Недропользование. 2025. Т. 25, № 1. С.27-35. DOI: 10.15593/2712-8008/2025.1.4

ISSN 2712-8008
Том / Volume 25 №1 2025
Домашняя страница журнала: http://vestnik.pstu.ru/geo/

НЕДРОПОЛЬЗОВАНИЕ

UDC 622.323
Article / Статья

Cyclic Loading and Transport Properties of Porous Rocks: Experimental Studies

Evgenii V. Kozhevnikov[1], **Evgenii A. Gladkikh**[1], **Mikhail A. Guzev**[1], **Chengzhi Qi**[2],
Arina E. Panteleeva[1], **Zakhar G. Ivanov**[1], **Aleksandr A. Shcherbakov**[1]

[1]Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)
[2]Beijing University of Civil Engineering and Architecture (1 Zhanlanguan Rd, Xicheng District, Beijing, 100044, People's Republic of China)

Циклические нагрузки и фильтрационные свойства пористых горных пород: экспериментальные исследования

Е.В. Кожевников[1], **Е.А. Гладких**[1], **М.А. Гузев**[1], **Чэнчжи Ци**[2], **А.Е. Пантелеева**[1], **З.Г. Иванов**[1], **А.А. Щербаков**[1]

[1]Пермский национальный исследовательский политехнический университет (Российская Федерация, 614990, г. Пермь, Комсомольский пр., 29)
[2]Пекинский университет гражданского строительства и архитектуры (Китай, 100044, г. Пекин, Чжанланьлу Сичэн, 1)

Получена / Received: 31.07.2024. Принята / Accepted: 05.12.2024. Опубликована / Published: 24.02.2025

Keywords:
permeability, cyclic loading, colloid's migration, microcracks, porous rock. transport properties, sandstones, limestones, rock samples.

The study of the transport properties of porous rocks under cyclic loading is important for predicting the operation of underground reservoirs for storing natural gas or hydrogen, in which the pore pressure fluctuates during seasonal extraction or filling. Under cyclic loading, the permeability of rocks decreases irreversibly, however, despite a significant amount of research, there is a gap in understanding the true causes of this decrease. The paper presents the results of experimental studies of the effect of cyclic loading on the permeability of porous limestones and sandstones. The mechanism of permeability hysteresis is revealed. Incomplete recovery of permeability during unloading is due to the presence of a threshold for the opening of microcracks in rocks. The effect of colloid and fines migration when measuring the permeability of samples is also established. The magnitude of permeability change under cyclic confining pressure exhibits a strong correlation with initial permeability. Our findings indicate that in porous sandstones and limestones with initial permeability below 50 mD, permeability degradation is primarily attributed to microcrack closure. The impact of colloid migration is less evident in less permeable rocks, likely due to reduced colloid mobility. However, for rocks with initial permeability exceeding 50 mD, both compaction and the migration of colloids and fines contribute to permeability reduction. In more permeable rocks, colloid mobility is higher, potentially leading to significant permeability reductions of up to 60%.

Ключевые слова:
проницаемость, циклическое нагружение, миграция коллоидов, микротрещины, пористые породы, фильтрационные свойства, песчаники, известняки, образцы горных пород

Изучение фильтрационных свойств пористых пород при циклическом нагружении важно для прогнозирования использования подземных резервуаров для хранения природного газа или водорода, в которых поровое давление колеблется в процессе сезонной добычи или заполнения. При циклическом нагружении проницаемость пород необратимо уменьшается, однако, несмотря на значительный объем исследований, существует пробел в понимании истинных причин этого снижения. В работе представлены результаты экспериментальных исследований влияния циклического нагружения на проницаемость пористых известняков и песчаников. Выявлен механизм гистерезиса проницаемости. Неполное восстановление проницаемости при разгрузке обусловлено наличием порога раскрытия микротрещин в породах. Также установлено влияние миграции коллоидов и мелкодисперсных частиц при измерении проницаемости образцов. Величина изменения проницаемости при циклическом всестороннем давлении обнаруживает сильную корреляцию с начальной проницаемостью. Результаты исследований показывают, что в пористых песчаниках и известняках с начальной проницаемостью ниже 50 мД ухудшение проницаемости в первую очередь связано с закрытием микротрещин. Влияние миграции коллоидов менее очевидно в менее проницаемых породах, вероятно, из-за сниженной подвижности коллоидов. Однако для пород с начальной проницаемостью более 50 мД как уплотнение, так и миграция коллоидов и мелких частиц способствуют снижению проницаемости. В более проницаемых породах подвижность коллоидов выше, что потенциально приводит к значительному снижению проницаемости до 60 %.

© **Evgenii V. Kozhevnikov** (Author ID in Scopus: 55531698200, ORCID: 0000-0002-6084-0795) – PhD in Engineering, Scientific Director of the Laboratory of Natural Gas Hydrates (e-mail: kozhevnikov_evg@mail.ru). The contact person for correspondence.
© **Evgenii A. Gladkikh** (Author ID in Scopus: 6601914558, ORCID: 0000-0003-1917-8995) – PhD in Engineering, Leading Researcher at the Laboratory of Natural Gas Hydrates (e-mail: gladkih.ea@mail.ru).
© **Mikhail A. Guzev** (Author ID in Scopus: 55976318100, ORCID: 0000-0001-9344-154X) – Professor, Doctor of Physics and Mathematics, Chief Researcher of the Laboratory of Natural Gas Hydrates (e-mail: guzev@iam.dvo.ru).
© **Chengzhi Qi** (Author ID in Scopus: 35490194400, ORCID: 0000-0003-1196-3972) – Doctor in Physics and Mathematics, Dean of Graduate School (e-mail: qichengzhi65@163.com).
© **Arina E. Panteleeva** – Laboratory Research Assistant at the Laboratory of Natural Gas Hydrates (e-mail: rinapan01@mail.ru).
© **Zakhar G. Ivanov** – Laboratory Research Assistant at the Laboratory of Natural Gas Hydrates (e-mail: zakhar.ivanov.2013@gmail.com).
© **Aleksandr A. Shcherbakov** (Author ID in Scopus: 55531112100, ORCID: 0000-0001-6502-970X) – Senior Lecturer at the Department of Oil and Gas Technologies (e-mail: aleksandr.a.shcherbakov@gmail.com).

© **Кожевников Евгений Васильевич** – кандидат технических наук, научный руководитель лаборатории природных газовых гидратов (e-mail: kozhevnikov_evg@mail.ru). Контактное лицо для переписки.
© **Гладких Евгений Александрович** – кандидат технических наук, старший научный сотрудник лаборатории природных газовых гидратов (e-mail: gladkih.ea@mail.ru).
© **Гузев Михаил Александрович** – профессор, доктор физико-математических наук, главный научный сотрудник лаборатории природных газовых гидратов (e-mail: guzev@iam.dvo.ru).
© **Чэнчжи Ци** – доктор физико-математических наук, профессор Школы гражданского и транспортного строительства (e-mail: qichengzhi65@163.com).
© **Пантелеева Арина Евгеньевна** – лаборант-исследователь лаборатории природных газовых гидратов (e-mail: rinapan01@mail.ru).
© **Иванов Захар Григорьевич** – лаборант-исследователь лаборатории природных газовых гидратов (e-mail: zakhar.ivanov.2013@gmail.com).
© **Щербаков Александр Анатольевич** – старший преподаватель кафедры «Нефтегазовые технологии» (e-mail: aleksandr.a.shcherbakov@gmail.com).

