UDC 622.276:552.578.2.061.4

LABORATORY SIMULATION OF CHANGE IN MECHANICAL AND FLOW PROPERTIES OF RESERVOIR FORMATIONS AT VARIOUS STAGES OF OIL-FIELD DEVELOPMENT

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ЛАБОРАТОРНОЕ МОДЕЛИРОВАНИЕ ИЗМЕНЕНИЯ МЕХАНИЧЕСКИХ И ФИЛЬТРАЦИОННЫХ СВОЙСТВ ПОРОД КОЛЛЕКТОРОВ НА РАЗЛИЧНЫХ ЭТАПАХ РАЗРАБОТКИ МЕСТОРОЖДЕНИЙ НЕФТИ

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Key words:
effective pressure, reservoir pressure, rock pressure, porosity, permeability, saturation, watercut, deformations, strength properties, elastic properties, poroelasticity, uniaxial compression.

At different stages of oil and gas field development, a reservoir undergoes various stress-strain states. The change of reservoir pressure during development results in the change in physical and mechanical properties of the reservoir. In terms of geochemistry, the fluids also affect the properties of the host rocks. The process of reservoir fluid extraction can clog flow channels with washed-out rock particles and deposited paraffins and salts, but also decrease the strength and elastic characteristics of the rock.

The article provides a brief analysis of operations affecting the causes of changes in the physical, mechanical, porosity and permeability properties of formations during drilling and oil-field development. The method of theoretical calculation of changes in the formations' porosity and permeability is provided.

To establish the convergence of theoretical calculation methods with real data, the tests to determine the uniaxial compressive strength and the filtration experiments on terrigenous samples of a West Siberian field were carried out. Water and kerosene in different proportions were used as saturating fluids in the experiment to determine physical and mechanical properties. Based on the data obtained, the dependencies of the modulus of elasticity and the uniaxial compressive strength on different types of saturation were derived, with diagrams and calculating formulas given. In the filtration experiment, the influence of effective pressure on permeability of samples at volumetric compression was determined. The dependencies of permeability decline on the sample axial load were established.

The obtained dependencies can be used to work out geological and engineering procedures for well stimulation and field development management during the entire operational life cycle.

Ключевые слова:
эффективное давление, пластовое давление, горное давление, пористость, проницаемость, насыщенность, обводненность, деформации, прочностные свойства, упругие свойства, пороупругость, одноосное сжатие.

На различных этапах разработки нефтяных и газовых месторождений пласт испытывает различные напряженно-деформированные состояния. Изменение пластового давления в процессе разработки приводит к смене физико-механических свойств пласта. С точки зрения геохимии, на свойства вмещающих пород также оказывают влияние сами флюиды. Процесс извлечения пластовой жидкости может вызывать не только закупоривание фильтрационных каналов вымываемыми частицами породы и выпадением парафинов и солей, но и уменьшение прочностных и упругих характеристик породы.

В статье приведен краткий анализ работ, затрагивающих причины изменения физико-механических и фильтрационно-емкостных свойств пластов в процессе бурения и разработки месторождений нефти. Приведена методика теоретического расчета изменений пористости и проницаемости пластов.

Для установления сходимости теоретических методов расчета с реальными данными были проведены испытания по определению предела прочности при одноосном сжатии и фильтрационные эксперименты на терригенных образцах одного из месторождений Западной Сибири. В эксперименте по определению физико-механических свойств в качестве жидкостей насыщения использовались вода и керосин в различном соотношении. На основе полученных данных были выведены зависимости модуля упругости и предела прочности при одноосном сжатии от различного вида насыщенности, приведены графики и расчетные формулы. В фильтрационном эксперименте при объемном сжатии определялось влияние эффективного давления на проницаемость образцов. Установлены зависимости уменьшения проницаемости от осевой нагрузки на образец.

Полученные зависимости можно использовать при подготовке геолого-технических мероприятий по интенсификации притока и при управлении разработкой месторождения на протяжении всего жизненного цикла.

