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Study of the elastic modulus and tensile strength for limestone reservoirs of the first tier of the middle carboniferous

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Исследование модуля упругости и предела прочности известняковых коллекторов первого яруса среднего карбона

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loading, stress, Young's modulus, deformations, tensile strength, permeability, porosity.

To determine the strength of rocks, experimental studies are carried out with loading of samples. It is not always possible to conduct a significant number of experimental studies on loading. It is possible to predict the strength parameters of rocks based on lithology, porosity, density of rocks, etc. The current study assessed the possibility of using known methods to predict the statistical Young's modulus of limestones of the Bashkir horizon of the Moskudinskoe deposit. Eight rock samples were selected from the field; density, porosity, and permeability before loading were determined for each sample. During the loading process, the static and dynamic Young's modulus and tensile strength were determined. It is noted that the known methods correctly reflect the direction of change in the statistical Young's modulus from the dynamic value, but for each geographical area it is necessary to introduce clarifying coefficients. The dependence of the static Young's modulus on the dynamic one is obtained. Based on the least squares method, it was revealed that the density and porosity of rocks have the most significant effect on the known parameters before loading on the static Young's modulus, and the tensile strength is additionally affected by permeability. Low-permeability rocks have a greater tensile strength. With a decrease in permeability from 5223 to 0.002 mD and porosity from 22.9 to 0.54 %, the tensile strength in reservoir conditions increased from 44.1 to 166.2 MPa. Accordingly, in highly permeable porous rocks, lower pressures are required to create fractures during hydraulic fracturing.

Ключевые слова:
нагрузка, напряжение, модуль Юнга, деформации, прочность на растяжение, проницаемость, пористость.

Для определения прочности горных пород проводятся экспериментальные исследования с нагружением образцов. Не всегда удается провести значительное количество экспериментальных исследований с нагружением. Прогнозировать прочностные показатели горных пород можно на основе литологии, пористости, плотности пород и т.д. В данном исследовании оценивалась возможность использования известных методов для прогнозирования статистического модуля Юнга известняков башкирского горизонта Москудинского месторождения. На месторождении отобрано восемь образцов горных пород, для каждого образца определены плотность, пористость и проницаемость до нагружения. В процессе нагружения определялись статический и динамический модуль Юнга и предел прочности на растяжение. Отмечено, что известные методы правильно отражают направление изменения статистического модуля Юнга от динамического значения, но для каждого географического района необходимо вводить уточняющие коэффициенты. Получена зависимость статического модуля Юнга от динамического. На основе метода наименьших квадратов выявлено, что из известных параметров до нагружения на статический модуль Юнга наибольшее влияние оказывают плотность и пористость горных пород, а на предел прочности на разрыв дополнительно влияет проницаемость. Большим пределом прочности на разрыв обладают низкопроницаемые породы. При снижении проницаемости с 5223 до 0,002 мД и пористости с 22,9 до 0,54 % предел прочности на разрыв в пластовых условиях увеличился с 44,1 до 166,2 МПа. Соответственно, в высокопроницаемых пористых породах для создания трещин при гидроразрыве пласта требуются меньшие давления.

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Introduction

Issues related to the dynamics of changes in the structure of the pore space and the development of fracturing are relevant for a reliable forecast of filtration and fluid production [1–5]. For a complete study of the mechanical properties of rocks, it is necessary to use the methods of triaxial loading [6–12]. To expand the scope of applicability of existing models for changing the filtration and mechanical properties of rocks or to create new, more accurate and universal methods, more experimental data are needed [13]. The reduction in porosity and pore size in the samples increases with increasing loading rate, and the degree of reduction in porosity depends on the structure and strength of the rocks [14]. Rock strength parameters are vital for creating reliable geomechanical models for wellbore stability, hydrocarbon production and hydraulic fracturing [15, 16]. The mechanical behavior and fracture characteristics of deep rocks under true triaxial dynamic and static stress require additional study, despite the existing research [17]. The process of rock destruction is closely related to the occurrence, propagation and penetration of internal microcracks, accompanied by dissipation and release of energy [18, 19]. The strength parameters of rocks are determined using various methods, which can produce different results. For example, compressive stresses arising in the contact zone during the Brazilian test show higher strength than the strength during direct testing [20]. At the same time, the greatest difference in results is demonstrated by coarse-grained rocks. This is likely because longer intergranular cracks create longer weakening paths, which can be closed by compression, around the load contact. A more accurate assessment of the strength of such rock masses can only be achieved by taking into account factors such as the shape of the rock blocks, the roughness of the joints and the strength of the joints [21].

