ISSN 2712-8008
Volume / Том 24 №1 2024
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.276+552.578.2.061.4
Article / Статья

Determination of Clayey Reservoir Rock Properties at Various Stages of Oil Field Development

Daniil A. Karmanskiy, Dmitriy G. Petrakov

Saint Petersburg Mining University (2 21st Line, Vasilyevsky island, Saint Petersburg, 199106, Russian Federation)

Определение свойств глинистых пород-коллекторов на различных стадиях разработки месторождений нефти

Д.А. Карманский, Д.Г. Петраков

Санкт-Петербургский горный университет (Российская Федерация, 199106, г. Санкт-Петербург, 21-я линия Васильевского острова, д. 2)

Received / Получена: 31.08.2023. Accepted / Принята: 29.02.2024. Published / Опубликована: 31.03.2024

Keywords:
effective pressure, reservoir pressure, rock pressure, porosity, permeability, piezoelectric conductivity, saturation, water cut, filtration, deformation, strength properties, elastic properties, elasticity modulus, Poisson's ratio, uniaxial compression, Buckley-Leverett function.

The article describes the issue of determining the properties of rocks with different fluid saturation and the relationship between changes in these properties from the stage of oil field development. The mineral composition of the studied clayey samples of oil reservoir rocks was given. The process of changes in the strength and elastic properties of the rock due to different saturation with kerosene and water was described. The dependences of the ultimate strength under uniaxial compression, elastic modulus and Poisson's ratio for rocks of different fluid saturation were presented. The decrease in the strength and elastic modulus of rock samples with complete replacement of kerosene with water reached 15-20%, and in comparison with the results obtained for a sample in an air-dry state, the decrease in these same properties reached 30-40%. Based on the theoretical and practical studies the need to determine the strength and elastic properties of rocks depending on saturation in real field conditions became obvious. The results of filtration studies for clay rock samples were presented. It was established that a decrease in reservoir pressure contributed to an irreversible decrease in the permeability of the studied clayey rocks. It followed that the introduction of systems for maintaining reservoir pressure must be carried out as early as possible. An example of calculating relative permeability, pressure distribution in the reservoir at a constant flow rate was given, graphs of the distribution of the water/oil displacement front were constructed by year of field development with a plane-radial inflow into the well. The dependences of the elastic capacity coefficient and piezoelectric conductivity of the rock on fluid saturation were presented. The obtained results and the established dependencies are recommended to be used when predicting changes in the strength, elasticity and filtration-capacitive properties of pore-type clay rocks at various stages of oil field development, including for planning well treatment.

Ключевые слова:
эффективное давление, пластовое давление, горное давление, пористость, проницаемость, пьезопроводность, насыщенность, обводненность, фильтрация, деформации, прочностные свойства, упругие свойства, модуль упругости, коэффициент Пуассона, одноосное сжатие, функция Бакли – Леверетта.

Поднимается вопрос определения свойств горных пород различной насыщенности флюидами и связи изменений этих свойств от стадии разработки месторождения нефти. Приведен минеральный состав исследуемых глинистых образцов пород-коллекторов нефти. Описан процесс изменения прочностных и упругих свойств породы от различной насыщенности керосином и водой. Приведены графики зависимостей предела прочности при одноосном сжатии, модуля упругости и коэффициента Пуассона для пород различной насыщенности флюидами. Снижение прочности и модуля упругости образцов породы при полном замещении керосина водой достигает 15–20 %, а в сравнении с результатами, полученными для образца в воздушно-сухом состоянии, снижение этих же свойств достигает 30–40 %. Исходя из проведенных теоретических и практических исследований, становится очевидной необходимость определения прочностных и упругих свойств горных пород в зависимости от их насыщенности в реальных условиях на месторождении. Приведены результаты фильтрационных исследований для образцов глинистых пород. Установлено, что снижение пластового давления способствует необратимому снижению проницаемости исследованных глинистых пород. Отсюда следует, что внедрение систем поддержания пластового давления на месторождении необходимо осуществлять как можно раньше. Приведен пример расчета относительных фазовых проницаемостей, распределения давления в пласте при постоянном дебите, построены графики распределения фронта вытеснения нефти водой по годам разработки месторождения при плоскорадиальном притоке в скважину. Приведены зависимости коэффициента упругоемкости и пьезопроводности породы от насыщенности флюидами. Полученные результаты и установленные зависимости рекомендуется использовать при прогнозировании изменения прочностных, упругих и фильтрационно-емкостных свойств глинистых пород порового типа на различных стадиях разработки месторождений нефти, в том числе для планирования проведения геолого-технологических мероприятий.

© **Daniil A. Karmanskiy** (Author ID Scopus: 57209507897, ORCID: 0000-0002-3214-5322) – Lead Engineer of the Laboratory of Physical and Mechanical Properties and Rock Fracture of the Scientific Center for Geomechanics and Mining Problems (tel.: +007 (921) 865 20 64, e-mail: Karmanskij_DA@pers.spmi.ru). The contact person for correspondence.
Dmitriy G. Petrakov (Author ID Scopus: 57015158900, ORCID: 0000-0002-0461-1621) – PhD in Engineering, Associate Professor, Vice-Rector for Educational Activities (tel.: +007 (921) 788 19 62, e-mail: Petrakov_DG@pers.spmi.ru)

© **Карманский Даниил Александрович** (ORCID: 0000-0002-3214-5322) – ведущий инженер лаборатории физико-механических свойств и разрушения горных пород научного центра геомеханики и проблем горного производства (тел.: +007 (921) 865 20 64, e-mail: Karmanskij_DA@pers.spmi.ru). Контактное лицо для переписки.
© **Петраков Дмитрий Геннадьевич** (ORCID: 0000-0002-0461-1621) – кандидат технических наук, доцент, проректор по образовательной деятельности (тел.: +007 (921) 788 19 62, e-mail: Petrakov_DG@pers.spmi.ru).

Please cite this article in English as:
Karmanskiy D.A., Petrakov D.G. Determination of clayey reservoir rock properties at various stages of oil field development. *Perm Journal of Petroleum and Mining Engineering*, 2024, vol.24, no.1, pp.27-34. DOI: 10.15593/2712-8008/2024.1.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Карманский, Д.А. Определение свойств глинистых пород-коллекторов на различных стадиях разработки месторождений нефти / Д.А. Карманский, Д.Г. Петраков // Недропользование. – 2024. – Т.24, №1. – С.27–34. DOI: 10.15593/2712-8008/2024.1.4

Introduction

The process of development and operation of oil fields includes a set of various technical and technological measures. It is customary to distinguish four main stages of oil field development.

The first stage is characterized by an intensive and constant increase in oil production, a rapid increase in the operating well stock, and a sharp drop in reservoir pressure.

Rock, which has been in equilibrium for a long time, is deformed at the beginning of field development and the construction of surface structures, underground workings and gas storage facilities. The deformation of the rock affects its filtration and capacitive and physical and mechanical properties. The withdrawal of fluid from the reservoir and the decrease in reservoir pressure leads to an increase in the load on the rock skeleton, which was previously supported by reservoir (pore) pressure [1–12]. The stress state in which oil and gas reservoirs are located is characterized by effective pressure [13–17]:

$$p_{эф} = p_{вн} - np_{пл}, \qquad (1)$$

where $p_{вн}$ – external pressure of overlying rocks; $p_{пл}$ – reservoir pressure (internal); n – coefficient characterizing the value of reservoir pressure going to the discharge of external pressure [18–23].

The processes of pressure redistribution, deformation and change in the structure of the void space (compaction of the pore matrix, closure of cracks and caverns) are mechanical in nature [24, 25].

The second stage of oil field development is characterized by an increase in the number of wells, oil production and the beginning of an increase in water cut.

Researchers [24, 25] note the importance of chemical phenomena in hydrocarbon production. The authors note that by the use of reservoir pressure maintenance systems with water injection, chemical reactions, salt precipitation, dissolution or leaching of reservoir rocks in the zones of injection water penetration are possible in the reservoir.

The third stage is characterized by a decrease in the volume of produced oil, a significant decrease in the number of operating wells and a constant increase in the water cut of the extracted products.

The fourth stage is characterized by low rates of oil production, high water cut, and a further decrease in the number of operating wells.

