On rock deformation during hydraulic fracturing in horizontal wells

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Abstract. The article studies problems of rock deformation during the hydraulic fracturing in horizontal wells. The schemes show stresses acting on the rock during the fracturing. The article analyzes the Prats equation showing that powerful deformation processes can occur during fracturing operations in tectonically active areas. Schemes of deformation processes during the multi-stage hydraulic fracturing and formation fluid selection are presented. The rock mass above the reservoir between the cracks in the unperturbed part is held in zones with initial reservoir pressure (reference zones). The sizes of these zones decrease with an increase in the sizes of the well drainage zones and become destroyed. When the drainage areas are closed, the rock mass moves over the reservoir between the cracks. An increase in the number of hydraulic fracturing stages and a decrease in the distance between fractures can cause seismic manifestations during hydrocarbon production, especially in tectonically active areas.

1. Introduction
In recent years, deformation processes caused by hydraulic fracturing are of great interest. Hydraulic fracturing has become one of the main and most effective methods of intensifying oil production [5].

In this regard, it is necessary to study approaches to deformation processes that occur during the hydraulic fracturing. The use of a hydraulic fracturing technology can affect the environment [6]. Figure 1 shows stresses acting on a bed section.

2. Results and discussion
If \( \sigma_{\text{vert}} > \sigma_{\text{hort max}} > \sigma_{\text{hort min}} \) (\( \sigma_{\text{vert}} \) – vertical stress of the top rock, \( \sigma_{\text{hort max}}, \sigma_{\text{hort min}} \) – horizontal maximum and minimum stresses), the crack is vertical (Fig. 1 a). If \( \sigma_{\text{vert}} < \sigma_{\text{hort}} \), the crack is horizontal. In both cases, the crack develops perpendicular to the minimum stress. With the formation of a vertical hydraulic fracture in the horizontal well, the minimum stress can be determined by the Prats equation [5]:

\[
\sigma_{\text{hort min}} = \frac{\vartheta}{1 - \vartheta} \left( \sigma_{\text{vert}} - \alpha p_p \right) + \alpha p_p + \sigma_{\text{ex}}
\]

(1)

where \( \vartheta \) – Poisson’s ratio; \( \alpha = 0.5 - 1 \) – Biot’s ratio; \( p_p \) – bed movement; \( \sigma_{\text{ex}} \) – additional stresses caused by tectonic activity.

In hydraulic fracturing areas with significant tectonic activity (beds with an additional stress value greater than zero), significant deformation processes may occur during the fracturing.
In [3], it was noted that the dynamics of technogenic deformation processes is mainly affected by the following factors:

1) the size and shape of the deposit;
2) petrophysical properties of reservoirs and layers surrounding them;
3) activity of the surrounding aquifer system;
4) a decrease in reservoir pressure.

Considering all these factors, we see that the first three ones are objective, and we can influence technogenic deformation processes during the hydraulic fracturing through the fourth condition - changing the number of hydraulic fracturing stages and the propagation of cracks over the area of the reservoir. This circumstance should be taken into account when considering various options for hydraulic fracturing and choosing the optimal number of hydraulic fracturing stages by optimizing formation fluid production and minimizing technogenic consequences.

As noted in [1], as the initial reservoir pressure decreases in productive formations, the effective stress increases; under its action, the rocks of the producing strata deform and the entire thickness of the rocks falls above the productive reservoir. During the hydraulic fracturing, significant repression is created, the formation is deformed (shifted). Since the formation rocks have some specific strength properties depending on their lithological composition and the field depth, the deformation of fluid-producing layers and the movement of the layers above the field begin when the zone of a decrease in the initial reservoir pressure (disturbance zone) of some critical value is reached. Let us analyze the dynamics of the development of these deformation processes on the example of a well with a three-stage hydraulic fracturing. During hydraulic fracturing, significant repression is applied to the bed. Repression funnels p (r) develop (Figure 2).

When this well is put into operation, the sizes of the areas drained by cracks increase. This is shown in Figure 3.

Let us assume that critical radius (rcr), that is, the bearing capacity of the overlying rocks, is less than half the distance between the cracks. Until the closure of depressing funnels, the bed roof moves to the disturbance zone, and the rock mass above the productive bed between the cracks in the unperturbed part is held in zones with an initial reservoir pressure – reference zones (Figure 3). The sizes of these support zones decrease, they become destroyed. When the drainage areas are closed, the support zone between the cracks disappears, the roof of the productive bed begins to precipitate to the disturbance zone between the cracks, while the three areas turn into one large drainage area.
Let us consider the dynamics of stresses in the roof and sole. Prior to the closure of drainage areas, the rock mass in the area of each crack bends. Compressive tangential stresses will grow in the bed roof near the wellhead. They are negative. Tensile tangential stresses will increase in the periphery of the roof under the boundaries of the drainage areas. They are positive (Figure 3).

When the drainage areas are closed, sedimentation of the rock mass begins above the reservoir between the cracks; therefore, in the center of the massif, where tensile stresses have been growing,
compressive tangential stresses appear. They increase with the growth of the earth’s surface sediment. Similarly, tangential stresses change in the center of the base of the rocks above the reservoir. Thus, in the disappeared supporting zone, an abrupt change in the direction of tangential stresses occurs in the roof of the rock mass above the reservoir. It can be concluded that an increase in the number of hydraulic fracturing stages and a decrease in the distance between fractures can serve as one of the reasons for seismic manifestations in hydrocarbon production. Additional stages of hydraulic fracturing, as well as thickening of cracks, can accelerate the closure of the drainage areas and eliminate the support zones between the cracks.

The amplitude of seismic events depends on the accumulated energy. This energy is proportional to a decrease in the initial reservoir pressure in the area of well drainage (i.e., the depth of depression funnels) and the size of these zones, i.e. the size of the masses involved in the rock mass movement [3].

3. Conclusion
All the negative consequences listed above can occur during the operation of wells under one-stage hydraulic fracturing or during the operation of a group of wells under hydraulic fracturing, when large repression and depression funnels are created. As a result, reservoir deformations and stresses arise (without changing their sign during the operation of wells under hydraulic fracturing); their values can exceed rock strength limits. The rock massif above the reservoir consists of various layers, each of which has its own strength properties. With the development of deformation processes, tangential stresses arise in the roof and sole of each layer. This means that during the contact of the layers, the stresses are opposite, i.e. during the deformation of the entire rock massif, the strata composing this massif can move.

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