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Introduction

The equilibrium state of rocks, which has established over geological time, undergoes changes starting from the exploration and development stage (Fig. 1). At each stage of development, different physical (variation/maintenance of reservoir pressure, perforation, hydraulic fracturing, etc.) and chemical (application of chemical methods to enhance oil recovery, etc.) factors have a certain effect on the reservoir's porosity, permeability and physical-mechanical properties [1–2].
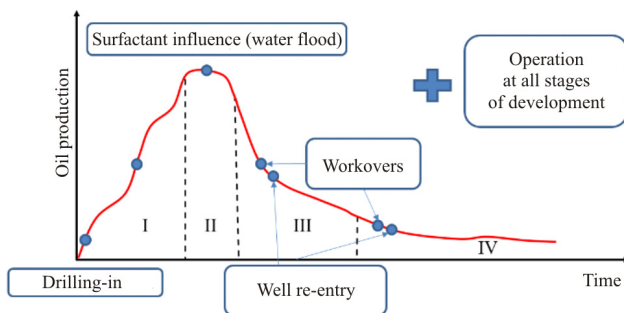

Fig. 1. Main stages of field development

Surfactant influence during well-drilling was determined in order to increase the drilling rate and reduce pressure at hydraulic fracturing [3–9]. However, due to the complexity of processes occurring in the formation, there is often little effect of reducing the strength of rocks from the application of surfactant solutions in practice [10–11]. In the research works [12–13], the change in rock properties is associated with the chemical composition, dielectric permeability and electrical conductivity of saturating fluids. Mineralization of water used in reservoir pressure maintenance system can influence rock permeability [14–18]. The influence of effective pressure on pore compressibility and change in permeability is studied in detail in [19–31].

To improve the accuracy of development engineering it is recommended to use all available data on the field and reservoir, as well as to constantly monitor their changes over time.

Porosity and Permeability of Formation as a Function of Reservoir Pressure

The main component of the stress state is formed by the weight of the overlying strata, and it almost never changes during field development. Provided there is a connection between the formation and surface waters, the pressure in the formation will correspond to the hydrostatic head pressure of exposed fluid. Where during pool formation the reservoir fluid had no possibility to reflux, such a reservoir will have abnormally high pressure. In both cases, optimum reservoir pressure should be maintained in order to prevent irreversible reservoir deformations that will result in significant reduction in porosity and permeability and sharp drop in flow rates.

The study [19] describes the procedure for calculating the change in permeability and porosity by the loading method while maintaining the constant pore pressure. The deformation at uniaxial compression at drainage is measured by the formula:

$$e = e_{11} = \frac{\sigma_{11}^f - (1 - m_0)\beta_1 K p_0}{(1 - m_0)(\lambda_1 + 2\lambda_2)} = -\frac{B}{1 - m_0}p_{ef},$$

where σ_{11}^f is fictitious stress, MPa; m_0 is porosity, unit fraction; $\beta_0 K, \beta_1 K$ is porous medium cementation; p_0 is reservoir pressure, MPa; p_{ef} is effective pressure, MPa; $B = \dfrac{1}{\lambda_1 + 2\lambda_2}$, where λ_1, λ_2 are the first and second Lamé parameters, respectively.

The ratio $\varepsilon = \beta_1 K$ is called mechanical characteristic of rock formation, a criterion of the degree of soil compaction or of rock cementation. The closer the cementation index ε is to unity, the harder is the particle repack, and the harder they are bound to each other [19].

The effective pressure is determined by the formula:

$$p_{ef} = -\sigma_{11}^f + (1 - m_0)\beta_0 K p_0 =$$
$$= q - (1 - m_0)\beta_1 K p_0 = q - n p_0,$$

where q is the full load applied, MPa.

The authors [32] claim that due to small capillary pressure values, its effect on the effective pressure is negligible.