Regardless of whether the true triaxial stress is static or dynamic, the principal stress σ_2 has a significant effect on the deformation, modulus, strength and failure mode of rock. As σ_2 increases, the strength first increases and then decreases, the fracture mode undergoes a brittle-plastic transition, and the fracture angle gradually increases. [22]. Rock fragility is an important factor influencing fracturing [23]. Accurate assessment of rock fragility is of great importance in the field of underground mining and unconventional oil and gas fields [24]. To date, significant research has been carried out to assess the static Young's modulus taking into account lithology, porosity, density of rocks, etc. [25].

In [26], they conducted experiments on limestone samples from deposits in Iran, and also proposed a power-law model reflecting the relationship between the static and dynamic Young’s modulus:

$$E_s = 0.014E_d^{1.96}. \tag{1}$$

In [27] they pointed out that the relationship between the logarithms of Young’s modulus varies depending on the formation. The formations are divided into four categories: 1 – sedimentary carbonate rocks, 2 – igneous rocks, 3 – gneisses and metamorphic shales, and 4 – clastics, siltstones, sandstones, siltstones and tuffs. The general equation is presented in equation (2):

$$\log E_s = A_0 + A_1 \log E_d. \tag{2}$$

In [28], based on experimental studies, they proposed a quadratic relationship between the static and dynamic Young’s modulus:

$$E_s = 0.278E_d^2 + 0.422E_d. \tag{3}$$

In [29], a linear relationship between the static and dynamic Young’s modulus was proposed:

$$E_s = 0.54E_d - 12.852. \tag{4}$$

In the absence of laboratory studies, indirect assessment of rock mechanics parameters is the only option. The value of Young's modulus and uniaxial compressive strength are primarily influenced by porosity, density and water saturation [30].

Empirically based models are not universal. Models based on one type of lithology for a particular geographic area may not be applicable to other geographic regions. Empirical models for a specific formation are more reliable than general ones. Due to the importance of rock mechanical properties in petroleum industry research, it is always worth predicting these parameters for a specific reservoir based on empirical models that are developed for the same reservoir in the same geographic area [31].

Samples with a crystalline carbonate texture have the lowest values of Young's modulus and uniaxial compressive strength [32]. Mineral composition and mechanical properties are critical parameters affecting the elastic behavior of carbonate rocks. However, despite the general tendency, homogenization leads to an overestimation of the Young’s modulus [33].

Experimental results show that the failure of limestone meets the Mohr – Coulomb criterion. There is a tendency for the initial permeability *k* to decrease as a function of the effective stress σ3eff according to an exponential function. Increasing the confining pressure will slow down the suppression of microcrack propagation. Under high confining pressure, limestone samples exhibit shear failure modes. This is due to the fact that limestone samples consist of tensile microcracks at the microscale under stress-filtration interaction conditions, and the proportion of shear microcracks increases as the principal stress σ_3 increases [34].

The mechanical properties of carbonates show a strong dependence on porosity. Compressive strength and brittle-to-ductile transition stress decrease as the porosity of the limestone carbonate approaches the loosest grain setting. The internal shear strength angle for limestone is not sensitive to porosity [35].

By performing direct tensile tests and indirect methods (e.g., Brazilian and point load tests) on porous limestone, it was observed that increasing water saturation led to a significant decrease in their uniaxial tensile strength (UTS), tensile modulus (E_t), Brazilian tensile strength (BTS) [36].

Mineralogical composition can be used to predict the strength of rocks under specific conditions, but the effect of mineralogical composition on rock strength is highly dependent on the lithology of the rock. Predictions of rock strength based on mineral content can be highly accurate in sandstone and carbonate rocks. The best indicator for predicting rock strength is the dolomite content of carbonate rocks [37].

When it is not possible to prepare suitable core samples to determine the tensile strength, a good alternative is to use indirect methods. [38]. In [39], an equation is given for predicting the uniaxial compressive strength

$$\mathrm{UCS} = 126.735 - 4.753m + 1.800 \cdot 10^{-3}\, V_p. \tag{5}$$

In [40] it is shown that linear regression models are optimal for predicting the strength parameters of carbonate rocks.