Please cite this article in English as:
Kozhevnikov E.V., Gladkikh E.A., Guzev M.A., Qi Chengzhi, Panteleeva A.E., Ivanov Z.G., Shcherbakov A.A. Cyclic loading and transport properties of porous rocks: experimental studies. *Perm Journal of Petroleum and Mining Engineering*, 2025, vol.25, no.1, pp. 27-35. DOI: 10.15593/2712-8008/2025.1.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Циклические нагрузки и фильтрационные свойства пористых горных пород: экспериментальные исследования / Е.В. Кожевников, Е.А. Гладких, М.А. Гузев, Чэнчжи Ци, А.Е. Пантелеева, З.Г. Иванов, А.А. Щербаков // Недропользование. – 2025. – Т.25, №1. – С. 27–35. DOI: 10.15593/2712-8008/2025.1.4

Introduction

Predicting permeability under cyclic loading, is an important task and is necessary for assessing the reservoir characteristics of natural formations for a wide range of human activities [1–5]. Modeling permeability taking into account pore mechanics and elastic properties of rocks is quite problematic due to the heterogeneity of materials and rock properties, so the simplest way is laboratory and empirical methods, according to which the generally accepted model of changes in permeability from load (pressure, effective pressure, pressure confining) is the power law [6–9]. However, the use of the power law is complicated by the presence of permeability hysteresis, in which the values of the coefficients and exponents are different during loading and unloading [6, 8, 10–12].

Under loading permeability changes nonlinearly with confining pressure due to mechanical compaction [6,9,13,14]. Mechanical compaction is accompanied by the closure of microcracks and narrowing of pore throats. Due to the reduction in the geometric dimensions of the porous channels, the resistance and tortuosity of the flow increases, which is expressed in a decrease in permeability. The magnitude and intensity of the decrease in permeability are dependent on the magnitude of the load and the plasticity of the rock and may not be evident at low loads and in dry stiff core samples [15–19].

Another reason that receives little attention in studies of the conductive properties of rocks is the migration of colloids and fines [20,21]. Researches [8, 17] shows, the deterioration of permeability during the migration of colloids correlates well with the time and volume of injected liquid, which is due to the growth of plugs and a decrease in their conductivity [5, 17, 22, 23]. In consolidated porous rocks microcracking of the matrix and chipping of grain and cement particles can occur under cyclic loading. Detached particles can move within the pores when fluids and gases are injected[24,25]. The flow with particles leads to blockage of pore throats due to the formation of colloidal plugs and bridges. Cyclic loading leads to the crushing of colloidal plugs and bridges, their compaction or unblocking.

Particle detachment does not occur equally in rocks with different permeability and porosity[26,27]. In more compact rocks with low permeability, the tendency for particle detachment is less. Small pore throat sizes also do not allow particles to move between pores. The effect of particle migration may be insignificant or barely noticeable, firstly due to compactness and small deformations, and secondly due to the low concentration of colloids. Also, in clean rocks (sandstones and limestones) with low clay content, the number of natural free particles is limited [28,29]. The decrease in permeability does not occur completely, and as particles migrate and are washed out, the permeability can be restored to the initial values or exceed them [15, 18, 30–32].

Despite the evidence of microcracking and formation of free debris that reduces permeability, there is currently no understanding of the amount of colloids and fines formed and their effect on permeability, nor of the permeability range at which migration of colloids and fines results in a visible decrease in permeability. Thus, the main problem of predicting permeability under loading is the reliability of the results of laboratory studies under cyclic loading, and specifically, establishing the true cause of deterioration in permeability. Another problem is the lack of research devoted to the joint influence of cyclic loading and migration of colloids. A small number of results of experimental studies cast doubt on the presence of such a phenomenon as the migration of colloids on permeability.

Table 1

Properties of rock samples

Sample	Rock	Porosity, %	Permeability, mD	Weight, g	
				Before test	After test
16	Limestone	13.42	15.5	49.275	49.271
1	Limestone	14.79	35.0	47.587	47.558
20	Limestone	15.63	40.8	45.381	45.367
8	Limestone	14.91	88.7	46.738	46.730
9	Limestone	14.97	156.1	46.172	46.168
6	Limestone	14.14	346.0	46.688	46.674
61	Sandstone	11.08	6.96	41.880	41.844
51	Sandstone	11.58	13.1	37.484	37.464
169	Sandstone	8.58	28.4	49.710	49.688
748	Sandstone	10.69	49.7	47.191	47.175
2019	Sandstone	13.06	50.0	46.802	46.801
131	Sandstone	15.19	134.1	38.777	38.753
181	Sandstone	15.19	442.5	41.469	41.427

This paper examines the effect of mechanical compaction and migration of colloids and fines in clean reservoirs – sandstones and limestones with a low clay content and no reactive flow. The experimental methodology and results, as well as discussion, are presented below.

1. Methodology

Limestone and sandstone samples were used in this study. The samples were obtained from oil formations, limestone from formation C2b (depth of occurrence 1500-1700 m), sandstone from formation C1bb (depth of occurrence 1700-2000 m). These rocks are the main sources of oil in the Perm region, Russia. The samples are cylindrical in shape, 3 cm in diameter, up to 3 cm in length. All samples have uniform porosity, without inclusions or visible cracks. The porosity and permeability of the samples are shown in Table 1, the samples are listed in the table in order of increasing permeability. Limestone samples are micro-fine-grained with grain sizes less than 0.2 mm, heterodetrital with fragments of skeletal forms up to 5 mm in size. The void space is represented by cavities, irregularly shaped pores up to 1 mm in size. The structure of the sandstones is fine-grained, the quartz content is more than 95 %. The grains are represented by well-rounded grains with a diameter of 0.1-0.3 mm, the contact of the grains is conformal and linear, the pore space is intergranular. Samples were also weighed before and after testing (Table 1) to monitor weight loss.

Analysis of SEM photographs of the surfaces of the samples showed that on the inner surface of the pores of the limestone samples there is a large number of secondary formed calcite crystals, these crystals have an angular shape and are almost the same size - 10-20 µm. Due to the fine-crystalline structure, it is difficult to determine the presence of free particles on the pore walls. In sandstone samples, the size of quartz crystals is relatively large, the pore surfaces are more regularly shaped, and poorly attached clastic particles are clearly visible on the pore walls. In both types of rocks, microstructural analysis revealed small particles on the surface of the pores, which can affect the transport properties of rocks under cyclic loading.

