Research Article

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The effect of fluid saturation on the elastic-plastic properties of oil reservoir rocks

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Abstract: Background: The success of planning geological and technical measures aimed at intensifying oil production is of high importance. **Methodology:** To increase the efficiency of operations aimed at oil recovery enhancement, it is necessary to use mathematical models of the rock mass deformation, taking into account the physical and mechanical properties of the rocks. **Results:** Currently, the application of these models is difficult due to a lack of data. As a result, the use of simpler models is resorted to, which is not always correct in the practical application of these models. This article describes experimental studies aimed at determining the mechanical properties of rock and establishing the correlation between properties and the fluid saturation of the rocks. The study determined the physical-mechanical properties of the rocks (taking into account the stage of field development) and established the dependencies of the change in the oil reservoir rock properties on the saturation and type of load on a sample. **Conclusions:** The results show that the saturation of the rock with a liquid phase (hydrocarbon or water) decreases the strength of the reservoir rock, which in turn depends on the type of saturating fluid.

Keywords: hydro-impulse action, low-permeable reservoirs, planning of geological-engineering operations, recovery enhancement, stress-strain state of the rock, volumetric compression

1 Introduction

The success of planning geological and technical measures aimed at oil recovery enhancement is of high importance [1–3]. During the exploitation of oil and gas fields, a decrease in reservoir pressure occurs, which inevitably leads to a change in the stress-strain state of the massif and the formation reservoir properties of the porous medium [4, 5]. When modeling geological and technical measures, the most often used parameters are those that were determined at the stage of prospecting and exploratory drilling without further refinement. In this regard, the oil recovery enhancement measures do not always have a positive outcome.

The prospects for the development of the Russian oil industry are largely determined by the state of hydrocarbon resources [6, 7]. More than 60% of current reserves are being mined and the degree of development of oil pools currently exceeds 50%, about 40% are located in the Tyumen region and 70% in the Volga-Ural oil and gas province [8]. Due to the faster extraction of the most productive oil pools, their structure changes qualitatively, the amount of hard-to-recover resources and low production wells increases, and the efficiency of oil production decreases [9]. In this regard, the design level of the oil recovery efficiency is not achieved at most fields [10].

When enhancing oil recovery, the critical issue is to reach the forecast level of oil recoverability factor. This forecast is of particular importance at the later stage of field development, when a large amount of water is present in the wellbore fluids, the yield is reduced as compared to the initial data, and technogenic processes occur in the productive zones associated with fluid selection, which decrease the formation reservoir properties [11]. Despite the significant successes achieved in recent years, the data on the current state of development of exploited reservoirs usually remains incomplete, which complicates the development and constant updating of multidimensional deterministic filtration models of productive reservoirs [12]. Therefore, when predicting the effectiveness of works aimed at enhancing oil recovery, specialists of mining enterprises mainly use specially designed displacement curves, as well as correlation analysis [13, 14].

During the operation of production wells, a depression funnel is formed in the bottomhole formation zone, which leads to a significant decrease in reservoir pressure. The reservoir rock experiences an additional vertical load

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in the bottomhole formation zone, which leads to deformation of the pore and fracture spaces [15]. In this case, elastic deformations occur resulting in a decrease in the reservoir properties of the rocks [16]. In the fields of Western Siberia, it was revealed that an irreversible deformation of reservoir rocks leads to a decrease in the production rate of recovery wells and oil recovery in general [17].

One of the most difficult sections of rock mechanics is the study of the physical-mechanical and filtration properties of the productive formations. The evaluation of parameters to determine the physical and mechanical properties of rocks using mathematical models of deformation of the rock mass is impossible for the practical application of these models. To do this, one must use the simplest models and select the data based on empirical dependencies, which is not always correct. Thus, the problems of planning well interventions to increase the productivity of wells in oil and gas companies are quite complex and multifaceted, especially at the later stage of field development [13].

The aim of the study is to examine physical-mechanical properties of the reservoir depending on the conditions and stages of oil and gas development. The strength properties of rock structures were investigated, taking into account fluid saturation and vertical stress. The data on these properties may contribute to a more realistic understanding of rock mass deformation at various stages of exploitation.

2 Methods

The studies were carried out at St. Petersburg Mining University in the laboratories for enhancing oil recovery and physical-mechanical properties and rock destruction of the Scientific Center for Geomechanics and Mining Issues [18, 19] using the latest laboratory equipment from world famous manufacturers.