Research area

To conduct special studies to determine the physical and mechanical properties of rocks, core samples were provided from the Russian platform, from the southwestern slope of the Kaltasinsky aulacogenan, a structural ledge of the southeastern part of the Verkhkamsk depression from the deposits of the Bashkirian stage. The deposits are represented by organogenic, organogenic-clastic limestones, with rare interlayers of dolomites. The limestones are gray, yellowish-gray, with characteristic admixtures of greenish clay, which often gives the rock a brecque appearance; sometimes fragments of darker limestones are found. The thickness varies from 32 to 65 m. A total of 8 core samples were obtained. Sample size 30×60 mm. The porosity, density of rocks, and gas permeability were determined from the samples (Table 1).

Studies of the geomechanical properties of core material under conditions of volumetric (pseudo-triaxial) compression were carried out using the PIK-UIDK/PL installation. The PIK-UIDK/PL installation is a multifunctional system for performing standard and non-standard tests to measure the mechanical and petrophysical properties of rocks in reservoir conditions. A general view of the installation is shown in Fig. 1.

Materials and Methods

The test methodology takes into account the ISRM recommendations for triaxial testing [41] and the ASTM standard [42].

Axial loading and unloading were carried out at a constant rate of axial deformation, the same for all experiments, which was 10^{-5} s^{-1}.

The general program of triaxial testing of samples to determine elastic properties under reservoir conditions is given below:

– raising compression and pore pressures to reservoir conditions at a rate of 1 MPa/min. The compression pressure was 16.8 MPa, the pore pressure was 11.4 MPa;

– holding the sample until volumetric deformations stabilize $\left(\frac{\partial \varepsilon_{\text{vol}}}{\partial t} = 0\right)$;

– velocity measurement V_P и V_S. Calculation of dynamic values of elastic modulus and Poisson's ratio.

Raising the axial load to determine elastic parameters. At a pressure corresponding to the initial stress state, at least two load/unload cycles were carried out, not exceeding the elastic limit. A sufficient level of load was determined from the condition of obtaining the most straight line on the stress-strain graph on the load branch.

Continuous recording of axial stress, axial and transverse strains, as well as all other parameters was carried out throughout the experiment.

The elastic modulus was located in the straight section of the repeated load branch of the sample on the “axial stress – axial deformation” diagram in the elastic deformation region. The modulus of elasticity is defined as the ratio of the change in stress (axial load) to the change in longitudinal (axial) strain.

The static Poisson's ratio was determined by the ratio of transverse to longitudinal strains in a straight section, on which Young's modulus was determined. Dynamic elastic moduli E_d and Poisson's ratio ν_d were determined from the velocities of longitudinal and transverse waves in reservoir conditions using the formulas:

$$R = \frac{V_S}{V_P}; \qquad (6)$$

Table 1

Properties of rock samples

Sample	Core sampling depth	ρ, g/sm^3	m, %	k, mD
1-1	1119.15	2.25	22.99	5223.92
2-1	1119.15	2.28	21.31	4810.17
3-1	1114.5	2.44	9.20	0.93
4-1	1114.5	2.53	7.046	0.935
1-2	1123.75	2.58	5.24	1.95
2-2	1123.75	2.58	6.18	3.43
3-2	1115.95	2.67	0.54	0.002
4-2	1115.95	2.68	1.29	0.003

Fig. 1. General view of the PIK-UIDK/PL installation

Table 2

Results of determining sample parameters in reservoir conditions

Sample	E_s, GPa	$\nu_{\text{стат.}}$	V_p, m/s	V_S, m/s	E_d, GPa	$\nu_{\text{дин}}$	$\sigma_{\max}$, MPa
1-1	18.8	0.307	3850	2190	27.2	0.261	44.1
1-2	26.4	0.222	3974	2232	28.8	0.230	47.0
2-1	44.3	0.109	5036	3105	56.1	0.193	208.7
2-2	37.2	0.251	5025	2985	55.3	0.227	105.7
3-1	47.1	0.223	5428	2946	57.8	0.291	111.7
3-2	45.1	0.302	5338	2881	55.4	0.295	102.0
4-1	63.2	0.237	5967	3201	68.0	0.307	169.1
4-2	55.8	0.267	5888	3140	68.8	0.301	166.2

$$\nu_d = \frac{0.5 - R^2}{1 - R^2}; \qquad (7)$$

$$E_d = V_P \cdot \rho \cdot \frac{(1+\nu_d)\,(1-2\nu_d)}{1-\nu_d}. \qquad (8)$$

After performing the experiments described above, all eight samples were destroyed under reservoir conditions. The experimental procedure coincides with paragraph 1.2 with the exception that the axial load was increased until the sample was destroyed. Table 2 presents certain tensile strength values. For each pair of samples, except for 2-1, 2-2, fairly close values of the ultimate strength in reservoir conditions are observed. There is a general trend of increasing strength with increasing longitudinal wave speed for all samples except sample 2-1. The increased strength value for this sample is explained by the lithological heterogeneity of the reservoir in the core sampling interval. The results of determining the parameters are presented in Table 2.