The study of the dynamics of the permeability of samples under cyclic loading was carried out in accordance with the methodology described in the work [8]. Permeability was measured with nitrogen using an UltraPoroPerm-500 installation (Core Lab Instruments, USA). Permeability was measured over time by the Darcy formula:

$$k = \frac{2 \cdot \mu \cdot Q \cdot L \cdot P_a}{S \cdot \left(P_{in}^2 - P_a^2\right)}, \tag{1}$$

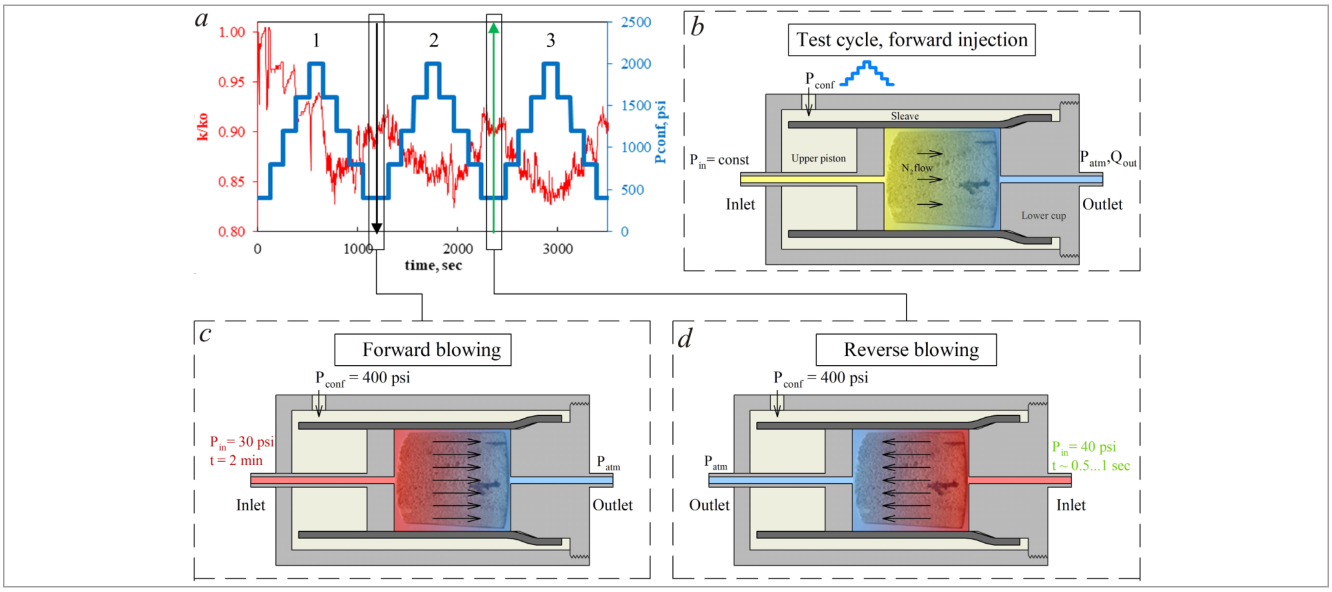


Fig. 1. An example of a program for testing samples under cyclic loading (*a*), blue solid line – confining pressure, black down arrow – forward blowing, green – reverse; schematic representation of a core sample in a core holder and the direction of nitrogen flow during permeability measurements (*b*), direct blowing (*c*), and reverse blowing (*d*)

where μ is the viscosity of nitrogen, Q is the flowrate, L is the length of the sample, P_a is the atmosphere pressure and equal to the outlet pressure, S is the samples' cross-section, P_{in} is the injection gas pressure.

The core samples were tested at cyclic confining pressure (Fig. 1, *a*). In each cycle, the confining pressure was stepwise changed from 2.76 MPa to 13.8 MPa. The maximum load value 13.8 MPa is less than the weight of rocks in situ conditions. This load was chosen specifically to reduce the likelihood of irreversible deformations and creep during loading. During the loading and unloading cycle, permeability was measured with a constant forward nitrogen flow, under a constant pressure gradient (Fig. 1, *b*). Blowings between cycles were carried out in order to detect the effect of the smallest particles (colloids or fines) on the change in permeability. Blowings was carried out both in the forward (Fig. 1, *c*) and in the reverse (Fig. 1, *d*) directions.

2. Results and Discussion

2.1. Permeability dynamics

The test results of core samples are presented on graphs (Fig. 2) in the form of dynamics of permeability and confining pressure over time.

In limestone samples 8, 9 which have slightly higher permeability, the effect of blowing is noticeable on the dynamics of permeability (Fig. 2, *a*, *b*). In samples 8 and 9, the permeability does not change during the first 3 cycles (Fig. 2, *a*, *b*), however, reverse blowing leads to a decrease in the permeability of sample 8 and an increase in the permeability of sample 9 in the 4th cycle. Direct blowing helps to increase the permeability of sample No. 8 in the 7th cycle above the initial value, then the permeability decreases and in the 8th cycle is almost independent of loading. For sample No. 9, blowing after the 4th cycle does not affect the permeability.

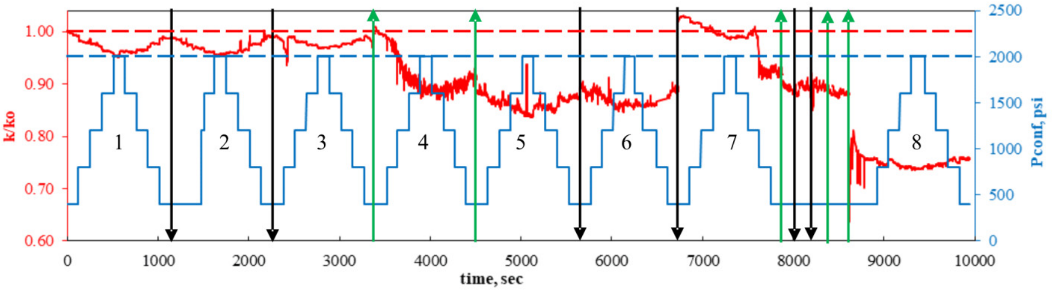
In sandstone sample, the change in permeability in almost all cycles corresponds to confining pressure (Fig. 2, *c*). In less permeable sample No. 61, the change in permeability is the same; blowing does not affect the permeability between cycles in sample No. 61; reverse blowing led to a short-term increase in permeability at the beginning of cycles 5 and 7.

2.2. Mechanical compaction

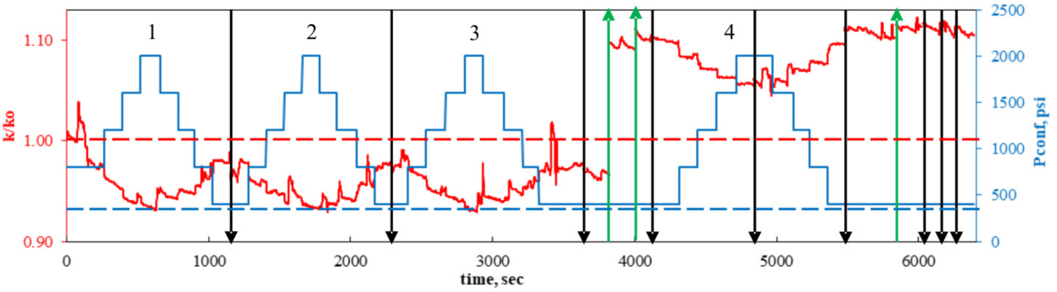
The porous medium of natural rock samples according to [33] is represented by a set of voids of different sizes and nature. The model of a porous medium consisting of macropores, micropores and microcracks is schematically shown in Fig. 3, *a*. The voids connected to each other determine the transport and capacity properties of rocks. Large pores largely determine the capacity properties, and the throats between them determine the connection between the pores and the transport properties. Micropores accumulate less fluids, but are more responsible for the elastic and mechanical properties of rocks. Another type of void space is microcracks. Microcracks make the least contribution to the transport properties of rocks, but microcracks play an important role in the deformation of rocks during loading and unloading.