When determining the physical-mechanical properties and choosing the main parameters for the adaption of the enhanced oil recovery technology, studies were conducted on samples of porous-fractured polymictic rocks of the Volga-Ural oil and gas bearing provinces. The drilling depth of wells varies between 1.5 and 2 km. The experimental studies were carried out in accordance with GOST 21153.8-88 “Mountain rocks. Method for determining the tensile strength in volumetric compression” [20], OST 39-181-85 “Oil. Laboratory method for determining the porosity of hydrocarbon-containing rocks” [21] and the requirements of Rosstandart.

The preparation of core samples for research included the following steps: drilling cylindrical core samples of the required size, extracting the prepared samples, saturating the samples with reservoir fluid models. These steps were carried out using the specialized laboratory equipment:

- Core samples were drilled with special crowns on a core drill MDP-405 manufactured by Coretest Systems Corporation from a full-sized core sample. The length adjustment and processing of the ends of the drilled core is carried out on a cutting saw with a DTS-430 end grinding wheel from Coretest Systems Corporation.
- The length and diameter of the prepared core samples were measured with a SHTZ-1-125 caliper (measurement accuracy up to 0.01 cm). The weight of the samples was determined by weighing on a high-precision scale company Mettler Toledo AB-204-S / FACT (accurate to 0.01 g).
- After drilling and core processing to the required size, they were extracted using an alcohol-benzene mixture in a percentage ratio of 30:70 to remove various contaminants in a CE-520 centrifuge from Coretest Systems Corporation. After extraction, the core samples were dried in a heating cabinet at a temperature of 105°C to constant weight [22].
- At the final stage, the prepared core samples were saturated with reservoir fluid models on a MS-535 saturator from Coretest Systems Corporation. TS-1 brand kerosene and specially mineralized distilled water were used as models of reservoir fluids. Initially, the prepared core samples were evacuated in the saturation chamber of the MS-535 installation for 12 hours. At the same time, the saturating liquids and the system were evacuated. At the end of the process the pumping air was created in the chamber with a pneumatic pump (pressure of up to 13 MPa). The system was kept under pressure for 2 hours. At the end, the samples were removed from the chamber and placed in a container with a saturating liquid (Figure 1).

For the volumetric compression tests, the end surfaces of the samples are processed on a stone processing equipment to ensure the quality of surfaces meet the requirements of GOST.

The tensile strength during volumetric compression was determined on a servo-hydraulic testing unit MTS 815 (MTS, USA) by continuously loading cylindrical samples at a rate of 0.5-1.0 MPa/s until fracturing.

This apparatus is designed to study the processes of deformation and destruction of rocks and other materials

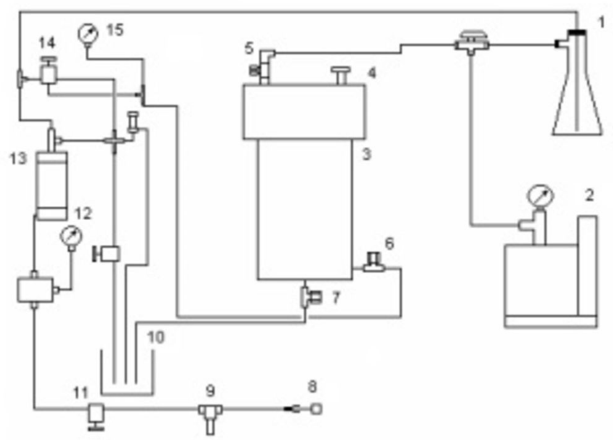

Figure 1: Schematic diagram of the saturator MS-535: 1 – chamber of the saturating liquid; 2 – a vacuum pump; 3 – saturation chamber; 4 – saturation chamber cover; 5 – the upper valve of the chamber; 6 – shut-off valve; 7 – drain valve; 8 – gas source; 9 – air pressure regulator; 10 – drainage tank; 11 – air supply valve to the system; 12 – air pressure gauge; 13 – pneumatic high-pressure pump; 14 – pneumatic distribution valve; 15 – pressure gauge in the chamber [24, 25]

Figure 2: Preparation of samples for testing

at the micro and macro levels and the formation reservoir properties, it allows testing of rock, half rock and concrete for compression, tension and volumetric strength while recording the a set of indicators (deformation, load, acoustic emission, elastic wave velocities, pore pressure) and visualization of the process of nucleation and development of cracks [23]. The apparatus is used to simulate the natural state (stress, temperature, pore pressure) of geomaterials and study the effects of changes in these states. The complex includes a set of dynamometers and extensometers for accurate measurement of the load acting on the sample and its deformations.

The main technical parameters of the MTS 815 apparatus are the following: axial load under compression is up to 4600 kN; tensile is up to 2600 kN; lateral pressure is up to 80 MPa; cylindrical samples with a diameter of up to 300 mm and a height of up to 600 mm.