At the described stages of oil field development, in order to increase oil recovery and reduce the water cut of the extracted products, various geological and technical measures are used: acid or alkaline treatment of the bottomhole zone of the reservoir (increasing permeability and eliminating contaminants), using surfactants (increasing the oil recovery factor), using hydraulic fracturing, etc. All methods used to stimulate oil inflow into the well affect the condition of reservoir rocks.

Thus, from the beginning to the end of the development of an oil field, the host rocks are subjected to mechanical and chemical action, their stress-strain state, filtration and strength properties change. All the changes undergoing by reservoir formations are interconnected. The research task of the authors of this article is to elaborate recommendations for the operation of oil fields at any stage of their development taking into account the obtained dependencies of strength, elastic and filtration properties of rocks on the type of saturating fluid.

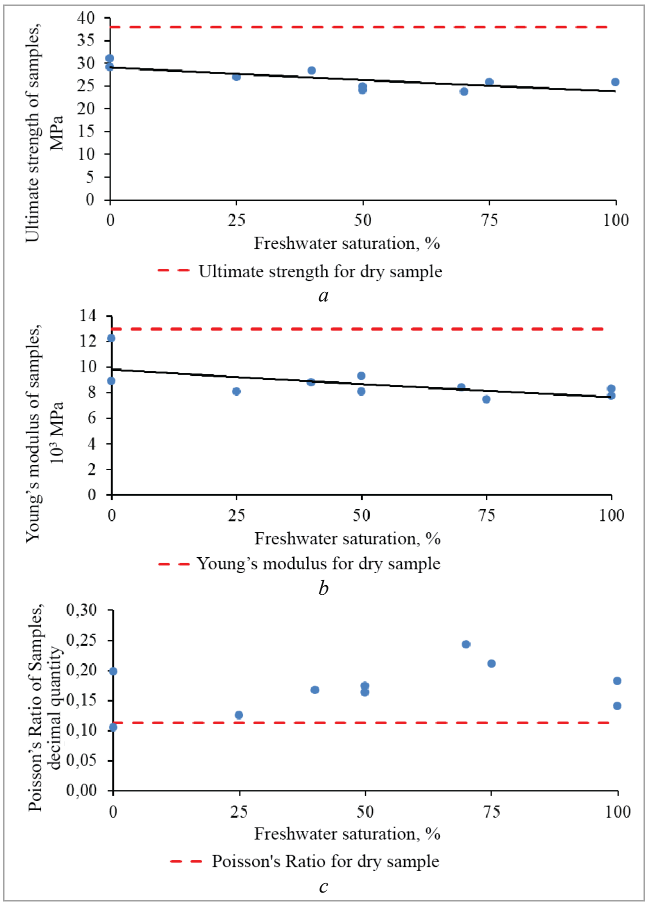

Fig. 1. Samples of rock pre-saturated with kerosene: *a* – dependence of tensile strength on the content of fresh water in the samples; *b* – dependence of the modulus of elasticity of rock samples on the content of fresh water in the samples; *c* is the distribution of Poisson's ratio values according to the freshwater content of the samples

Experimental Part

A series of experiments on fine-grained sandstone samples were performed to simulate various stages of oil field development. The composition of the rock-forming part is arkose – feldspars (45–50 %), quartz (35–40 %), as well as siliceous, quartz, quartz-micaceous and effusive differences (about 15 %). Clay cement, main clay minerals kaolinite and chlorite.

1. To determine the dependence of the strength and elastic properties of rocks on the type of saturating fluid, rock samples were saturated with fresh water and kerosene in different ratios. In Fig. 1 freshwater saturation of 0 % means that the sample is completely saturated with kerosene. The tensile strength of the dry specimen is shown separately in the graphs.

The determination of the modulus of elasticity E and the Poisson's ratio ν of the rock samples was carried out simultaneously with the determination of the tensile strength of the samples under uniaxial compression. The reduction in the tensile strength of the specimens at full kerosene saturation reaches an average of 20 % compared to the tensile strength of the specimen in the air-dry state (see Fig. 1, *a*). When oil is displaced by water, the water content in the reservoir gradually increases, and the phase "Oil-water" ratio changes in the rock.

In the experiment kerosene was used as a hydrocarbon liquid in the samples. With a ratio of 50 % water to 50 % kerosene the tensile strength of the specimens continues to decrease to values of about 30 % of the tensile strength of the specimen in the air-dry state. An increase in the water content of the samples leads to a decrease in the tensile strength values of the samples up to 40 % of the tensile strength of the rock sample in the air-dry state.

The decrease in strength of saturated rocks is explained by the Rebinder effect [26–30]. Hydrophilic rock interacts with saturating fluids (kerosene, water), the liquid is adsorbed on the surfaces of existing micro cracks. In the process of loading the specimen there operate forces which have a proppant effect under the influence of fluid pressure. As a result, existing cracks grow and new ones develop. Due to this process the strength of the rock decreases and its plasticity increases [31–37]. There are known the effects of reducing the strength of the rock from the influence of surfactants [38–40] and water of different mineralization [41, 42]. While using the techniques of determining the mechanical properties of rock by loading spherical indenters [43, 44] a similar decrease in rock strength with an increase in water saturation has been established.

The reduction of the elastic modulus of the samples at full kerosene saturation can reach values of 10–30% of the elastic modulus of the samples in the air-dry state (see Fig. 1, *b*). With a water/kerosene ratio of 50/50 %, the modulus of elasticity of the samples can be reduced to 30–35 %. With a further drop of the hydrocarbon phase percentage in the samples the modulus of elasticity of the rock decreases by up to 40 % compared to the modulus of elasticity of the rock in the air-dry state.

Dependence of the modulus of elasticity of rock samples on water saturation can be represented by the formula:

$$E = 9{,}8127\exp(-0{,}002 \cdot S_B), \qquad (1)$$

where E – modulus of elasticity, 10^3 MPa; S_B – water saturation, decimal quantity.

Fig. 1, *b*, shows the distribution of the values of the Poisson's ratio of samples from water saturation. From the data presented, it can be seen that the Poisson's ratio of a dry sample is less than the Poisson's ratio of saturated samples. In the process of saturation, the rock interacts with water and kerosene. An increase in the value of the Poisson's ratio indicates that the rock in the saturated state is more susceptible to irreversible plastic deformations and becomes less brittle.

Analyzing the results obtained, it can be concluded that the tensile strength, Young's modulus of elasticity and Poisson's ratio of the studied rocks depend on the type and composition of the fluid saturating the rock. When determining the properties of rocks in laboratory conditions, it is necessary to recreate the composition of the fluid saturating the rock according to the operating conditions of the deposit. When sampling, special attention should be paid to maintaining their natural saturation.

Much work has been devoted to the study of the permeability of reservoir rocks [45–49]. However, in order to ensure a high degree of confidence in the proposed recommendations due to the wide variability of the described test conditions and the uniqueness of the studied groups of the samples it is necessary to determine the properties of the rocks for each specific case.

Filtration experiments were carried out on rock samples to determine the dependence of permeability on effective pressure. Fresh water was used for filtration. The main parameters of the samples are given in Table 1.