As shown by the results of experimental studies [20, 34], under loading, the pores are the least compressed even at high loads. The deformation of the samples is caused by the compression of microcracks (Fig. 3, *b*) [35]. Microcracks, depending on the orientation angle, close in the compression or compression with shear mode [36, 37]. Compression is prevented by the rigidity of the cracks, and shear is prevented by sliding friction. The deformation of microcracks in the pure compression mode is the same under loading and unloading. And the shear mode of deformation of microcracks has hysteresis due to friction. In [38], a model of rock deformation is proposed that takes into account the sliding friction of microcracks during deformation. Friction has virtually no effect on the overall deformation under loading, since the stress coming from the outside is sufficient to compress the cracks. During unloading, cracks do not open completely (Fig. 3, *c*) since the accumulated elastic energy is not enough to overcome internal friction, as a result of which hysteresis is observed not only in mechanical properties [39, 40], but also in permeability [14, 41, 42].

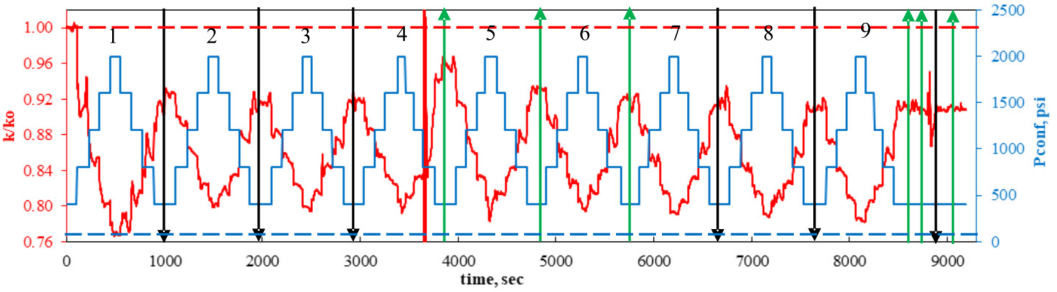
Unlike pores, which are natural voids between rock grains, microcracks appear during deformation of the porous medium associated with a change in the stress-strain state. The porous medium in natural conditions of occurrence is consolidated and there are no microcracks in it. Microcracks are absent due to high lithostatic pressure, and pore water has led to their healing with cement.



(*a*) Sample 8



(*b*) Sample 9



(*c*) Sample 61

Fig. 2. Dynamics of confining pressure (blue solid line) and permeability (red solid line) of samples: 8 (*a*), 9 (*b*), 61 (*c*), The cycles are numbered in sequential order. Vertical arrows show the boundaries between cycles, a black down arrow indicates forward blowing, and a green up arrow indicates reverse blowing. The red horizontal dotted line is the initial permeability, the blue dotted line is the lowest permeability in the first cycle

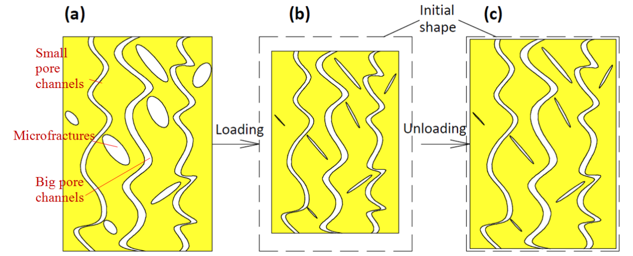


Fig. 3. Schematic representation of mechanical compaction of the pore space (*a*) during loading (*b*) and unloading (*c*)

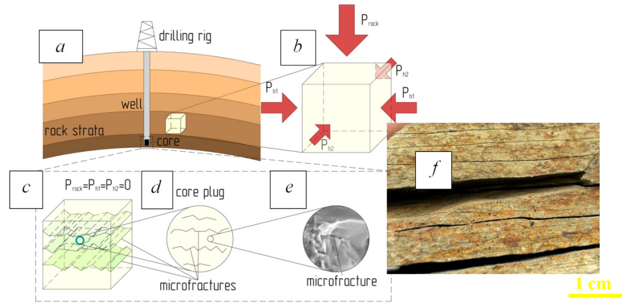


Fig. 4. Scheme of relaxation crack formation during rock excavation. Sample coring (*a*), stress in rock mass (*b*), stress relief and formation of relaxation cracks perpendicular to the main stress (*c*). Drilled core plug with microcracks (*d*). Relaxation microcrack under microscope (*e*). Relaxation macrocracks on rock sample (*f*)

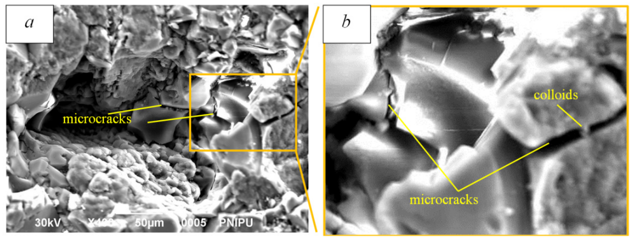


Fig. 5. SEM photographs of the surfaces of sandstone samples at different magnifications

All rocks drilled from depths are equally characterized by the release of natural stresses during core extraction. Relaxation microcracks with a predominant direction perpendicular to the principal stress are formed in rock samples (Fig. 4). Core samples with relaxation cracks are disturbed and their measured porosity and permeability are very different from natural ones, especially under cylindrical loading.

Relaxation cracks are most pronounced in strong, highly compressed, low-porosity rocks and manifest themselves as a core disking effect [43]. In porous rocks, relaxation cracks are less pronounced and manifest themselves at the micro level as cracks in grains or between grains. Microstructural analysis of the samples showed the presence of relaxation microcracks on the studied samples (Fig. 5). Relaxation microcracks have characteristic smooth surfaces that do not show any signs of erosion or crystal formation. Microcracks are mainly

