are key factors during developing shelf hydrocarbon fields [1–4] with reference to the Shtokman gas condensate field is of high scientific and practical importance. The sea shelf rock mass has rather complicated geological and block structure, as the continental Earth’s crust does. At that the blocks’ geometric dimensions can be from tens or hundreds meters to tens or hundreds kilometers.

In a case when geometric dimensions of geological blocks of a lower rank in comparison with those observed in the work [1, 5] are comparable with the deposit’s dimensions in a plan or smaller, during the gas production due to natural balance disturbance the blocks can move along separating planes of tectonic faults. At that different blocks displace relatively each other unevenly due to faults’ heterogeneous properties and parameters and create a complicated mosaic image of the stress-strain state of rocks [1, 3, 4, 6, 7]. This can influence significantly on processes of gas condensate extraction and on geodynamic safety of a production region in a whole.

2. Geological fluid-mechanical model of the Shtokman field
Such as the character of distribution of stresses and blocks’ relative movements depends on many factors, which diversity is impossible to take into account simultaneously, there had been taken certain assumptions and simplifications implemented in a stratified geological fluid-mechanical model developed earlier [1]. As a result a calculation model was designed (see figure 1). A productive gas-
bearing collector with length $L + 2l$ (where $L$ – a collector’s part between tectonic faults, and $l$ – an edge part behind the fault, at that $L = 2l$) is located at the depth $H$ of the sea bottom. Relatively to the collector’s centre two tectonic faults are symmetrically located. Distance between them is $L$, and dip of angle $\alpha$ can be vertical and different to a vertical by $20^\circ$ either of the two sides (figure 1). The rock mass’s geological blocks being formed are indicated as I, II, III.

At lateral edges of the calculation scheme the horizontal efforts are set $\sigma_x = T + \lambda \gamma y$ ($T$ – tectonic forces; $\lambda = \mu / (1 - \mu)$ – lateral repulse of rocks; $\mu$ - Poisson’s ratio; $\gamma$ - rocks’ volume weight; $y$ – a vertical coordinate). A proper weight of rocks $\sigma_y = \gamma y$ acts in vertical direction downright; an upper edge is loaded with a load $\sigma_y^{const}$, which imitates the weight of the water’s overlying thickness from sea surface to the bottom. The collector’s internal contours are under normal stresses $\sigma_n$ (intra-layer gas pressure) which magnitude is initially $\sigma_n = -T$ and reduces to the zero as a result of production. The model’s lower edge is constructed on the foundation of the calculation scheme, and its center (along the symmetry axis) is strengthened hingedly, i.e., on the lower edge $\nu = 0$; $u \neq 0$, and on the symmetry axis $u = 0$; $\nu \neq 0$, where $u$, $\nu$ - horizontal and vertical displacements, correspondently. The rock mass elastic characteristics were set in accordance with the data [1, 5], and elastic characteristics of the fault zones are in 5, 10 and 20 times lower.

The model designed was primary studied on the basis of the mathematical modeling with using the boundary element method implemented in a mixed task of the elasticity theory [5]. The authors have used the computer simulation to examine the task’s variants as follows: $H / L = 0.5$; $l = L / 4$; $\alpha = 70^\circ$, $90^\circ$, $110^\circ$; $\sigma_n = -T$, $-0.5T$, $-0.25T$, $0$; $e = E_1/E_2 = 5$, $10$, $20$; $\mu_1 = 0.25$; $\mu_2 = 0.35$. Here $E_1$, $\mu_1$ - Young’s modulus and Poisson’s ratio of rock mass; $E_2$, $\mu_2$ - Young’s modulus and Poisson’s ratio of fault zones.
3. Impact of tectonic faults on stress state
The calculations performed have allowed obtaining the values of relative horizontal and vertical stresses within the calculation scheme given. It has been established that vertical stresses are compacting everywhere and don’t exceed critical values; as a result they can’t induce losses in homogeneity of the rock mass, excluding narrow local parts in the end part of the collector. According to the authors’ the tensile horizontal stresses are the most dangerous in the collector’s roof and at the sea bottom in the points selected $K$ and $O$ (see figure 1). Therefore, let’s pay attention to the change of these stresses depending on values $\alpha$, $\sigma_n$, $\varepsilon$ (figure 2).

![Figure 2. Dependencies of relative values of horizontal stresses at the sea bottom (point O) and in the collector’s roof (point K) from the fault zones’ dip of angle: a - $\sigma_n = -T$; b - $\sigma_n = 0$.](image)

The figure’s data analysis has shown that in the point $O$ the stresses $\sigma^O_x$ are compacting everywhere and increase with increase of dip of angles of fault zones $\alpha$, ratios of their elastic characteristics and main rocks $\varepsilon$; and decrease of intra-layer gas pressure $\sigma_n$. It should be noted that the most abrupt increase of values $\sigma^O_x$ occurs with the dip of angle of fault zones $\alpha$, equal to $110^\circ$.