The coefficient $n = (1 - m_0)\beta_1 K$ shows what share of pore pressure should be taken into

account. In the article, the value $n = 0.8$ was used for the calculations, which corresponds to the calculated cementation factor value $\varepsilon = \beta_1 K = 0,2 - 0,3$ [19, 33–43].

The relation between the porosity increment Δm, the sample volumetric deformation Δe and the pore pressure increase increment [19] is established from the equations of continuity and generalized Hooke's law [19]:

$$\Delta m = (1 - m_0)(1 - \beta_1 K)(\Delta e + \beta_1 \Delta p).$$

Compressibility coefficients of pores, medium and skeleton of the rock are determined by the formulas [19]:

$$\beta_{\text{п}} = \left(\frac{1}{v_{\text{пор}}}\right)\frac{\Delta v_{\text{пор}}}{\Delta p_*} = \frac{\beta_{\text{с}}}{m_0},$$

$$\beta_{\text{с}} = \frac{\Delta m}{\Delta p_*} = \frac{1}{v_0}\frac{\Delta v_{\text{пор}}}{\Delta p_*},$$

$$\beta_{\text{тв}} = \frac{\Delta e}{\Delta p_*} = \frac{1}{v_0}\frac{\Delta v}{\Delta p_*},$$

where $\beta_{\text{п}}$ is compressibility of pores, MPa^{-1}; $\beta_{\text{с}}$ is compressibility of medium, MPa^{-1}; v_0 is compressibility of rock skeleton, MPa^{-1}; v_0 is initial volume of sample; Δv is change of its full volume; $\Delta v_{\text{пор}}$ is change of pore volume; Δp_* is recorded (simultaneously with pore pressure) value of applied load (effective pressure), MPa.

The diagram of porosity dependency on effective pressure is described with high accuracy by the exponential relation [19]:

$$m = m_0 \exp[a_m(p^f - p_0^f)],$$

where m is the porosity coefficient at pressure p^f; m_0 is the porosity coefficient at initial pressure p_0^f; $a_m \approx \beta_{\text{п}}$ is the pore compressibility coefficient, MPa^{-1}.

Permeability is calculated as a function of porous medium:

$$k = k_0 \left(\frac{m}{m_0}\right)^{a_k/a_m},$$

where k, m is permeability and porosity at effective pressure; a_k, a_m are coefficients of change in permeability and compressibility of pores, respectively, MPa^{-1}, $a_k/a_m \approx 10$ for sandy rocks.

Results of Experimental Studies

To determine the effect of rock saturation on the properties of terrigenous rocks, the strength and elastic characteristics were studied [44-46]. Rocks (mainly sandstone) from West Siberian deposits, occurring at a depth of approx. 1,800 m, were used as the sample material.

Figure 2 shows the results of determining the uniaxial compressive strength and modulus of elasticity. Following the study results, no dependency between water saturation of the sample and the Poisson's ratio was determined. The following designations were adopted: group 0 – air-dried samples; group 1 – samples fully saturated with kerosene; group 2 – samples saturated with 25 % water and 75 % kerosene; group 3 – samples saturated with 50 % water and 50 % kerosene; group 4 – samples saturated with 75 % water and 25 % kerosene; and group 5 – samples fully saturated with water.
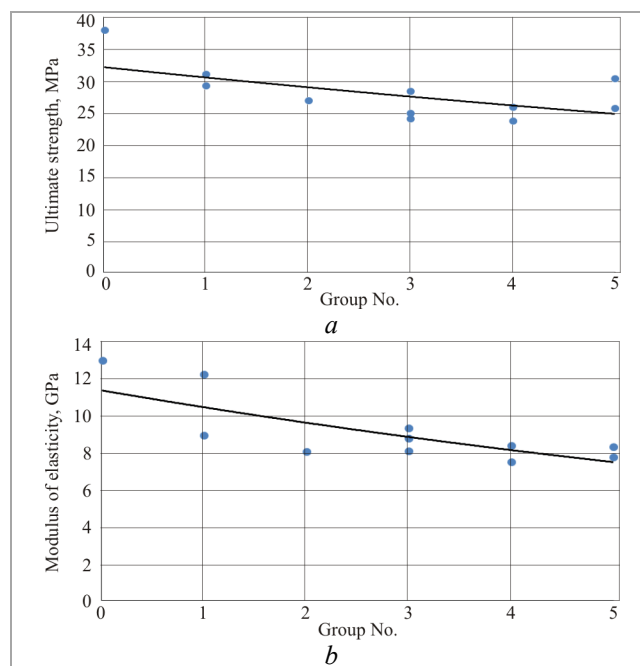

