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STUDYING THE DEPENDENCIES BETWEEN THE SANDSTONE PHYSICAL AND MECHANICAL PROPERTIES AND THE ELASTIC WAVE VELOCITY

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ИССЛЕДОВАНИЕ ЗАВИСИМОСТЕЙ МЕЖДУ ФИЗИКО-МЕХАНИЧЕСКИМИ СВОЙСТВАМИ ПЕСЧАНИКА И СКОРОСТЬЮ ПРОХОЖДЕНИЯ УПРУГИХ ВОЛН

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Stress-strain state of formation, Poisson's ratio, Young's modulus, P-wave, S-wave, uniaxial compressive strength.

The engineering of hydrocarbon field development requires a detailed estimate of the oil and gas reserves and their production. In order to estimate the size of hydrocarbon reserves, the first engineering stage includes a reservoir characterization. The second stage is a hydrodynamic simulation. One of its objectives is to study filtration processes that depend on many factors. A correct description of these factors will ensure accurate calculations of the main development parameters. The filtration processes are closely connected with the physical and mechanical properties of the reservoir formations. These parameters can be estimated using different methods, including by measuring the elastic wave velocity.
The work presents the results of laboratory studies that determine dependencies between certain physical and mechanical properties of sandstone rocks and the velocity of a compressional wave (P-wave) and a shear wave (S-wave). The dynamic parameters (Young's Modulus and Poisson's Ratio) were determined as per ASTM D2845-08. The uniaxial compressive strength of the rock formations was determined in accordance with the GOST 21153.2-84 standard. Samples of sandstone were tested to determine the dependence of P-wave and S-wave velocities on uniaxial compressive strength, dynamic Young's modulus and dynamic Poisson's ratio in sandstone reservoirs.
As a result of the laboratory studies, empirical dependences of uniaxial compressive strength (σ_c), dynamic elasticity modulus (E), Poisson's ratio (η) and velocity of P-waves (V_p) and S-waves (V_S) have been obtained. This will enable tracking any changes in these parameters during the entire period of the oil and gas field development. The obtained values have been estimated over the entire measurement range.

Ключевые слова:
напряженно-деформированное состояние пласта, коэффициент Пуассона, модуль Юнга, продольная волна, поперечная волна, предел прочности при одноосном сжатии.

При проектировании разработки месторождения углеводородов необходимо детально оценивать запасы нефти и газа и их выработку. Первым этапом проектирования является построение геологической модели, позволяющей определить величину запасов углеводородов. Вторым этапом осуществляется гидродинамическое моделирование. Одна из целей гидродинамического моделирования – изучение фильтрационных процессов, которые зависят от многих факторов. Правильное описание этих факторов обеспечит точные расчеты основных показателей разработки. Фильтрационные процессы тесно связаны с физико-механическими свойствами породы-коллектора. Эти параметры можно оценивать с помощью разных методов, один из которых – замер скорости прохождения упругих волн.
В статье представлены результаты лабораторных исследований, устанавливающих зависимости между некоторыми физико-механическими свойствами горных пород песчаника и скоростью прохождения продольной и поперечной волн. Динамические показатели (модуль Юнга и коэффициент Пуассона) определялись на основании ASTM D2845-08. Предел прочности горных пород при одноосном сжатии находили в соответствии с ГОСТ 21153.2-84. Испытывали образцы песчаника с целью оценки зависимости скорости прохождения продольной и поперечной волн от предела прочности на одноосное сжатие, динамического модуля Юнга и динамического коэффициента Пуассона в коллекторах из песчаника.
В результате лабораторных исследований были получены эмпирические зависимости предела прочности при одноосном сжатии (σ_c), динамическом модуле упругости (E), коэффициенте Пуассона (η) и скорости прохождения продольных (V_p) и поперечных волн (V_p), которые позволят отслеживать их изменения в течение всего периода разработки месторождений нефти и газа. Дана оценка полученных значений на всем диапазоне измерений.

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Introduction

The permeability is one of the key parameters affecting the fluid flow through a porous material. A permeability value depends on several processes [1–7]. The change in stress-strain state (SSS) is one of such phenomena. Many factors influence SSS, including:

1. Rock strength parameters. Many authors analysed how physical and mechanical properties, SSS included, were changing in various geological conditions [8–12].

2. Rock and pore pressure. A good number of studies are dedicated to the influence of pore and rock pressure on SSS, as well as to the parameters affecting them [13–39].

3. Saturating fluid properties, etc.

The dependence between physical and mechanical properties of rocks and properties of saturating fluids has been analysed in many papers [40–43].

There is an array of methods to determine how SSS depends on physical and mechanical properties; among others, this can be done by measuring the elastic wave velocity.

The development of a new oil reserve and the development management are carried out with the help of well geophysical surveys, 2D and 3D-seismic exploration, vertical seismic profiling, etc.

Geophysical studies are applied to the following processes:

– surveying the subsurface geology of wells;

– oil and gas reservoir identification;

– monitoring the coordinates of directional wellbores;

– reserve estimation;

– determining the wellbore technical condition;

– monitoring the cementing quality of casing strings;

– oil production stimulation.