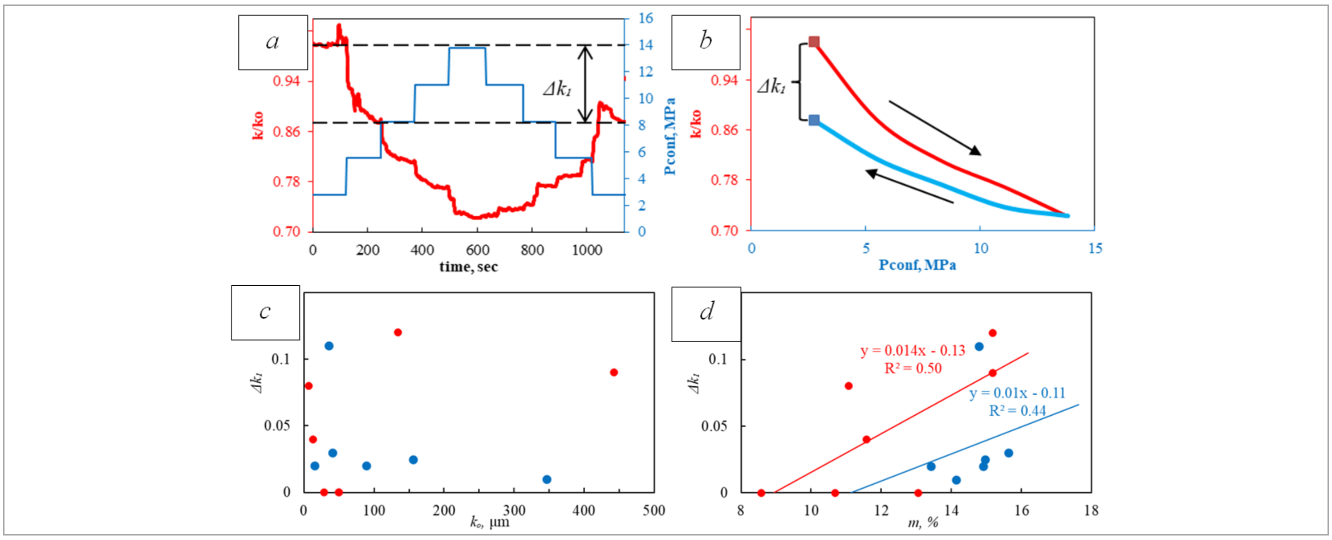


Fig. 6. Permeability dynamics versus time (*a*) and confining pressure (*b*). Correlation plots of permeability decrease in the first cycle and initial permeability (*a*) and porosity (*b*). Red color – sandstone, blue – limestone

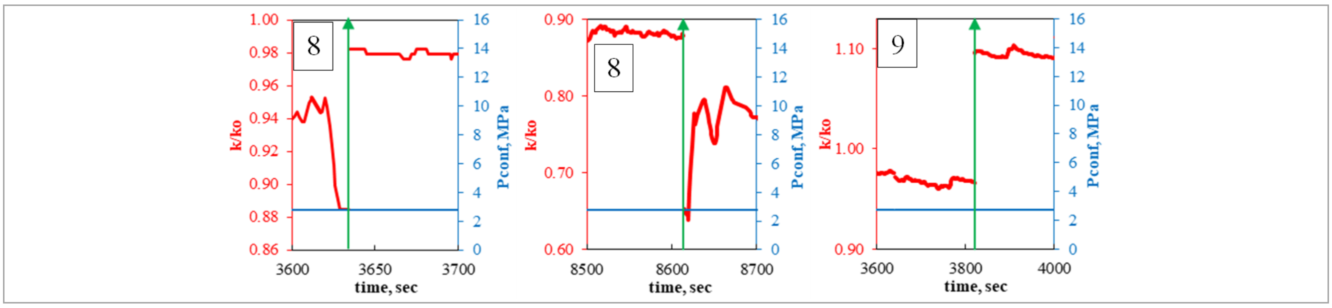


Fig. 7. Permeability jumps after blowing. Green arrow – reverse blowing. The number corresponds to the sample number

intergranular. The width of microcracks ranges from a few microns to 20 µm.

The effect of rock compaction on permeability hysteresis due to microcrack closure is observed in the first loading/unloading cycle. As shown by the results of cyclic loading (Fig. 2), most samples in the first cycle have the greatest difference between permeability at the beginning and end of the cycle. In the first cycle, microcracks close during compression, and not all microcracks open during unloading, which is caused by friction. Friction determines the threshold for microcrack opening during unloading and the mechanical hysteresis of permeability [44].

The value of permeability hysteresis in the first cycle Δk_1 (Fig. 6, *a*, *b*) shows how much elastic energy is lacking to overcome friction and open shear cracks. A comparative analysis showed that Δk_1 weakly depends on permeability (Fig. 6, *c*), but correlates well with the porosity of the samples (Fig. 6, *d*). More porous samples, due to lower elasticity, have a larger permeability hysteresis caused by mechanical compaction. With almost the same elasticity, sandstone samples have greater internal friction and permeability hysteresis (Fig. 6, *d*). Thus, the decrease in permeability after the first cycle occurs due to the closure of microcracks, and the magnitude of this decrease is due to the crack opening threshold during friction.

The analysis of the cyclic loading results also showed that in the samples in which blowing does not affect the permeability dynamics (sample No. 61), at maximum pressure, the permeability in the first cycle has a minimum value among all subsequent cycles. This is due to the stress memory [10] of the samples and the absence of plastic deformations. It was also found that in subsequent cycles, the permeability at maximum confining pressure becomes higher than in the 1st cycle, this is especially noticeable in sample 61 (Fig. 2, *c*). The microphoto (Fig. 5) shows that colloids and fairly large particles are located inside the cracks. During blowing, colloids get into microcracks and can act as a propping agent, preventing crack closure under loading. Most likely, this is the reason why the permeability does not reach the level of the first cycle at maximum confining pressure.

2.3. The influence of colloid migration

Colloids and fines can be free inside the pore space, but as a rule their presence is caused by anthropogenic impact. With cyclic change of the stress-strain state of the formation, deformations cause cyclic opening of microcracks. Microcracks compression and shear contribute to the splitting of crystals or cement of the rock. Split and fragmented particles can be carried away with the flow and migrate through the void space. Migration of colloids with blocking of pores reduces the transport properties of rocks. A significant effect of colloids on permeability is observed only with their large number or sizes comparable to the pore throats.

Porous sandstones are represented by strong grains and thin cement. The pores are of regular shape, intergranular. In carbonate rocks, due to high chemical activity, the grains have a regular shape, secondary crystallization, while the porosity can be low or high, cavernous with an unpredictable shape.

Based on the results of core studies under cyclic loading, we can conclude that blowing between cycles have a significant impact on the measured permeability of limestone samples No. 8, 9. In these samples, loading and unloading, the permeability does not correspond to loading and unloading. Permeability jumps are observed between testing cycles (Fig. 7), blowing leads to both an increase and a decrease in permeability, the change in permeability varies from 5 % to 25 %. This is a consequence of the blocking and unblocking of pores during colloid migration.

In other samples, the influence of colloid migration on permeability is not observed, which may indicate its absence, however, permeability behaves as if it is influenced by colloid migration, in some samples, there is no reduction in permeability at maximum load in subsequent cyclic loads, which does not correspond to mechanical compaction under loading.

The porous medium consists of a network of large pore channels, small pores and microcracks, the migration of colloids can affect the permeability of each type of voids differently. Large pores create highly conductive channels and provide the greatest contribution to the transport capacity of rocks, most of the flow passes through them. Blocking of such channels leads to a significant change in permeability. Blocking of large pore channels with colloids is possible only if there are a lot of them, or if there are sufficiently large free particles in the pores. In the work [8] it is shown that for limestone samples, inter-cycle blowing led to a significant change in the apparent permeability of core samples, analysis of microphotographs of sample surfaces showed that colloids can be of various shapes and up to 50 μm in size, which is quite sufficient to block large pores and reduce permeability (Fig. 2).

Small pores can be easily clogged with colloids, but since they make a small contribution to the overall permeability, their blocking is barely noticeable on the permeability dynamics. Low-permeability rocks are usually more compacted and microdestruction inside the pores is unlikely compared to highly porous rocks, in addition, due to the low conductivity, the transfer of particles between small pores is also difficult, since the particles are proportionate to the pore throats. In low-permeability sandstone No. 61, permeability changes due to blowing between cycles were not observed.