Figure 2 shows the dependence of the coefficient of relative change in the permeability k/k0 of rock samples on the effective pressure. As the effective pressure increases, the specimen begins to deform. The existing filtration channels begin to close, microcrack systems are formed, and previously

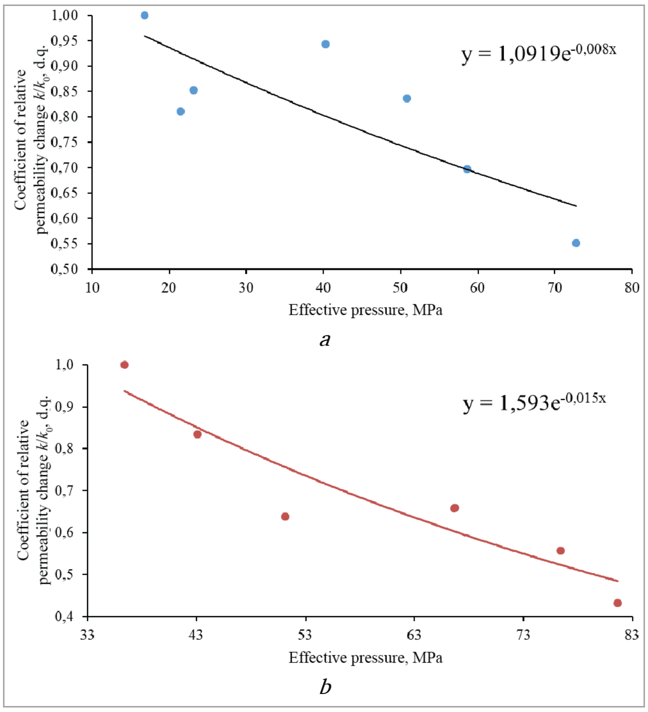

Fig. 2. Dependence of the coefficient of relative changes in permeability on the effective pressure: *a* – sample No. 1; *b* – model No. 2

Table 1

Initial Parameters of Rock Samples for Filtration Experiment

№ sample	Porosity, %	Tensile strength of specimens under uniaxial compression, MPa	Modulus of elasticity, 10^3 MPa	Poisson coefficient
1	17,3	28,08	8,02	0,16
2	10,3	27,16	8,08	0,17

closed pore voids are involved in the filtration process. Despite the positive effect of creating microfracture systems in the rock, the simultaneous development of the clay swelling process is possible in clay reservoirs, which, in turn, will adversely affect the permeability of the rock. As shown in Fig. 2, a significant decrease in the coefficient of relative change in permeability with an increase in effective pressure to 22–24 MPa is associated with the active development of the clay swelling process and an increase in the plasticity of the rock due to the interaction of the rock with fresh water. A further increase in the coefficient of relative change in permeability (at an effective pressure of 40 MPa) is associated with an increase in the opening of cracks in the sample.

During the test for the sample No. 2, a discharge was carried out to determine the permeability of the sample when the effective pressure on the it was reduced after realization of 50 % of loading from the ultimate sample strength at volumetric compression (Fig. 3). Sample unloading was carried out stepwise and identical to the experiment during loading.

When the load was removed, the permeability was not restored, which indicates the lack of elastic recovery of the pore space for the tested clay reservoir samples. The overall permeability reduction is up to 50 % of the original value.

A decrease in reservoir pressure leads to an increase in effective pressure and to an irreversible decrease in the permeability of clay reservoirs. In the fields, it is necessary to use appropriate reservoir pressure maintenance systems

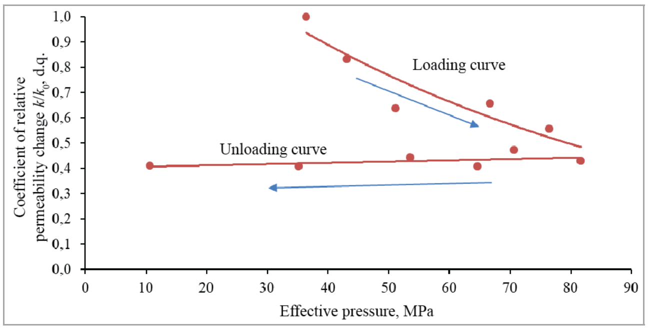

Fig. 3. Dependence of the coefficient of relative permeability change k/k_0 of sample No. 2 on the effective pressure (loading-unloading curve)

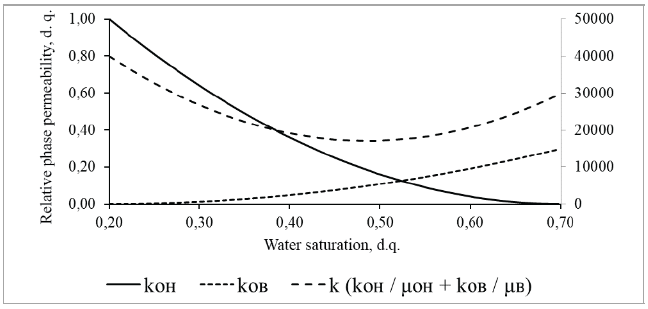

Fig. 4. Graph of relative phase permeability versus water saturation

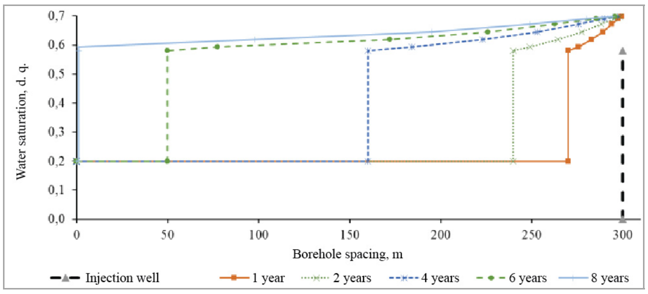

Fig. 5. Position of the Oil Displacement Front in the reservoir by years water saturation; Borehole spacing; Injection well

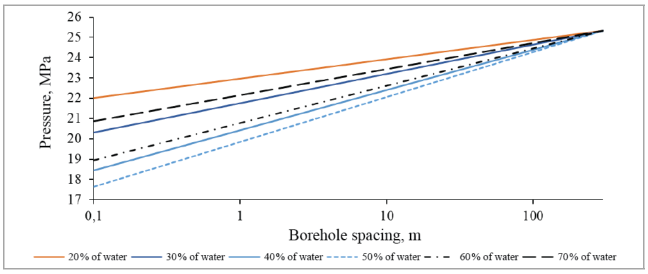

Fig. 6. Reservoir Pressure Distribution from water saturation in logarithmic coordinates

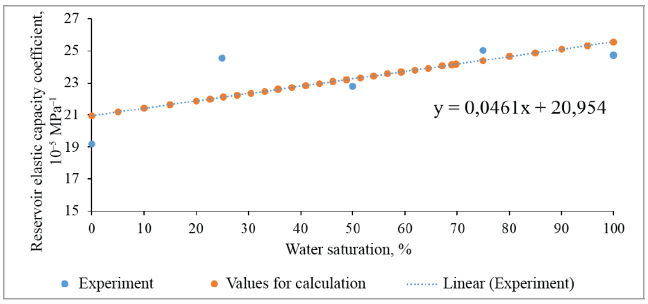

Fig. 7. Graph of coefficient changes of reservoir elastic capacity depending on water saturation

from the beginning of development. When planning and carrying out geological and technical measures at wells, it is necessary to take into account the influence of the composition of injected fluids on the properties of rocks, when conducting hydraulic fracturing, it is necessary to consider the decrease in rock strength from the current water cut.

Calculation of pressure distribution in the reservoir considering water saturation

To determine the relative permeability coefficients of rocks the following expressions were used:

$$k_{OB} = \left(k_{OB}\right)_{S_{OH}} \left(\frac{\bar{S}_B - S_{BC}}{1 - S_{OH} - S_{BC}}\right)^{EXO}, \qquad k_{OH} = \left(k_{OH}\right)_{Swir} \left(\frac{1 - S_{OH} - \bar{S}_B}{1 - S_{OH} - S_{BC}}\right)^{EXW}, \tag{2}$$

where $\left(k_{OB}\right)_{S_{OH}}$ – final value of relative water permeability; $\bar{S}_B$ – current value of water saturation, decimal quntity; S_{OH} – residual oil saturation, decimal quantity saturation by the connected water; S_{BC} – saturation by the connected water, decimal quantit.; EXO – exponential value of relative oil permeability; $\left(k_{OH}\right)_{Swir}$ – final value of relative oil permeability; EXW – exponential value of relative water permeability.

Fig. 4 shows the curves of relative phase permeability together with the curve $k\left(k_{OH}/\mu_H + k_{OB}/\mu_B\right)$ according to the auxiliary scale.

Let's consider a flat-radial inflow into a well. The flow rate of a production well is determined by the formula (3):

$$Q = 2\pi k \left(\frac{k_{OH}}{\mu_H} + \frac{k_{OB}}{\mu_B}\right) h_{ЭФ} \frac{\Delta P}{\ln \frac{R_K}{r_c}}, \tag{3}$$

where μ – fluid viscosity, MPa·c; k – permeability, mD; $h_{ЭФ}$ – reservoir thickness, m; ΔP – differential pressure, MPa; $R_к$ – radius of external reservoir boundary, m; r – borehole radius, m.