Before testing in laboratory conditions, all the measuring sensors are calibrated to comply with the accuracy parameters. The preparation of the samples for triaxial compression tests involves sealing the lateral surface of the samples to prevent the penetration of the working fluid (silicone oil), which creates lateral pressure on the sample. The heat-shrink PVC pipes of an appropriate diameter are used as waterproofing sheath. The ends of the sample are isolated from the liquid by steel plates (Figure 2).

Out of nine collected samples, three met the above GOST requirements and were transferred to further analysis. Sample No. 1 was unsaturated, sample No. 2 was saturated with respect to mineralized water, and sample No. 3 consisted of hydrocarbon-saturated rocks.

The physical-mechanical and the formation reservoir properties of the rocks were determined for conditions as close as possible to the reservoir: the value of the lateral crimp is 60 MPa; the temperature is 32°C; the loading speed (by rod movement) is 0.5 mm/min. These parameters are specific for rocks under consideration, i.e., medium-strength rocks (52-80 MPa).

3 Results

The physical properties of experimental samples are presented in Table 1.

According to the results of the experiments, the relation between the saturation of the sample and type of loading were determined (Figures 3-9). The graphs (Figures 3, 5, 7, 9) show the average statistical results for each type of saturation.

In the absence of fluid saturation of the reservoir sample (Figure 3), a dependence graph starts with a linear relationship between deformation and stress, which slightly reduces with decreasing stress after reaching a certain threshold (tensile strength). This trend demonstrated good agreement with the elastic model of the rock mass. Deformations within the latter model mass are exclusively elastic, time independent, and directly proportional to the amount of stress applied to the model rock mass [26].

The type of deformation within the rock mass in sample 1 indicates elasticity of the continuous media (Figure 4). As can be seen from the figure, an unsaturated rock sample is destroyed according to the classical scheme with the formation of a single crack, which is mainly parallel to the axial stress and fissure-like. This behavior corresponds to the mechanics of a continuous medium.

Table 1: The underlying physical properties of experimental samples

Sample	Weight, g	Length, mm	Diameter, mm	Initial porosity, %	Density, g/sm^3	Tensile strength, MPa	Breaking strength, kN
1	101.37	60.10	29.86	11.26	2.41	13.049	9.134
2	95.44	59.94	29.67	11.35	2.30	3.953	2.735
3	100.68	60.52	29.44	11.57	2.27	3.67	2.497

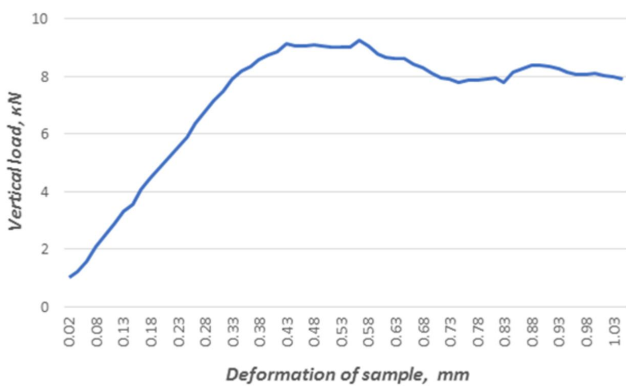

Figure 3: The tensile strength of an unsaturated sample No. 1

Figure 4: Unsaturated sample of the reservoir rock after testing (sample No. 1)

A water-saturated sample demonstrated a completely different behavior (Figure 5). The dependence between deformation and stress is not linear and insignificant stress fluctuations that take place as the stress increases indicate heterogeneity and plasticity of the rock mass. In addition, deformations occur if the current stress is low. It is obvious that water-saturated rocks have mineralized water oc-

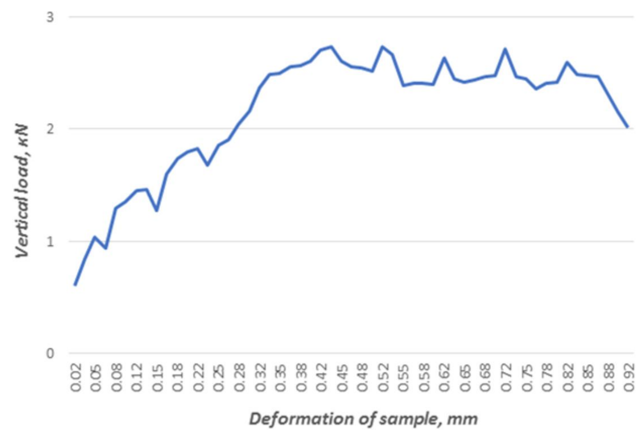

Figure 5: The tensile strength of the sample saturated with produced water (sample No. 2)

cupying their pores, which contributes to the quasi-plastic softening of the rock.