The results obtained clearly show that the method of measuring permeability plays an important role on their reliability; transport properties determined using the injection of fluids [26] and gases [34] can vary significantly due to the migration of colloids and fines, and taking into account the influence of these factors should help in determining the true conductive properties of rocks, as well as their behavior under loading. The mechanism of change in permeability described in [34] quite well describes the dynamics of permeability observed in the graphs (Fig. 2).

To determine the type of pore blockage, we analyzed the particles blown out of the samples. The analysis method is shown in Fig. 8. The particles were captured by a paper filter installed at the sample outlet (Fig. 8, *a*). After permeability measurements, the filter was removed (Fig. 8, *b*) and examined using an optical microscope (Fig. 8, *d*, *e*). In the original photograph (Fig. 8, *d*), using ImageJ software, particles were highlighted for contrast (Fig. 8, *e*), they were counted, and their geometric dimensions were determined.

The amount of emitted colloid was measured after two tests in the following steps:

1. After filtration, with a constant flow rate of 0.8 cm^3/sec and direct blowing for 2 minutes;
2. After 1 cycle of filtration with loading and unloading and direct blowing for 2 minutes.

Between steps the sample was evacuated to recharge the filter. The permeability dynamics with particle capture and filter recharges are shown in Fig. 9.

Figure 9 shows that after recharging with a new filter, the permeability is slightly higher than at the beginning. In the first cycle, there is a noticeable decrease in permeability with confining pressure and incomplete recovery of permeability upon unloading, which is due to incomplete opening of microcracks at residual confining pressure. After repeated recharging with a new filter, the permeability of the samples at the beginning of the second cycle is slightly higher than at the beginning of the first cycle. Permeability recovery after sample evacuation is associated with complete crack opening after unloading. The observed effects additionally confirm that permeability hysteresis is also caused by incomplete crack opening due to friction at residual confining pressure.

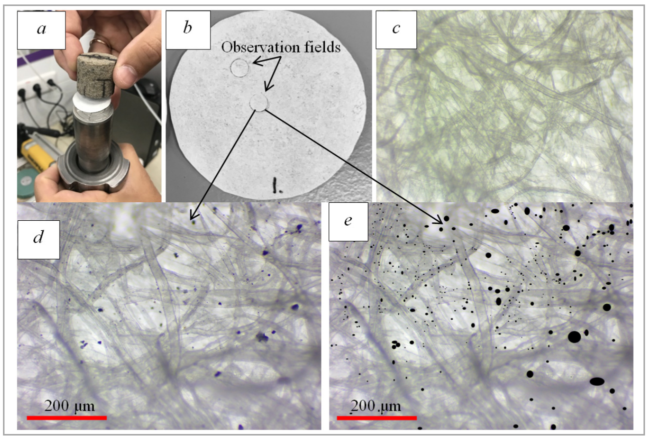


Fig. 8. Methodology for capturing and counting the number and size of emitted particles: *a* – paper filter at the sample outlet; *b* – filter after the test, general view. Enlarged image of filters: *c* – initial clean filter; *d* – filter with particles, raw image; *e* – filter with highlighted particles

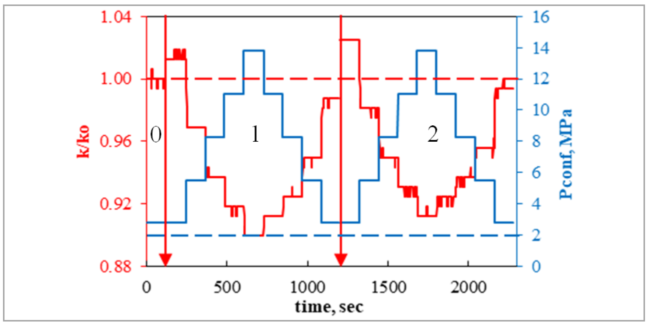


Fig. 9. Dynamics of permeability and confining pressure over time (Sample 61). The red arrow shows direct blowing and filter recharging procedure with sample evacuation from the core holder. The red horizontal dotted line is the initial permeability, the blue dotted line is the lowest permeability in the first cycle. The numbers indicate the loading and unloading cycles

Fig. 10 shows the particle size distribution of the samples with minimum permeability. The number 0 denotes the histograms of the particles emitted from the sample during permeability measurements without cyclic loading at constant confining pressure and with direct blowing. The number 1 denotes the histograms of the particles emitted from the sample after 1 loading/unloading cycle and direct blowing.

The histograms show that all samples have particle emissions, but in low permeable rocks the maximum particle size does not exceed 5 μm. It was also found that after the second blowing, despite the test duration, fewer particles with sizes of up to 1.5 μm were emitted. The decrease in the number of fine particles is due to their loss during the first blowing, as well as their possible attachment to the pore walls due to static electric charge when moving through the pores. After the loading/unloading cycle, the proportion of large particles increased and indicates an increase in their mobility due to the expansion of the pore throats.

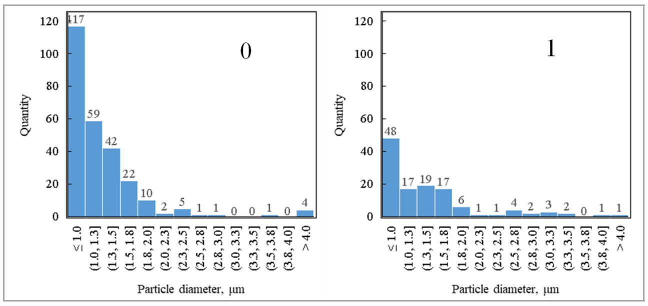


Fig. 10. Number and size distribution of emitted particles (Sample 61). Numbers 0 and 1 refer to filters, see Fig. 9

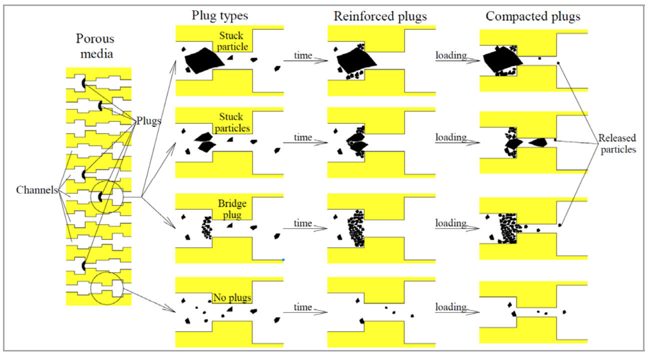


Fig. 11. Schematic representations of pore space, types of colloidal plugs and their evolution over time and compaction

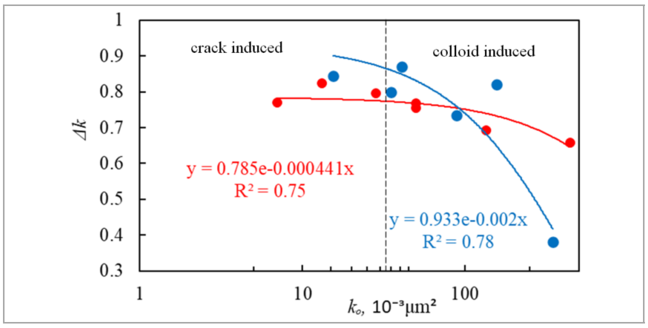


Fig. 12. Dependence of the magnitude of permeability change under cyclic loading on the initial permeability. The vertical dotted line is the conventional boundary between the dominant mechanisms of permeability degradation: on the left is fracture-induced permeability degradation, on the right is colloid-induced permeability degradation

The difference in the sizes of emitted particles with and without cyclic loading is caused by the types of colloidal and fine plugs. The classification and mechanisms of plug formation are shown in Fig. 11. Depending on the size and number of particles, as well as the size of the pore throats, these can be either individually stuck particles of a relatively large size than the pore throat, or several relatively large particles proportionate to the pore throat. At high concentrations of colloids, bridge plugs can form in the pore throats. At large pore throats and a small amount of colloids and fines, as well as at their relatively small size, plugs may not form at all. Under natural conditions, the amount of free colloids [8] in the pores of the samples is very small and bridge plugs are rarely formed.