The Buckley-Leverett method [50–57] was used to determine saturation at the displacement front $S_{BФB} = 58$ %. To determine the time of breakthrough of the displacement front into the well it can be used the formula (4):

$$t = \frac{m_{пор}\, \pi R_K^2 h_{ЭФ}}{Q f\left(S_в\right)}. \tag{4}$$

The position of the displacement front at any given time is determined by formula (5). The results of the calculations are presented graphically in Fig. 5. The displacement front breaks through from the injection well to the production well in 2289 days (6 years and 4 months).

$$x = \sqrt{R_K^2 - \frac{t Q f\left(S_в\right)}{\pi h_{ЭФ} m_{пор}}}. \tag{5}$$

In addition, the calculation of the pressure distribution in the reservoir at a constant flow rate of the well from the distance between the wells was performed according to the formula (6):

$$p(r) = p_{\text{К}} - \frac{Q_0}{2\pi k\left(\frac{k_{\text{ОН}}}{\mu_{\text{Н}}} + \frac{k_{\text{ОВ}}}{\mu_{\text{В}}}\right)h_{\text{ЭФ}}} \ln\left(\frac{R_{\text{К}}}{r_{\text{С}}}\right), \quad (6)$$

where $p_к$ – pressure at external reservoir boundary, atm; Q_0 – well flow rate, m³/day.

The pressure distribution in the reservoir is shown in Fig. 6 in logarithmic coordinates.

The curve corresponding to 50% water content and 50 % oil content in the rock has the largest pressure reduction in the graph – the pressure at the bottom of the well is 25 % lower than when the well is started at the saturation by the bound water S_{BC} = 20 %. For the "50 % water" plot, the minimum pressure at the bottom of the well is explained by the dependence on the relative phase permeability (see Fig. 4). The rate of decline in oil permeability is higher than the rate of increase in water permeability.

Determination of the dependence of elastic capacity and piezoconductivity on saturation

Based on the results of studies of physical-mechanical and filtration-capacitance properties it was found that elasticity changes depending on saturation and stage of development.

The relationship (7) is used to determine the reservoir compressibility factor:

$$\beta = \frac{1}{K}; \ \beta = \frac{3(1-2\nu)}{E}, \quad (7)$$

where β – compressibility factor, Pa⁻¹; K – modulus of volumetric elasticity, Pa; E – modulus of elasticity, Pa; ν – Poisson's ratio (ν = 0,17).

The elastic capacity of a reservoir is determined by the expression (8):

$$\beta^* = m\beta_{\text{ж}} + \beta_{\text{п}}, \quad (8)$$

where $\beta_ж$ – fluid compressibility coefficient, Pa⁻¹; $\beta_п$ – compressibility coefficient of rock, Pa⁻¹; m – porosity coefficient, decimal quantity.

For saturated rock samples, the elastic capacitance coefficient was assumed to be equal to the compressibility coefficient. Figure 7 shows the values of the reservoir elastic capacity coefficient. A trend line was drawn to the average values obtained as a result of the calculation based on experimental data.

The piezoconductivity factor is determined by the relationship (9):

$$\chi = \frac{k}{\mu\beta^*} = k\left(\frac{k_{\text{ОН}}}{\mu_{\text{Н}}} + \frac{k_{\text{ОВ}}}{\mu_{\text{В}}}\right)\frac{1}{\beta^*}, \quad (9)$$

where χ – piezo conductivity, m²/s; k – permeability, mD; μ – fluid viscosity, mPa·c; β^* – reservoir elastic capacity coefficient, Pa⁻¹.

Figure 8, *a*, shows a graph of the dependence of piezoconductivity on water saturation. The graphs are limited to the values of water saturation of 20 and 70 %, since in the conditions of solving the problem the values of the saturation of the bound water were S_{BC} = 20 % and residual oil saturation S_{OH} = 30 %. The change in piezoconductivity is parabolic in nature.

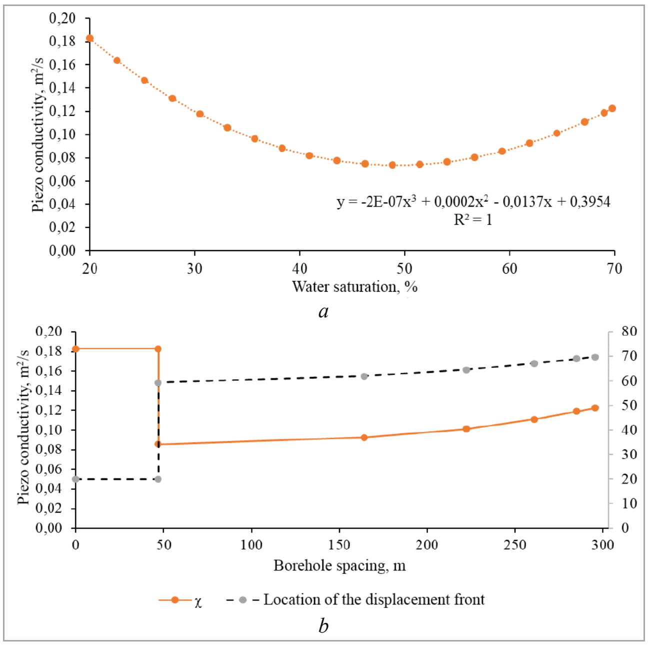

Fig. 8. Graph of piezoconductivity variation: *a* – as a function of water saturation; *b* – as a function of distance between wells at the moment of approach of the displacement front to the well

Using the dependencies of the piezo conductivity distribution of the reservoir on the saturation of the reservoir with water, it is possible to determine the dependence of the change in the piezo conductivity of the reservoir at a certain point in time on the distance between the wells.

The fall of piezo conductivity with an increase in water saturation is explained by a decrease in the mobility of oil and water to a ratio of 50/50 %, as well as by the inversely proportional relationship to the compressibility coefficient, which, in turn, with increasing water saturation, increases. After crossing the point corresponding to the oil-water values 50/50 %, there is an increase in piezo conductivity from water saturation.

Figure 8, *b*, shows the curve of change in piezo conductivity as a function of the distance between the wells at the moment of the displacement front approaching the production well. The sharp jump in water cut and piezo conductivity is explained here by the application of the model of non-piston displacement of oil by water, according to which before the displacement front, the water saturation is equal to the saturation of bound water $S_{\text{ВС}}$ = 20 %. The relative phase permeability values for oil in this area are significantly higher than the relative phase permeability for water at the displacement front and beyond it ($S_{\text{ВФВ}}$ = 58 %).

From the performed calculations it can be seen that the piezo conductivity in the watered and non-watered zones of the reservoir differs by about 2 times and, therefore, the rates of pressure redistribution in these zones will be different. This difference must be taken into account during implementation of reservoir pressure maintenance systems in order to prevent pressure reduction in individual zones and thus reduce their permeability.

Conclusion

Based on the results of theoretical and experimental studies, the following recommendations can be made:

1. When taking samples in the field, special attention should be paid to maintaining their natural saturation.

2. In case of leakage of the package of samples selected for testing in laboratory conditions it is necessary to recreate the composition of the fluid saturating the rock according to the stage of field development since the strength, elastic and filtration properties of the rock depend on this.

3. From the beginning of field development, it is necessary to compensate for fluid withdrawal from the reservoir by injection using reservoir pressure maintenance systems. An increase in the effective pressure on the reservoir rock in the process of oil field development leads to an irreversible loss of permeability of clay rocks.

4. When choosing the water injection pressure in the reservoir pressure maintenance system, take into account the physical and chemical impact of water on the reservoir and the associated decrease in strength and elastic properties in order to prevent the effect of auto-fracturing and water breakthrough into undesirable areas of the reservoir.

5. While planning and carrying out geological and engineering operations at wells, it is necessary to take into account the influence of the composition of injected fluids on the strength, elastic and filtration properties of rocks.

6. Performing hydraulic fracturing take into account the decrease in rock strength due to the current water cut of the bottom-hole zone of the reservoir.