In the collector’s roof (point $K$) under initial conditions (prior to gas production) $\sigma_x$ stresses are also compacting at the fault zone’s dip of angles. But if there is a considerable difference in elastic characteristics of rocks and a fault zone ($\varepsilon = 20$), the stresses turn to tensile ones at the fault zone’s dip of angle equal to $110^\circ$ (figure 2 a). The forecasted decrease of intra-layer pressure of gas due to its production will determine decrease of compacting horizontal stresses at the fault zones’ angles of 70 and $90^\circ$ almost to the zero, as well as transfer to tensile values and their abrupt increase at $\alpha = 110^\circ$.
(figure 2 b). With elevation of the dip of angles of fault zones $\alpha$ the tensile stresses $\sigma^K_x$ in the layer’s roof increase under equal values $\sigma_n$ and at $\alpha=const$ the stresses increase with decrease of internal gas pressure $\sigma_n$. Increase $\varepsilon$, i.e., decrease of rock stiffness in the fault zones results to increase of concentration of tensile stresses $\sigma^K_x$.

It is interesting to note that at $\alpha = 70^\circ$, $\alpha = 90^\circ$ and $\sigma_n = -T$ the stresses $\sigma^K_x$, $\sigma^O_x$ almost don’t depend on $\varepsilon$ and are close to both dips of angles of the fault zones (figure 2 a). At that, the stresses are compacting; the magnitudes don’t exceed $\sigma^K_x \leq 1.6T$; $\sigma^O_x \leq 1.2T$. So, it is confirmed that a case when the intra-layer gas pressure has a value of $\sigma_n = -T$, meets the condition of natural statistic balance of the rock mass in a whole.

It should be noted that in abrupt decrease of intra-layer gas pressure from -0.5T till the zero the concentration of both tensile and compacting stresses $\sigma_n$ in some cases can reach very large magnitudes. It is evident that under such conditions the change of the rocks’ stress-strain state gets nonlinear character and further solving of the task in the elastic setting is incompetent.

It seems to be interesting to study particularities in changing average values of vertical displacements $U_c$ of a geological block II relatively the blocks I and III in dependence of the fault zones’ dips of angles $\alpha$, a ratio of their elastic characteristics and main rocks $\varepsilon$, as well as intra-layer gas pressure $\sigma_n$.

The analysis has shown that values $U_c$ for all the variants considered are negative, i.e. the block II decreases downward, excluding a case with $\alpha = 70^\circ$, $\sigma_n = -T$, where the block II slightly displaces upward. In this case the central block II, being a wedge, as a matter of fact, is extruded by impact of subhorizontal tectonic forces on its lateral edges in combination with high intra-layer pressure.

In all other cases the central block II is extruded downwards. If to take the gas collector’s location depth as $H = 2000$ m which corresponds to the location conditions of the Shtokman field, the largest displacement of the block II at $\sigma_n = 0$, $\alpha = 70^\circ$ and $\varepsilon = 20$ will be $U_c \approx 1$ sm upward, and if $\sigma_n = 0$, $\alpha = 110^\circ$ and $\varepsilon = 20 - U_c \approx 28$ sm downward. The displacement of a large geological rock block along tectonic faults by 20-30 sm integrally is a significant value in terms of loss of the rock mass statistic balance and rock strength. As the world experience in oil and gas field development shows these are displacements which can be cause of earthquakes and increased seismicity. The latter can lead to severe complications and emergencies [3, 4, 8].

4. Conclusions
The stress-strain state of the foliated block rocks at the Shtokman gas condensate field considerably depends on a ratio of magnitudes of initial acting forces and intra-layer gas pressure, direction of maximum forces and dips of angles of fault zones and elastic characteristics of the main rock mass and fault zones.

Decrease of intra-layer gas pressure due to production operations up to values $\sigma_n < -0.5T$ determines appearance of tensile horizontal stresses in the collector’s roof. This can result in formation of local softening zones and increased micro-fissuring.

Increase of a dip of angle of tectonic faults and decrease of stiffness of rocks results in increase of tensile horizontal stresses in the collector’s roof and at the sea bottom behind a tectonic fault as well as in increase of compacting horizontal stresses at the sea bottom above the collector’s central part. The combination of the influencing factors increases the potential and a magnitude of vertical displacement of the central geological block (block II) downward relatively the main rock mass.

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