The duration of the flow and the volume of injected fluid have a positive effect on the density of the plugs, which leads to an almost complete loss of their conductivity [45]. The narrowing and opening of the pore throats during cyclic loading leads to compaction and partial breakage of the plugs. The movement of the pore throats leads to a partial release of stuck particles and an increase in the conductivity of the samples at the beginning of the second cycle above the initial value (Fig. 9).

Conclusions

Predicting permeability under cyclic loading is challenging due to the complex interplay of rock mechanics and heterogeneous material properties. The power law is commonly used, but variability in permeability hysteresis complicates its application. Mechanical compaction during loading reduces permeability by closing microfractures and pore throats, while the migration of colloids and fines, though less studied, also contributes to permeability deterioration by forming plugs and bridges. The extent of migration depends on rock permeability and porosity, and detachment of particles is influenced by particle size and concentration. However, the impact of colloid migration on permeability and the mechanisms responsible for permeability recovery remain poorly understood.

The presented experimental study investigated the transport properties of porous limestones and sandstones under cyclic loading. The results showed that the decrease in permeability can be partially attributed to mechanical compaction and the migration of colloids and fines. The study demonstrated that this phenomenon manifests itself in both limestones and sandstones. Factors such as the presence of natural small crystals in rock pores and relatively high permeability enhance the sensitivity of rock conductivity to changes in flow conditions, making the migration of colloids a significant factor in permeability changes.

By shedding light on the mechanisms of colloid migration and its impact on permeability, this research contributes to a more comprehensive understanding of reservoir behavior under cyclic loading conditions. This knowledge is essential for optimizing reservoir management strategies and ensuring the long-term sustainability of hydrocarbon production.

The magnitude of permeability change (Δk) under cyclic confining pressure exhibits a strong correlation ($R^2 > 0.75$) with initial permeability (Fig. 12). Our findings indicate that in porous sandstones and limestones with initial permeability below 50 mD, permeability degradation is primarily attributed to microcrack closure. The impact of colloid migration is less evident in less permeable rocks, likely due to reduced colloid mobility and the difficulty in establishing a baseline for comparison without colloids. However, for rocks with initial permeability exceeding 50 mD, both compaction and the migration of colloids and fines contribute to permeability reduction. In more permeable rocks, colloid mobility is higher, potentially leading to significant permeability reductions of up to 60 %.

In low-permeability rocks, change in permeability does not necessarily indicate the absence of colloids but rather suggests limited colloid mobility. The low transport capacity of low-permeability formations can be advantageous, as it limits deep colloid migration and localized pore clogging. However, the transfer of colloids from high-permeability zones to low-permeability zones can reduce the permeability of the latter and hinder fluid communication between different reservoir compartments.

This research has significant practical implications for example for optimizing well perforation strategies. Recognizing that high-permeability formations are a source of larger particles that can migrate and block pores in low-permeability layers, a revised approach to perforation is recommended. Specifically, perforating low-permeability layers in injection wells minimizes the risk of colloid-induced clogging. Conversely, targeting high-permeability layers for production wells maximizes production while minimizing the impact of colloid migration from low-permeability zones.

References

1. Li S., Zhang S., Xing H., Zou Y. CO_2-brine-rock interactions altering the mineralogical, physical, and mechanical properties of carbonate-rich shale oil reservoirs. *Energy*, 2022, no. 256, 124608 p. DOI: 10.1016/j.energy.2022.124608

2. Chen M., Al-Maktoumi A., Izady A., Cai J., Dong Y. Use closed reservoirs for CO_2 storage and heat recovery: A two-stage brine-extraction and CO_2-circulation strategy. *Sustainable Energy Technologies and Assessments*, 2022, no. 52, 102346 p. DOI: 10.1016/j.seta.2022.102346

3. Riabokon E., Turbakov M., Kozhevnikov E., Poplygin V., Guzev M. Study of the influence of nonlinear dynamic loads on elastic modulus of carbonate reservoir rocks. *Energies*, 2021, vol. 14, no. 24. DOI 10.3390/en14248559

4. Riabokon E., Kozhevnikov E., Wiercigroch M., Kozhevnikov E., Kobiakov D., Guzev M., Wiercigroch M. Nonlinear Young's Modulus of New Red Sandstone: Experimental Studies. *Acta Mechanica Solida Sinica*, 2021, vol. 34, no. 6, pp. 989-999. DOI 10.1007/s10338-021-00298-w

5. Turbakov M.S., Chernyshov S.E., Ust'kachkintsev E.N. Analiz effektivnosti tekhnologii preduprezhdeniia obrazovaniia asfal'tosmoloparafinovykh otlozhenii na mestorozhdeniiakh Permskogo Prikam'ia [Efficiency analysis of technologies for prevention the formation of asphaltene tar wax-bearing deposits on the mines of Perm Prikamye]. *Neftianoe khoziaistvo,* 2012, no. 11, pp. 122-123.

6. Shcherbakov A.A., Khizhniak G.P., Galkin V.I. Otsenka effektivnosti meropriiatii po intensifikatsii dobychi nefti (na primere mestorozhdenii Solikamskoi depressii) [Effectiveness evaluation of oil production stimulation measures (on the example of the Solikamsk depression fields)]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2019, no. 2, pp. 70-73.

7. Riabokon E., Gladkikh E., Turbakov M., Kozhevnikov E., Guzev M., Popov N., Kamenev P. Effects of ultrasonic oscillations on permeability of rocks during the paraffinic oil flow. *Géotechnique Letters*, 2023, no. 13, pp. 1-20. DOI: 10.1680/jgele.22.00137

8. Kozhevnikov E.V., Turbakov M.S., Riabokon E.P., Gladkikh E.A. Apparent Permeability Evolution Due to Colloid Migration Under Cyclic Confining Pressure: On the Example of Porous Limestone. *Transp Porous Media*, 2023. DOI: 10.1007/s11242-023-01979-5

9. Turitsyna M.V. et al. Gazozhidkostnye promyvochnye smesi dlia pervichnogo vskrytiia plastov v usloviiakh anomal'no nizkikh plastovykh davlenii [Gas-liquid washover mixtures for the primary opening of productive layers in conditions of abnormally low reservoir pressure]. *Neftianoe khoziaistvo*, 2012, no. 9, pp. 58-59.