Fig. 2. Dependency of ultimate strength (*a*) and modulus of elasticity (*b*) on the type of saturating fluid

The indicated groups can be related to the stages of development: groups 1 and 2 can be referred to the

stages of well bringing-in and production build-up in the field; group 3 corresponds to the stage of consistently high level of production; and group 4 and 5 denote the stages of production decline and watercut increase in the well production.

The dependency of the rock sample modulus of elasticity E, GPa, on fluid saturation can be represented as follows:

$$E = 9,8127 \exp(-0,002 \cdot Sw),$$

where Sw is water saturation, unit fraction.

The flow experiment (Fig. 3, *a*, *b*) was carried out at a confining pressure of 40 MPa, which corresponds to the rock pressure at a depth of 1,800 m. Low-mineralized water was pumped through the water-saturated sample with constant flow until the pore pressure level-off. After that, the axial load applied on the sample was increased in stages: the first stage of loading was 2 kN, followed by the increase from 10 to 50 kN in increments of 10 kN, six stages in total (see Fig. 3, *a*). After testing, the sample was broken down to determine the ultimate strength [47–49].

The core sample permeability coefficient k, m^2 (1 Darcy = $1.02 \cdot 10^{-12}$ m^2), was calculated using Darcy's law

$$k = \frac{\mu \cdot L \cdot Q}{S \cdot \Delta P},$$

where μ is dynamic viscosity of fluid, Pa·s; L is length of the core sample, m; Q is a given rate of fluid flow through the core sample, m^3/s; S is the cross-sectional area of the core sample, m^2; ΔP is pressure drop at the core sample edges at the given flow rate, Pa.

The effective pressure for each stage was determined by the formula:

$$p_{ef} = p_{rock} + p_{vert} - p_{por},$$

where p_{rock} is confining pressure, MPa; p_{vert} is axial pressure applied, MPa; p_{por} is pore pressure in the sample, MPa.

The permeability change coefficient was calculated from the expression:

$$\Delta k = \frac{k_i}{k_0},$$

where k_i is the permeability coefficient of the *i-th* stage; and k_0 is the permeability coefficient of the first stage, mD.
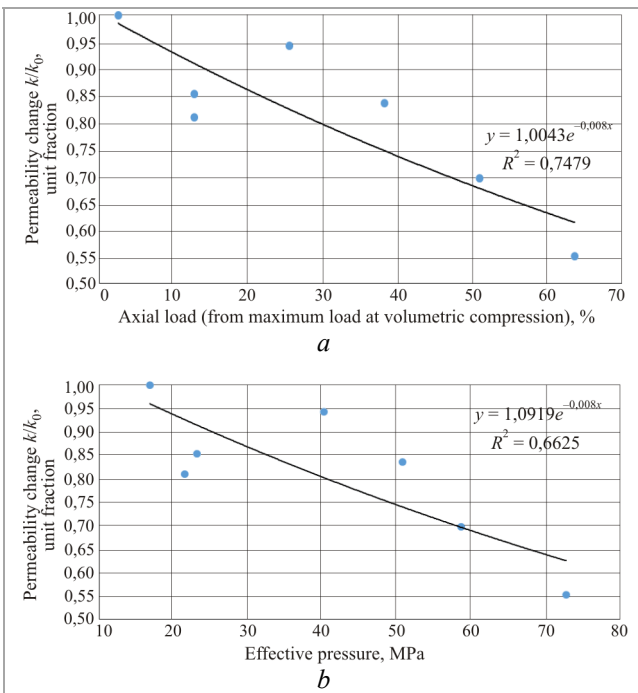