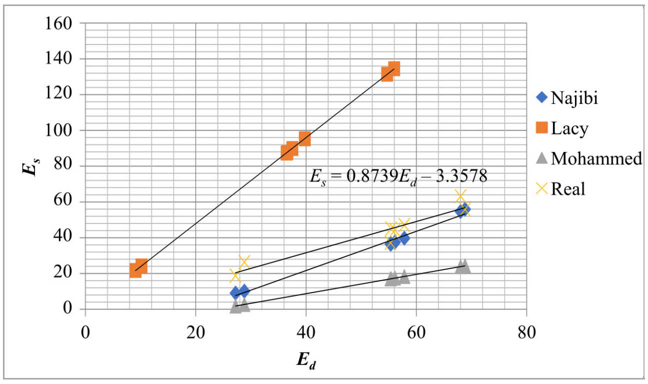

Fig. 2. Dependence of E_s on E_d

Table 3

Correlation matrix for E_s

Parameters	ρ, g/sm^3	m, %	k, mD	E_s
ρ, g/sm^3	1.000000	0.966791	–0.178323	0.823434
m, %		1.000000	0.064245	0.658568
k, mD			1.000000	–0.614216
E_s				1.000000

Discussion

E_s was determined using known equations and actual data (Fig. 2). For the conditions considered, the Najibi equation is the best suited of the known methods. The remaining models for estimating the static Young's modulus based on the dynamic modulus do not adequately reflect the nonlinear relationship between the static and dynamic relationship. For each geographic area, it is recommended to conduct research to identify the correct trend.

A correlation matrix was constructed between the main parameters of the rock before loading and E_s (Table 3).

Based on the values in table 3 the values of E_s have the greatest relationship with the porosity and density of rocks. Using the least squares method, an equation was obtained to estimate E_s from these parameters:

$$E_s = 2.08 \cdot \rho 1.59 \cdot m + 51.7. \tag{9}$$

A correlation matrix was constructed between the main parameters of the rock before loading and $\sigma_{\max}$ (Table 4).

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Table 4

Correlation matrix for $\sigma_{\max}$

Parameters	ρ, g/sm^3	m, %	k, mD	$\sigma_{\max}$
ρ, g/sm^3	1.000000	0.966791	–0.178323	–0.107517
m, %		1.000000	0.064245	–0.293451
k, mD			1.000000	–0.740100
$\sigma_{\max}$				1.000000

Based on it, an equation was obtained for predicting $\sigma_{\max}$ using the least squares method:

$$\sigma_{\max} = 0.48\rho - 0.92m - 0.016k + 147.18. \tag{10}$$

Using equation (10), it can be estimated that the porosity and permeability of rocks have a predominant effect on the tensile strength of rocks. Rocks with high values of porosity and permeability have a lower tensile strength. Low-permeability rocks have a higher tensile strength and, accordingly, in such rocks, high pressures are required to create cracks during hydraulic fracturing [43–45].

Results

The study reviewed known techniques for predicting static Young's modulus from rock parameters. It was noted that predictive models work best in the geographic area from which samples were selected for experimental studies. For the conditions considered, the Najibi equation is the best suited of the known methods. The strength limits of the samples under uniaxial compression conditions were determined. Models were built to predict the static Young's modulus and the uniaxial compressive strength. According to the obtained models, highly porous and permeable rocks have a lower tensile strength and, accordingly, lower pressures are required in such rocks to create cracks during hydraulic fracturing.

Nomenclature

Nomenclature			
V_p	P-wave velocity	E_s	Young's static modulus
σ_2	Main stress (MPa)	E_d	Young's dynamic modulus
σ_3	Main stress (MPa)	A_0	Constant
m	Porosity	A_1	Constant
ν	Poisson's ratio (fractions of units)	k	Permeability
ρ	Rock density	V_S	Shear wave velocity

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