The acoustic methods are based on velocity data of the elastic P-waves and S-waves in the rock formations.

The wave velocity is affected by mineralogical and grain composition of the formations, their density, porosity, presence of fluids in the rock pores and other factors. An analysis of the data obtained as a result of the research will enable determining the type and physical properties of rocks in a formation. Some scientists addressed the problem of establishing the dependence between rock formation properties and wave velocity [44–47].

The method of acoustic scanning can be used to determine the physical and mechanical properties (the dynamic Young's modulus of elasticity, Poisson's ratio, uniaxial compressive strength). The determination of physical and mechanical properties is essential in drilling wells, selecting a completion technology, stimulating production, selecting a technologically effective option for development and monitoring of the formation stress-strain state in the oil production process. For example, monitoring the SSS change is necessary for a crack growth prediction in the hydraulic fracturing process. A change in SSS following a formation pressure drop also results in lower porosity and permeability properties.

Formulating Research Aims and Objectives

To simplify the monitoring of changes in the SSS parameters, it is suggested to establish empirical dependencies between the properties of rock formations and the velocity of P-waves and S-waves.

The purpose of the studies is to estimate the dependence of the P-wave and S-wave velocity on the uniaxial compressive strength, dynamic Young's modulus and dynamic Poisson's ratio in sandstone reservoirs.

The objectives:

1. To conduct laboratory tests to measure the velocity of elastic waves and the uniaxial compressive strength [48].

2. To determine the dependence of the elastic P-waves and S-waves velocity on the uniaxial compression strength, dynamic modulus of elasticity and Poisson's ratio.

Findings

Samples of sandstone from the X deposit were selected for testing. The transit time of P-waves and S-waves was determined and their velocities calculated [49]:

$$V_P = L_P / T_P, \tag{1}$$
$$V_S = L_S / T_S,$$

where V_P, V_S are P-wave and S-wave velocities, m/s; L_P, L_S are wave transit lengths, m; T_P, T_S are transit times of P-wave and S-wave, s.

The Young's modulus of elasticity E, Pa, and the Poisson's ratio μ were determined by the formulas [1].

$$E = \frac{\rho V_S^2 \left(3V_P^2 - 4V_S^2\right)}{V_P^2 - V_S^2},$$
$$\mu = \frac{V_P^2 - 2V_S^2}{2\left(V_P^2 - V_S^2\right)}, \tag{2}$$

where ρ is density, kg/m³.

Upon determining the dynamic characteristics of the samples, tests were conducted to calculate the uniaxial compressive strength. The dependency values obtained from the laboratory tests are shown in Figure 1.

In order to estimate the accuracy of the established dependencies, a verification test was carried out by determining the values using the given formulas and comparing them with those obtained in the laboratory tests. The error in the calculated values is determined by the distance from the diagonal line as 1:1. The results of the verification test are shown in Figure 2.

Conclusions

The following conclusions can be drawn based on the results of the research conducted:

1. The empirical dependencies of the uniaxial compressive strength σc on the dynamic modulus of elasticity E, Poisson's ratio η and velocity of P-wave V_p and S-wave V_s have been determined as follows:

$$\sigma_c = 0{,}247V_p - 32{,}232,\ R^2 = 0{,}757,$$
$$\sigma_c = 0{,}0607V_s - 54{,}105,\ R^2 = 0{,}704,$$
$$E = 0{,}0104V_p - 13{,}489,\ R^2 = 0{,}992,$$
$$E = 0{,}0264V_s - 24{,}07,\ R^2 = 0{,}990,$$
$$\eta = 4\cdot 10^{-5}V_p + 0{,}138,\ R^2 = 0{,}741,$$
$$\eta = 0{,}0001V_s + 0{,}1041,\ R^2 = 0{,}646,$$

2. The given dependencies will enable tracking changes in strength and elastic properties and, therefore, in filtration properties of the reservoir formations during the entire period of the oil and gas field development.