References

1. Zhou X. et al. A combined method to measure Biot's coefficient for rock. *49th US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association, 2015, available at: https://www.onepetro.org/conference-paper/ARMA-2015-584?sort=&start=0&q=A+combined+method+to+measure+biot%E2%80%99s+coefficient+for+rock&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
2. Biot M.A. General theory of three-dimensional consolidation. *Journal of applied physics*, 1941, vol. 12, no. 2, pp. 155-164. DOI: 10.1063/1.1712886
3. Zhou X. et al. Biot's effective stress coefficient of mudstone source rocks. *51st US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics As strain condition sociation. San Francisco, 2017, available at: https://www.onepetro.org/conference-paper/ARMA-2017-0235?sort=&start=0&q=Biot%E2%80%99s+effective+stress+coefficient+of+mudstone+source+rocks+%2F+Zhou+X.+%5Bet+al&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
4. Bailin W. et al. Biot's effective stress coefficient evaluation: static and dynamic approaches. *ISRM International Symposium-2nd Asian Rock Mechanics Symposium*. International Society for Rock Mechanics and Rock Engineering. Beijing, 2001, available at: https://onepetro.org/ISRMARMS/proceedings-abstract/ARMS201/All-ARMS201/ISRM-ARMS2-2001-082/169992 (accessed 24 April 2023).
5. Qiao L.P. et al. Determination of Biot's effective-stress coefficient for permeability of Nikanassin sandstone. *Journal of Canadian Petroleum Technology*, 2012, vol. 51, no. 03, pp. 193-197. DOI: 10.2118/150820-PA
6. Franquet J.A. et al. Experimental evaluation of Biot's poroelastic parameter-Three different methods. *Rock Mechanics for Industry*, 1999, pp. 349-355.
7. He Jun, Rui Zhenhua, Ling Kegang. A new method to determine Biot's coefficients of Bakken samples. *Journal of Natural Gas Science and Engineering*, 2016, vol. 35, part A, pp. 259-264. DOI: 10.1016/j.jngse.2016.08.061
8. King M.S., Marsden J.R., Dennis J.W. Biot dispersion for P-and S-wave velocities in partially and fully saturated sandstones. *Geophysical Prospecting*. 2009. vol. 48, no. 6, pp. 1075-1089. DOI: 10.1111/j.1365-2478.2000.00221.x
9. Nermoen A., Korsnes R., Christensen H., Trads N., Hiorth A., Madland M.V. Measuring the Biot stress coefficient and its implications on the effective stress estimate. *47th US Rock Mechanics. Geomechanics Symposium*, 2013, available at: https://www.onepetro.org/conference-paper/ARMA-2013-282?sort=&start=0&q=Measuring+the+biot+stress+coefficient+and+is+implications+on+the+effective+stress+estimate+&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
10. Müller T.M., Sahay P.N. Skempton coefficient and its relation to the Biot bulk coefficient and micro-inhomogeneity parameter. *SEG Technical Program Expanded Abstracts 2014*. Society of Exploration Geophysicists, 2014, pp. 2905-2909.
11. Sahay P.N. Biot constitutive relation and porosity perturbation equation. *Geophysics*, 2013, vol. 78, no. 5, pp. L57-L67. DOI: 10.1190/geo2012-0239.1
12. Fjar E., Holt R.M., Horsrud P. et al. Petroleum related rock mechanics. 2nd ed. Elsevier, 2008, vol. 53, 492 p. DOI: 10.1016/j.ijrmms.2009.04.012
13. Bishop A.W. The influence of an undrained change in stress on the pore pressure in porous media of low compressibility. *Geotechnique*, 1973, vol. 23, no. 3. pp. 435-442. DOI: 10.1680/geot.1973.23.3.435
14. Alam M.M. et al. Effective stress coefficient for uniaxial strain condition. *46th US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association, 2012, available at: https://www.onepetro.org/conference-paper/ARMA-2012-302?sort=&start=0&q=Effective+stress+coefficient+for+uniaxial+strain+condition+&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
15. Nur A., Byerlee J.D. An exact effective stress law for elastic deformation of rock with fluids. *Journal of Geophysical Research*, 1971, vol. 76, no. 26, pp. 6414-6419. DOI: 10.1029/JB076i026p06414
16. Skempton A.W. Effective stress in soils, concrete and rocks-Pore pressure and suction in soils. *Conference of the British National Society*, 1961. London, pp. 4-16.
17. Terzaghi K. Theoretical soil mechanics. London: Chapman and Hall, Limited, 1951, pp. 123-130.
18. Wang, H.F. Theory of linear poroelasticity with applications to geomechanics and hydrogeology. Princeton University Press, 2001, 304 p. DOI: 10.1515/9781400885688
19. Zimmerman R.W., Somerton W.H., King M.S. Compressibility of porous rocks. *Journal of Geophysical Research: Solid Earth*, 1986, vol. 91, no. B12, pp. 12765-12777. DOI: 10.1029/JB091iB12p12765
20. Karmanskii A.T. Eksperimental'noe obosnovanie prochnosti i razrusheniia nasyshchennykh osadochnykh gornykh porod [Experimental substantiation of the strength and destruction of saturated sedimentary rocks]. Abstract of Doctor's degree dissertation. Saint Petersburg, 2010, 37 p.
21. Karmanskii A.T., Stavrogin A.N. Vliianie vlazhnosti, vida napriazhennogo sostoianiia i skorosti razrusheniia na fiziko-mekhanicheskie svoistva gornykh porod [The influence of humidity, type of stress state and rate of destruction on the physical and mechanical properties of rocks]. FTPRPI, 1992, no. 4, pp. 3-10.
22. Nikolaevskii V.N., Basniev K.S., Gorbunov A.T. Mekhanika nasyshchennykh poristykh sred [Mechanics of saturated porous media]. Moscow: Nedra, 1970, 339 p.
23. Khanin A.A. Porody-kollektory nefti i gaza i ikh izuchenie [Oil and gas reservoir rocks and their study]. Moscow: Nedra, 1969, 368 p.
24. Kolchitskaia T.N., Mikhailov N.N. Vliianie tsiklicheskikh rezhimov ekspluatatsii skvazhin na izmenenie sostoianiia neftegazovykh plastov [The influence of cyclic modes of well operation on changes in the state of oil and gas formations]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2002, no. 5, pp. 78-81.
25. Mikhailov N.N., Popov S.N. Eksperimental'nye i teoreticheskie issledovaniia vliianiia mekhanokhimicheskikh effektov na fil'tratsionno-emkostnye, uprugie i prochnostnye svoistva porod-kollektorov [Experimental and theoretical study of influence of mechanochemical effects on porosity, permeability, elastic and strength properties of reservoir rocks]. *Georesursy, geoenergetika, geopolitika*, 2015, no. 1 (11), available at: http://oilgasjournal.ru/vol_11/popov.html (accessed 24 April 2023).
26. Evseev V.D. O vozmozhnosti ispol'zovaniia effekta P.A. Rebindera pri burenii skvazhin [On the possibility of using the P.A. Rebinder effect when drilling wells]. *Izvestiia Tomskogo politekhnicheskogo universiteta*, 2010, vol. 317, no. 1, pp. 165-169.
27. Evseev V.D. Priroda effekta Rebindera pri razrushenii gornykh porod [The nature of the Rehbinder effect during rock destruction]. *Neftianoe khoziaistvo*, 2011, no. 11, pp. 38-40.
28. Rebinder P.A., Shreiner L.A. Fiziko-khimicheskii metod uskoreniia bureniia tverdykh porod s pomoshch'iu dobavok, ponizitelei tverdosti k promyvnym vodam [Physico-chemical method for accelerating drilling of hard rocks using additives, hardness reducers to wash water]. *Gornyi zhurnal*, 1938, no. 8-9, 16 p.
29. Rebinder P.A., Shreiner L.A., Zhigach K.F. Primenenie ponizitelei tverdosti dlia povysheniia skorostei bureniia na neft' v tverdykh porodakh Vostochnykh mestorozhdenii [Application of hardness reducers to increase oil drilling speeds in hard rocks of the Eastern fields]. *Neftianaia promyshlennost' SSSR*, 1940, no. 5, 54 p.
30. Rebinder P.A., Shchukin E.D. Poverkhnostnye iavleniia v tverdykh telakh v protsessakh ikh deformatsii i razrusheniia [Surface phenomena in solids during the processes of their deformation and destruction]. *Uspekhi fizicheskikh nauk*, 1972, vol. 108, iss. 1, pp. 3-42.
31. Lin S., Lai B. Experimental investigation of water saturation effects on Barnett Shale's geomechanical behaviors. *Society of Petroleum Engineers*, 2013. DOI: 10.2118/166234-MS
32. Najmud D., Hayatdavoudi A., Ghalambor A. Laboratory investigation of saturation effect on mechanical properties of rocks. *SPWLA 31st annual logging symposium*. June 24-27, 1990, pp. 1-23.
33. Liu K. et al. Predicting Reservoir Rock Mechanical Properties Directly from Sedimentary Characterisation. *SPE Asia Pacific Oil & Gas Conference and Exhibition*. Society of Petroleum Engineers, 2016, available at: https://www.onepetro.org/conference-paper/SPE-182342-MS. (accessed 24 April 2023). DOI: 10.2118/182342-MS
34. Vásárhelyi B., Ván P. Influence of water content on the strength of rock. *Engineering Geology*, 2006, vol. 84, no. 1-2, pp. 70-74. DOI: 10.1016/j.enggeo.2005.11.011
35. Bieniawski Z.T., Bernede M.J. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for determining deformability of rock materials in uniaxial compression. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 1979, vol. 16, iss. 2, pp. 138-140. DOI: 10.1016/0148-9062(79)91451-7
36. Suggested methods for determining the strength of rock materials in triaxial compression: Revised version. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 1983, vol. 20, iss. 6, pp. 285-290. DOI: 10.1016/0148-9062(83)90598-3
37. Zhao B. et al. The Effects of Long-Term Waterflooding on the Physical and Mechanical Properties of Tight Sandstones. *52nd US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association, 2018, available at: https://www.onepetro.org/conference-paper/ARMA-2018-409?sort=&start=0&q=The+effects+of+long-term+waterflooding+on+the+physical+and+mechanical+proper-ties+of+tight+sandstones+&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
38. Gladkov P.D., Rogachev M.K. Issledovanie vliianiia gidrofobiziruiushchikh sostavov na mekhanicheskuiu prochnost' obraztsov polimiktovykh peschanikov [Research of hydrophobic compositions` influence on mechanical strength of polymineral sandstone core samples]. *Neftegazovoe delo*, 2012, no. 1, pp. 360-366.