Fig. 3. Permeability change dependency on the axial load at volumetric compression (*a*) and on effective pressure (*b*)
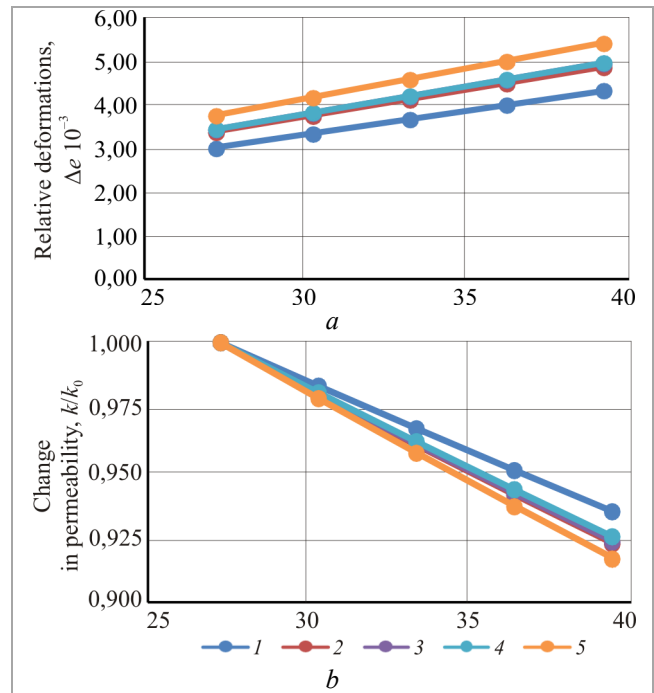

Fig. 4. Dependency of relative deformations (*a*) and change in permeability (*b*) on saturation and effective pressure

Figure 3, *b* presents the dependency of the change in permeability on effective pressure. With the increase of effective pressure on the sample from 20 to 40 MPa, a 20 % decrease in permeability is observed. At the effective pressure of 60 MPa, the permeability decrease is approx. 30 % from the initial value, and the process is gradually reduced.

Results of Theoretical Studies

Using the experimental elasticity modulus dependency on water saturation, changes in relative deformation and permeability were calculated.

Fig. 4 (*a*) shows the dependency of reservoir relative deformations on saturation and effective pressure.

With the growth of water content in the reservoir, relative deformations increase, i.e. the rock becomes more plastic, while the uniaxial compressive strength decreases. The prevalence of plastic deformations causes irreversible compression of the reservoir and results in decrease in the elastic strength of the rock. The relative deformation increment at the effective pressure increase is higher in water-saturated samples, which is also due to an increase in plasticity in the presence of water. Fig. 4 (*b*) presents the dependency of permeability change on saturation and effective pressure. The largest decrease in permeability is observed at a significant decline in formation pressure and increase in watercut (line *5*).

It should be noted that the results obtained experimentally and computationally are reproducible. The calculated decrease in permeability with an increase in effective pressure from 30 to 40 MPa is 6.67 % for fully water-saturated rock. A laboratory experiment with an identical sample retrieved a value of 6.6 % at an increase of effective pressure in the same range.

Conclusion

The results of theoretical and experimental research prove the necessity of studying the properties of rocks in various saturated states.

The type of saturating fluid determines strain, strength and elastic properties, as well as changes in porosity and permeability.

The decrease in strength of rocks and the prevalence of plastic deformations occur with the formation pressure decline, and also due to gradual increase in watercut. All of these can affect the projected outcome of mining engineering operations to enhance production.

The method used to estimate the change in permeability has produced the result similar to the experimental data. Nonetheless, it should be noted that since the studies were conducted for hydrophilic reservoirs, similar studies should be performed for hydrophobic rocks.

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