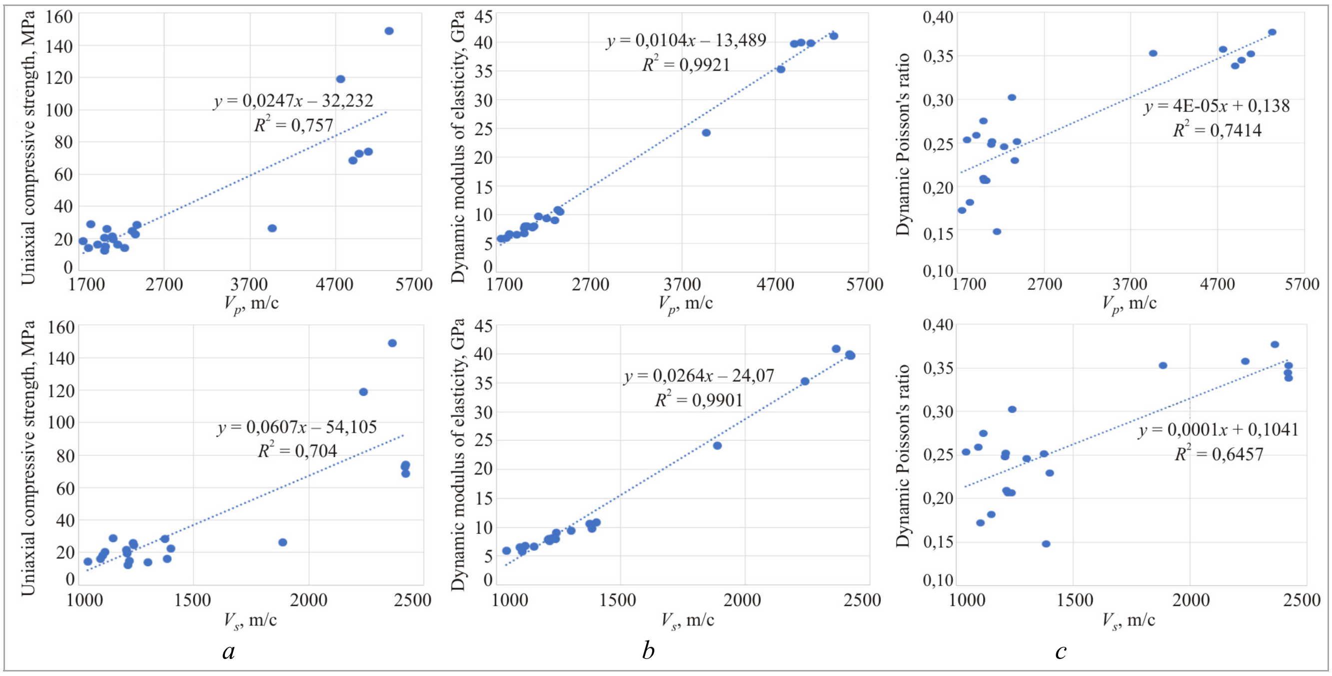

Fig. 1. Dependency of: *a* – uniaxial compressive strength; *b* – dynamic modulus of elasticity; *c* – Poisson's ratio on velocity of P-wave V_P and S-wave V_S

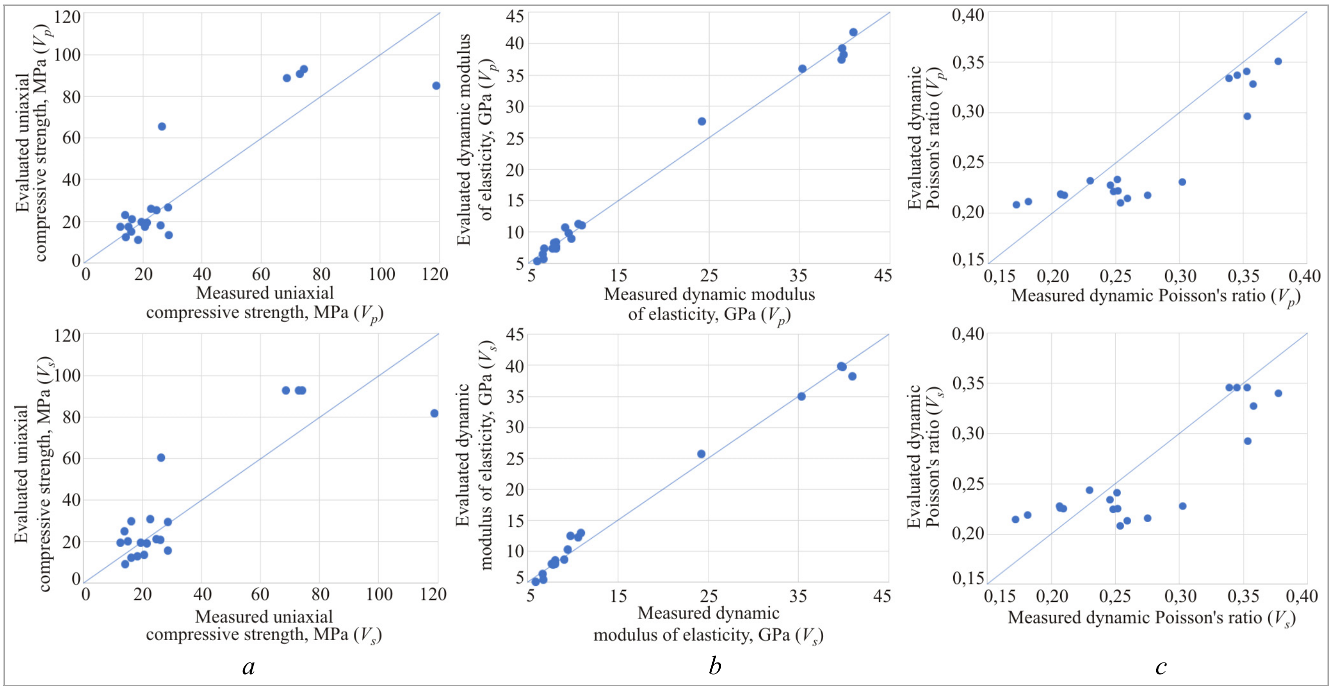

Fig. 2. Comparison of measured and calculated values σ_c (*a*); *E* (*b*) and η (*c*) (at transit of P-waves and S-waves)

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