39. Glushchenko V.N., Silin M.A. Ob"emnye i poverkhnostno-aktivnye svoistva zhidkostei [Volumetric and surface-active properties of liquids]. *Neftepromyslovaia khimiia*. Moscow: Interkontakt Nauka, 2010, vol. 2, 549 p.
40. Rebinder P.A. Poverkhnostnye iavleniia v dispersnykh sistemakh. Fiziko-khimicheskaia mekhanika [Surface phenomena in disperse systems. Physico-chemical mechanics]. *Izbrannye trudy*. Moscow: Nauka, 1979, 384 p.
41. Igdavletova M., Ismagilov T., Ganiev I., Telin A. Vliianie geologo-fizicheskikh kharakteristik produktivnykh plastov i svoistv plastovykh fliuidov na vybor vytesniaiushchego agenta pri zavodnenii [Influence of geological and physical characteristics of productive formations and properties of formation fluids on the choice of a displacement agent during waterflooding]. *Neftegaz.ru*, 2014, no. 7-8, pp. 18-25.
42. Deliia S.V. Abukova L.A., Abramova O.P., Anisimov L.A., Popov S.N., Vorontsova I.V. Eksperimental'noe i chislennoe modelirovanie vzaimodeistviia plastovykh i tekhnicheskikh vod pri razrabotke mestorozhdeniia imeni Iu. Korchagina [Experimental and numerical modeling of the interaction of formation and technical waters during the development of the Yu. Korchagin field]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2012, no. 10, pp. 34-41.
43. Karmanskiy D., Maltsev A. Theoretical and experimental evaluation of formation fluid composition influence on filtration and elastic properties of porous media. *Physical and mathematical modeling of Earth and environment processes*. Eds. V. Karev, D. Klimov, K. Pokazeev; PMMEEP 2017. Springer Geology. Springer, Cham, pp. 84-89. DOI: 10.1007/978-3-319-77788-7_10
44. Penkov G.M., Karmansky D.A., Petrakov D.G. Simulation of a fluid influx in complex reservoirs of Western Siberia. *Topical Issues of Rational Use of Natural Resources: Proceedings of the International Forum-Contest of Young Researchers, April 18-20, 2018*. St. Petersburg, 2018, pp. 119-124.
45. Fischer G.J. The determination of permeability and storage capacity: Pore pressure oscillation method. *International Geophysics*. Academic Press, 1992, vol. 51, pp. 187-211. DOI: 10.1016/S0074-6142(08)62823-5
46. Adenutsi C.D. et al. Pore pressure variation at constant confining stress on water–oil and silica nanofluid-oil relative permeability. *Journal of Petroleum Exploration and Production Technology*, 2019, no. 9, pp. 2065-2079. DOI: 10.1007/s13202-018-0605-6
47. Sato M., Takemura T., Takahashi M. Development of the permeability anisotropy of submarine sedimentary rocks under true triaxial stresses. *International Journal of Rock Mechanics and Mining Sciences*, 2018, vol. 108, pp. 118-127. DOI: 10.1016/j.ijrmms.2018.06.010
48. Yu J. et al. Triaxial test research on mechanical properties and permeability of sandstone with a single joint filled with gypsum. *KSCE Journal of Civil Engineering*, 2016, vol. 20, no. 6, pp. 2243-2252. DOI: 10.1007/s12205-015-1663-7
49. Ban A. et al. Vliianie svoistv gornykh porod na dvizhenie v nikh zhidkosti [The influence of the properties of rocks on the movement of fluid in them]. Moscow: Gostoptekhizdat, 1962, pp. 158-187.
50. Dake L.P. Fundamentals of reservoir engineering. Elsevier, 1983, vol. 8, 492 p.
51. Akhmetzianov A.V., Kushner A.G., Lychagin V.V. Integrability of Buckley - Leverett's Filtration Model **This work was supported by the Russian Science Foundation (the grants No 15-19-00275). *IFAC-PapersOnLine*, 2016, vol. 49, iss. 12, pp. 1251-1254. DOI: 10.1016/j.ifacol.2016.07.685
52. Akhmetzianov A.V., Kushner A.G., Lychagin V.V. Two-dimensional non-isothermal filtration and optimal control of oil field development **This work was supported by the Russian Science Foundation (the grants No 15-19-00275). *IFAC-PapersOnLine*, 2018, vol. 51, iss. 11, pp. 888-890. DOI: 10.1016/j.ifacol.2018.08.453
53. Akhmetzyanov A.V., Kushner A.G., Lychagin V.V. Mass and heat transport in the two-phase Buckley - Leverett model. *Journal of Geometry and Physics*, 2017, vol. 113, pp. 2-9. DOI: 10.1016/j.geomphys.2016.06.010
54. Yunus Khan Mohammad, Mandal Ajay. Improvement of Buckley-Leverett equation and its solution for gas displacement with viscous fingering and gravity effects at constant pressure for inclined stratified heterogeneous reservoir, Fuel, 2021, vol. 285, 119172. DOI: 10.1016/j.fuel.2020.119172
55. Siddiqui S., Hicks P.J., Grader A.S. Verification of Buckley-Leverett three-phase theory using computerized tomography. *Journal of Petroleum Science and Engineering*, 1996, vol. 15, iss. 1, pp. 1-21. DOI: 10.1016/0920-4105(95)00056-9
56. Rose W. Attaching new meanings to the equations of buckley and leveret. *Journal of Petroleum Science and Engineering*, 1988, vol. 1, iss. 3, pp. 223-228. DOI: 10.1016/0920-4105(88)90012-5
57. Rose W., Rose D.M. "Revisiting" the enduring Buckley - Leverett ideas. *Journal of Petroleum Science and Engineering*, 2004, vol. 45, iss. 3-4, pp. 263-290. DOI: 10.1016/j.petrol.2004.08.001