Figure 6 shows that the application of stress results in cracking. Perhaps, the cracking capacity of rocks is influenced by mineral leaching or interaction between water and the active chemical elements within the rock during water saturation.

A similar mechanical behavior was found in a hydrocarbon-saturated rock mass (Figure 7). The only difference is that rocks fracture at lower strain values. In this case, a dependence curve demonstrates quasi-plastic behavior during fracture and fewer spasmodic fluctuations in stress, indicating the involvement of the capillary force. The hydrocarbon fluid, however, has lower mobility, as compared to saline water. This makes forces more evenly redistribute under stress.

Similar to water-saturated sample, the hydrocarbon-saturated rock mass retains the integrity of its core while having a surface disturbed by complex intersecting micro-cracks (Figure 8).

Figure 9 depicts patterns of the mechanical behavior of all three samples. As can be seen from Table 1 and Figure 9, the tensile strength of saturated rocks, especially hydrocarbon-saturated rocks, is almost 4 times lower and their failure occurs at lower strain values.

Figure 6: A sample of the reservoir rock saturated with formation water after the test (sample No. 2)

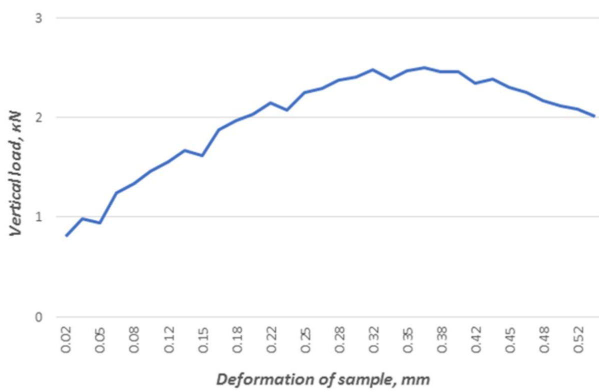

Figure 7: The tensile strength of a sample saturated with a hydrocarbon liquid (sample No. 3)

Figure 8: A sample of the reservoir rock saturated with hydrocarbon liquid after the test (sample No. 3)

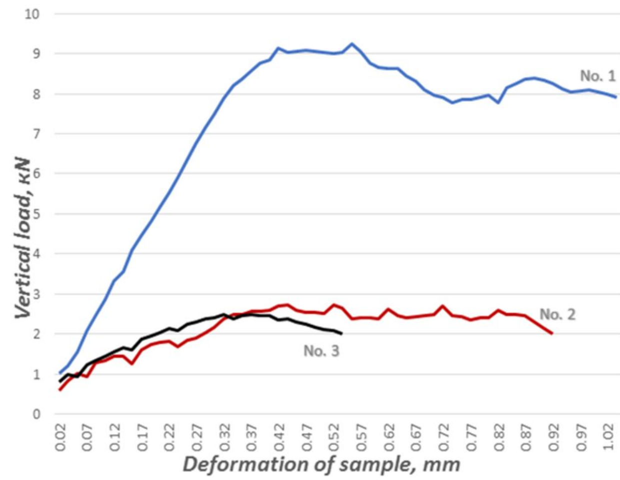

Figure 9: Summary graph of tensile strength of samples

4 Discussion and conclusions

The oil and gas exploitation causes compaction of the productive layers of a reservoir, which is taken into account when considering the surface subsidence over oil and gas fields. Since the magnitude of compaction depends on a drop in reservoir pressure and on physical-mechanical properties of rocks within the reservoir. If dimensions of the reservoir are significant, then the compaction process (as well as fracture) is often assumed to be uniaxial and vertical. The framework to evaluate rock properties in this study was most consistent with the reservoir conditions. The mechanical response of saturated rock masses showed that fluid saturation has caused the reservoir strength to decline. Furthermore, the resistance of the rock mass to stress is closely related to the type of fluid that occupies its pore volume.

The data obtained during the experiments will allow us to develop a technology for stimulating the inflow in wells with high water cut in fields with low permeable reservoirs using hydro-pulse treatment [8, 10].

In this paper, the experimental studies were conducted to determine the mechanical properties of rocks and to establish the dependence of their changes on the fluid saturation of the rocks. To justify the hydro-pulse effect on the bottomhole formation zone and the selection of technological parameters, it is necessary to conduct studies of the physical-mechanical and the formation reservoir properties, since the parameters of the studied reservoir properties are not always reflected in the strength certificates and are not available in the literature. The adaptation of the technology of hydro-pulse effect requires additional studies of the physical-mechanical and formation reservoir properties for specific fields and reservoir systems.

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