Библиографический список

1. Zhou X. et al. A combined method to measure Biot's coefficient for rock. *49th US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association, 2015, available at: https://www.onepetro.org/conference-paper/ARMA-2015-584?sort=&start=0&q=A+combined+method+to+measure+biot%E2%80%99s+coefficient+for+rock&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
2. Biot M.A. General theory of three-dimensional consolidation. *Journal of applied physics*, 1941, vol. 12, no. 2, pp. 155-164. DOI: 10.1063/1.1712886
3. Zhou X. et al. Biot's effective stress coefficient of mudstone source rocks. *51st US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics As strain condition sociation. San Francisco, 2017, available at: https://www.onepetro.org/conference-paper/ARMA-2017-0235?sort=&start=0&q=Biot%E2%80%99s+effective+stress+coefficient+of+mudstone+source+rocks+%2F+Zhou+X.+%5Bet+al&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
4. Bailin W. et al. Biot's effective stress coefficient evaluation: static and dynamic approaches. *ISRM International Symposium-2nd Asian Rock Mechanics Symposium*. International Society for Rock Mechanics and Rock Engineering. Beijing, 2001, available at: https://onepetro.org/ISRMARMS/proceedings-abstract/ARMS201/All-ARMS201/ISRM-ARMS2-2001-082/169992 (accessed 24 April 2023).
5. Qiao L.P. et al. Determination of Biot's effective-stress coefficient for permeability of Nikanassin sandstone. *Journal of Canadian Petroleum Technology*, 2012, vol. 51, no. 03, pp. 193-197. DOI: 10.2118/150820-PA
6. Franquet J.A. et al. Experimental evaluation of Biot's poroelastic parameter-Three different methods. *Rock Mechanics for Industry*, 1999, pp. 349-355.
7. He Jun, Rui Zhenhua, Ling Kegang. A new method to determine Biot's coefficients of Bakken samples. *Journal of Natural Gas Science and Engineering*, 2016, vol. 35, part A, pp. 259-264. DOI: 10.1016/j.jngse.2016.08.061
8. King M.S., Marsden J.R., Dennis J.W. Biot dispersion for P-and S-wave velocities in partially and fully saturated sandstones. *Geophysical Prospecting*. 2009. vol. 48, no. 6, pp. 1075-1089. DOI: 10.1111/j.1365-2478.2000.00221.x
9. Nermoen A., Korsnes R., Christensen H., Trads N., Hiorth A., Madland M.V. Measuring the Biot stress coefficient and its implications on the effective stress estimate. *47th US Rock Mechanics. Geomechanics Symposium*, 2013, available at: https://www.onepetro.org/conference-paper/ARMA-2013-282?sort=&start=0&q=Measuring+the+biot+stress+coefficient+and+is+implications+on+the+effective+stress+estimate+&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
10. Müller T.M., Sahay P.N. Skempton coefficient and its relation to the Biot bulk coefficient and micro-inhomogeneity parameter. *SEG Technical Program Expanded Abstracts 2014*. Society of Exploration Geophysicists, 2014, pp. 2905-2909.
11. Sahay P.N. Biot constitutive relation and porosity perturbation equation. *Geophysics*, 2013, vol. 78, no. 5, pp. L57-L67. DOI: 10.1190/geo2012-0239.1
12. Fjar E., Holt R.M., Horsrud P. et al. Petroleum related rock mechanics. 2nd ed. Elsevier, 2008, vol. 53, 492 p. DOI: 10.1016/j.ijrmms.2009.04.012
13. Bishop A.W. The influence of an undrained change in stress on the pore pressure in porous media of low compressibility. *Geotechnique*, 1973, vol. 23, no. 3. pp. 435-442. DOI: 10.1680/geot.1973.23.3.435
14. Alam M.M. et al. Effective stress coefficient for uniaxial strain condition. *46th US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association, 2012, available at: https://www.onepetro.org/conference-paper/ARMA-2012-302?sort=&start=0&q=Effective+stress+coefficient+for+uniaxial+strain+condition+&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
15. Nur A., Byerlee J.D. An exact effective stress law for elastic deformation of rock with fluids. *Journal of Geophysical Research*, 1971, vol. 76, no. 26, pp. 6414-6419. DOI: 10.1029/JB076i026p06414
16. Skempton A.W. Effective stress in soils, concrete and rocks-Pore pressure and suction in soils. *Conference of the British National Society*, 1961. London, pp. 4-16.
17. Terzaghi K. Theoretical soil mechanics. London: Chapman and Hall, Limited, 1951, pp. 123-130.
18. Wang, H.F. Theory of linear poroelasticity with applications to geomechanics and hydrogeology. Princeton University Press, 2001, 304 p. DOI: 10.1515/9781400885688
19. Zimmerman R.W., Somerton W.H., King M.S. Compressibility of porous rocks. *Journal of Geophysical Research: Solid Earth*, 1986, vol. 91, no. B12, pp. 12765-12777. DOI: 10.1029/JB091iB12p12765
20. Karmanskii A.T. Eksperimental'noe obosnovanie prochnosti i razrusheniia nasyshchennykh osadochnykh gornykh porod [Experimental substantiation of the strength and destruction of saturated sedimentary rocks]. Abstract of Doctor's degree dissertation. Saint Petersburg, 2010, 37 p.
21. Karmanskii A.T., Stavrogin A.N. Vliianie vlazhnosti, vida napriazhennogo sostoianiia i skorosti razrusheniia na fiziko-mekhanicheskie svoistva gornykh porod [The influence of humidity, type of stress state and rate of destruction on the physical and mechanical properties of rocks]. FTPRPI, 1992, no. 4, pp. 3-10.
22. Nikolaevskii V.N., Basniev K.S., Gorbunov A.T. Mekhanika nasyshchennykh poristykh sred [Mechanics of saturated porous media]. Moscow: Nedra, 1970, 339 p.
23. Khanin A.A. Porody-kollektory nefti i gaza i ikh izuchenie [Oil and gas reservoir rocks and their study]. Moscow: Nedra, 1969, 368 p.
24. Kolchitskaia T.N., Mikhailov N.N. Vliianie tsiklicheskikh rezhimov ekspluatatsii skvazhin na izmenenie sostoianiia neftegazovykh plastov [The influence of cyclic modes of well operation on changes in the state of oil and gas formations]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2002, no. 5, pp. 78-81.
25. Mikhailov N.N., Popov S.N. Eksperimental'nye i teoreticheskie issledovaniia vliianiia mekhanokhimicheskikh effektov na fil'tratsionno-emkostnye, uprugie i prochnostnye svoistva porod-kollektorov [Experimental and theoretical study of influence of mechanochemical effects on porosity, permeability, elastic and strength properties of reservoir rocks]. *Georesursy, geoenergetika, geopolitika*, 2015, no. 1 (11), available at: http://oilgasjournal.ru/vol_11/popov.html (accessed 24 April 2023).
26. Evseev V.D. O vozmozhnosti ispol'zovaniia effekta P.A. Rebindera pri burenii skvazhin [On the possibility of using the P.A. Rebinder effect when drilling wells]. *Izvestiia Tomskogo politekhnicheskogo universiteta*, 2010, vol. 317, no. 1, pp. 165-169.
27. Evseev V.D. Priroda effekta Rebindera pri razrushenii gornykh porod [The nature of the Rehbinder effect during rock destruction]. *Neftianoe khoziaistvo*, 2011, no. 11, pp. 38-40.

28. Rebinder P.A., Shreiner L.A. Fiziko-khimicheskii metod uskoreniia bureniia tverdykh porod s pomoshch'iu dobavok, ponizitelei tverdosti k promyvnym vodam [Physico-chemical method for accelerating drilling of hard rocks using additives, hardness reducers to wash water]. *Gornyi zhurnal*, 1938, no. 8-9, 16 p.
29. Rebinder P.A., Shreiner L.A., Zhigach K.F. Primenenie ponizitelei tverdosti dlia povysheniia skorostei bureniia na neft' v tverdykh porodakh Vostochnykh mestorozhdenii [Application of hardness reducers to increase oil drilling speeds in hard rocks of the Eastern fields]. *Neftianaia promyshlennost' SSSR*, 1940, no. 5, 54 p.
30. Rebinder P.A., Shchukin E.D. Poverkhnostnye iavleniia v tverdykh telakh v protsessakh ikh deformatsii i razrusheniia [Surface phenomena in solids during the processes of their deformation and destruction]. *Uspekhi fizicheskikh nauk*, 1972, vol. 108, iss. 1, pp. 3-42.
31. Lin S., Lai B. Experimental investigation of water saturation effects on Barnett Shale's geomechanical behaviors. *Society of Petroleum Engineers*, 2013. DOI: 10.2118/166234-MS
32. Najmud D., Hayatdavoudi A., Ghalambor A. Laboratory investigation of saturation effect on mechanical properties of rocks. *SPWLA 31st annual logging symposium*. June 24-27, 1990, pp. 1-23.
33. Liu K. et al. Predicting Reservoir Rock Mechanical Properties Directly from Sedimentary Characterisation. *SPE Asia Pacific Oil & Gas Conference and Exhibition*. Society of Petroleum Engineers, 2016, available at: https://www.onepetro.org/conference-paper/SPE-182342-MS. (accessed 24 April 2023). DOI: 10.2118/182342-MS
34. Vásárhelyi B., Ván P. Influence of water content on the strength of rock. *Engineering Geology*, 2006, vol. 84, no. 1-2, pp. 70-74. DOI: 10.1016/j.enggeo.2005.11.011
35. Bieniawski Z.T., Bernede M.J. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for determining deformability of rock materials in uniaxial compression. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 1979, vol. 16, iss. 2, pp. 138-140. DOI: 10.1016/0148-9062(79)91451-7
36. Suggested methods for determining the strength of rock materials in triaxial compression: Revised version. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 1983, vol. 20, iss. 6, pp. 285-290. DOI: 10.1016/0148-9062(83)90598-3
37. Zhao B. et al. The Effects of Long-Term Waterflooding on the Physical and Mechanical Properties of Tight Sandstones. *52nd US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association, 2018, available at: https://www.onepetro.org/conference-paper/ARMA-2018-409?sort=&start=0&q=The+effects+of+long-term+waterflooding+on+the+physical+and+mechanical+proper-ties+of+tight+sandstones+&from_year=&peer_reviewed=&published_between=&fromSearchResults=true&to_year=&rows=25# (accessed 24 April 2023).
38. Gladkov P.D., Rogachev M.K. Issledovanie vliianiia gidrofobiziruiushchikh sostavov na mekhanicheskuiu prochnost' obraztsov polimiktovykh peschanikov [Research of hydrophobic compositions` influence on mechanical strength of polymineral sandstone core samples]. *Neftegazovoe delo*, 2012, no. 1, pp. 360-366.
39. Glushchenko V.N., Silin M.A. Ob"emnye i poverkhnostno-aktivnye svoistva zhidkostei [Volumetric and surface-active properties of liquids]. *Neftepromyslovaia khimiia*. Moscow: Interkontakt Nauka, 2010, vol. 2, 549 p.
40. Rebinder P.A. Poverkhnostnye iavleniia v dispersnykh sistemakh. Fiziko-khimicheskaia mekhanika [Surface phenomena in disperse systems. Physico-chemical mechanics]. *Izbrannye trudy*. Moscow: Nauka, 1979, 384 p.
41. Igdavletova M., Ismagilov T., Ganiev I., Telin A. Vliianie geologo-fizicheskikh kharakteristik produktivnykh plastov i svoistv plastovykh fliuidov na vybor vytesniaiushchego agenta pri zavodnenii [Influence of geological and physical characteristics of productive formations and properties of formation fluids on the choice of a displacement agent during waterflooding]. *Neftegaz.ru*, 2014, no. 7-8, pp. 18-25.
42. Deliia S.V. Abukova L.A., Abramova O.P., Anisimov L.A., Popov S.N., Vorontsova I.V. Eksperimental'noe i chislennoe modelirovanie vzaimodeistviia plastovykh i tekhnicheskikh vod pri razrabotke mestorozhdeniia imeni Iu. Korchagina [Experimental and numerical modeling of the interaction of formation and technical waters during the development of the Yu. Korchagin field]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2012, no. 10, pp. 34-41.
43. Karmanskiy D., Maltsev A. Theoretical and experimental evaluation of formation fluid composition influence on filtration and elastic properties of porous media. *Physical and mathematical modeling of Earth and environment processes*. Eds. V. Karev, D. Klimov, K. Pokazeev; PMMEEP 2017. Springer Geology. Springer, Cham, pp. 84-89. DOI: 10.1007/978-3-319-77788-7_10
44. Penkov G.M., Karmansky D.A., Petrakov D.G. Simulation of a fluid influx in complex reservoirs of Western Siberia. *Topical Issues of Rational Use of Natural Resources: Proceedings of the International Forum-Contest of Young Researchers, April 18-20, 2018*. St. Petersburg, 2018, pp. 119-124.
45. Fischer G.J. The determination of permeability and storage capacity: Pore pressure oscillation method. *International Geophysics*. Academic Press, 1992, vol. 51, pp. 187-211. DOI: 10.1016/S0074-6142(08)62823-5
46. Adenutsi C.D. et al. Pore pressure variation at constant confining stress on water–oil and silica nanofluid-oil relative permeability. *Journal of Petroleum Exploration and Production Technology*, 2019, no. 9, pp. 2065-2079. DOI: 10.1007/s13202-018-0605-6
47. Sato M., Takemura T., Takahashi M. Development of the permeability anisotropy of submarine sedimentary rocks under true triaxial stresses. *International Journal of Rock Mechanics and Mining Sciences*, 2018, vol. 108, pp. 118-127. DOI: 10.1016/j.ijrmms.2018.06.010
48. Yu J. et al. Triaxial test research on mechanical properties and permeability of sandstone with a single joint filled with gypsum. *KSCE Journal of Civil Engineering*, 2016, vol. 20, no. 6, pp. 2243-2252. DOI: 10.1007/s12205-015-1663-7
49. Ban A. et al. Vliianie svoistv gornykh porod na dvizhenie v nikh zhidkosti [The influence of the properties of rocks on the movement of fluid in them]. Moscow: Gostoptekhizdat, 1962, pp. 158-187.
50. Dake L.P. Fundamentals of reservoir engineering. Elsevier, 1983, vol. 8, 492 p.
51. Akhmetzianov A.V., Kushner A.G., Lychagin V.V. Integrability of Buckley - Leverett's Filtration Model **This work was supported by the Russian Science Foundation (the grants No 15-19-00275). *IFAC-PapersOnLine*, 2016, vol. 49, iss. 12, pp. 1251-1254. DOI: 10.1016/j.ifacol.2016.07.685
52. Akhmetzianov A.V., Kushner A.G., Lychagin V.V. Two-dimensional non-isothermal filtration and optimal control of oil field development **This work was supported by the Russian Science Foundation (the grants No 15-19-00275). *IFAC-PapersOnLine*, 2018, vol. 51, iss. 11, pp. 888-890. DOI: 10.1016/j.ifacol.2018.08.453
53. Akhmetzyanov A.V., Kushner A.G., Lychagin V.V. Mass and heat transport in the two-phase Buckley - Leverett model. *Journal of Geometry and Physics*, 2017, vol. 113, pp. 2-9. DOI: 10.1016/j.geomphys.2016.06.010
54. Yunus Khan Mohammad, Mandal Ajay. Improvement of Buckley-Leverett equation and its solution for gas displacement with viscous fingering and gravity effects at constant pressure for inclined stratified heterogeneous reservoir, Fuel, 2021, vol. 285, 119172. DOI: 10.1016/j.fuel.2020.119172
55. Siddiqui S., Hicks P.J., Grader A.S. Verification of Buckley-Leverett three-phase theory using computerized tomography. *Journal of Petroleum Science and Engineering*, 1996, vol. 15, iss. 1, pp. 1-21. DOI: 10.1016/0920-4105(95)00056-9
56. Rose W. Attaching new meanings to the equations of buckley and leveret. *Journal of Petroleum Science and Engineering*, 1988, vol. 1, iss. 3, pp. 223-228. DOI: 10.1016/0920-4105(88)90012-5
57. Rose W., Rose D.M. "Revisiting" the enduring Buckley - Leverett ideas. *Journal of Petroleum Science and Engineering*, 2004, vol. 45, iss. 3-4, pp. 263-290. DOI: 10.1016/j.petrol.2004.08.001

Funding. The study had no sponsorship.
Conflict of interest. The authors declare no conflict of interest.
The authors' contributions are equivalent.