10. Kluge C., Blöcher G., Hofmann H., Barnhoorn A., Schmittbuhl J., Bruhn D. The Stress-Memory Effect of Fracture Stiffness During Cyclic Loading in Low-Permeability Sandstone. *J. Geophys. Res. Solid Earth*, 2021, no. 126. DOI: 10.1029/2020JB021469

11. Li L., Yang D., Liu W., Zhang X., Zhao L., Zhu X. Experimental Study on the Porosity and Permeability Change of High-Rank Coal under Cyclic Loading and Unloading. *ACS Omega*, 2022, no. 7, pp. 30197-30207. DOI: 10.1021/acsomega.2c03304

12. Chen L., Zhang D., Zhang W., Guo J., Yao N., Fan G., Zhang S., Wang X., Wu P. Experimental Investigation on Post-Peak Permeability Evolution Law of Saturated Sandstone under Various Cyclic Loading–Unloading and Confining Pressure. *Water (Basel)*, 2022, no. 14, 1773 p. DOI: 10.3390/w14111773

13. Golosov A.M., Riabokon E.P., Turbakov M.S., Kozhevnikov E.V., Poplygin V.V., Guzev M.A., Jing H. The Effect of Dynamic Loads on the Creep of Geomaterials. *IUTAM: IUTAM Symposium Creep in Structures*, 2023, pp. 143-150. DOI: 10.1007/978-3-031-39070-8_9

14. Civan F. Effective-Stress Coefficients of Porous Rocks Involving Shocks and Loading/Unloading Hysteresis. *SPE Journal*, 2021, no. 26, pp. 44-67. DOI: 10.2118/200501-PA

15. Deb D., Chakma S. Colloid and colloid-facilitated contaminant transport in subsurface ecosystem - a concise review. *International Journal of Environmental Science and Technology*, 2022. DOI: https://doi.org/10.1007/s13762-022-04201-z

16. Samari Kermani M., Jafari S., Rahnama M., Raoof A. Direct pore scale numerical simulation of colloid transport and retention. Part I: Fluid flow velocity, colloid size, and pore structure effects. *Adv. Water Resource*, 2020, no. 144. DOI: 10.1016/j.advwatres.2020.103694

17. Kozhevnikov E.V., Turbakov M.S., Gladkikh E.A., Riabokon E.P., Poplygin V.V., Guzev M.A., Qi C., Kunitskikh A.A. Colloid Migration as a Reason for Porous Sandstone Permeability Degradation during Coreflooding. *Energies (Basel)*, 2022, no. 15, 2845 p. DOI: 10.3390/en15082845

18. Wang C., Wang R., Huo Z., Xie E., Dahlke H.E. Colloid transport through soil and other porous media under transient flow conditions: a review. *WIREs Water*, 2020, no. 7. DOI: 10.1002/wat2.1439

19. Zhao D., Yang H., Wei Y., Li Z., Yang W., Shen G., Tang Z., Wang L., Li J., Chen J., Feng H. pH-responsive phenol-formaldehyde resin: aggregation mechanism and plugging science. *Colloid Polym. Sci.*, 2023. DOI: 10.1007/s00396-023-05144-8

20. Hu C., Agostini F., Jia Y. Porosity and Permeability Evolution with Deviatoric Stress of Reservoir Sandstone: Insights from Triaxial Compression Tests and In Situ Compression CT. *Geofluids*, 2020, no. 2020, pp. 1-16. DOI: 10.1155/2020/6611079

21. Hu C., Agostini F., Skoczylas F., Jeannin L., Egermann P., Jia Y. Transport property evolution during hydrostatic and triaxial compression of a high porosity sandstone. *European Journal of Environmental and Civil Engineering*, 2020, pp. 1-14. DOI: 10.1080/19648189.2020.1763854

22. Kozhevnikov E., Riabokon E., Turbakov M. A Model of Reservoir Permeability Evolution during Oil Production. *Energies (Basel)*, 2021, no. 14, 2695 p. DOI: 10.3390/en14092695

23. Kozhevnikov E.V., Turbakov M.S., Gladkikh E.A., Riabokon E.P., Poplygin V.V., Guzev M.A., Qi C., Jing H. Colloidal-induced permeability degradation assessment of porous media. *Géotechnique Letters*, 2022, no. 12, pp. 217-224. DOI: 10.1680/jgele.22.00017

24. Anyim K., Gan Q. Fault zone exploitation in geothermal reservoirs: Production optimization, permeability evolution and induced seismicity. *Advances in Geo-Energy Research*. 2020. no. 4, pp. 1-12. DOI: 10.26804/ager.2020.01.01

25. Lei G., Liao Q., Lin Q., Zhang L., Xue L., Chen W. Stress dependent gas-water relative permeability in gas hydrates: A theoretical model. *Advances in Geo-Energy Research*, 2020, no. 4, pp. 326-338. DOI: 10.46690/ager.2020.03.10

26. Kozhevnikov E., Turbakov M., Riabokon E., Gladkikh E., Guzev M., Qi C., Li X. The mechanism of porous reservoir permeability deterioration due to pore pressure decrease. *Advances in Geo-Energy Research*, 2024, no. 13, pp. 96-105. DOI: 10.46690/ager.2024.08.04

27. Raziperchikolaee S. Impact of stress dependence of elastic moduli and poroelastic constants on earth surface uplift due to injection. *Advances in Geo-Energy Research*, 2023, no. 10, pp. 56-64. DOI: 10.46690/ager.2023.10.06

28. Almutairi A., Saira S., Wang Y., Le-Hussain F. Effect of fines migration on oil recovery from carbonate rocks. *Advances in Geo-Energy Research*, 2023, no. 8, pp. 61-70. DOI: 10.46690/ager.2023.04.06

29. Kozhevnikov E., Turbakov M., Riabokon E., Gladkikh E., Guzev M., Panteleeva A., Ivanov Z. Rock permeability evolution during cyclic loading and colloid migration after saturation and drying. *Advances in Geo-Energy Research*, 2024, no. 11, pp. 208-219. DOI: 10.46690/ager.2024.03.05

30. Ramachandran V., Fogler H.S. Plugging by hydrodynamic bridging during flow of stable colloidal particles within cylindrical pores. *J. Fluid Mech.*, 1999, no. 385, pp. 129-156. DOI: 10.1017/S0022112098004121

31. Chen C., Packman A.I., Gaillard J.F. Pore-scale analysis of permeability reduction resulting from colloid deposition. *Geophys. Res. Lett.*, 2008, no. 35. DOI: 10.1029/2007GL033077

32. Awan F.U.R., Arif M., Iglauer S., Keshavarz A. Coal fines migration: A holistic review of influencing factors. *Adv. Colloid Interface Sci.*, 2022, no. 301, 102595 p. DOI: 10.1016/j.cis.2021.102595

33. Pimienta L., Quintal B., Caspari E. Hydro-mechanical coupling in porous rocks: hidden dependences to the microstructure? *Geophys. J. Int.*, 2020, no. 224, pp. 973-984. DOI: 10.1093/gji/ggaa497

34. Karev V.I., Khimulia V.V., Shevtsov N.I. Experimental Studies of the Deformation, Destruction and Filtration in Rocks: A Review. *Mechanics of Solids*, 2021, no. 56, pp. 613-630. DOI: 10.3103/S0025654421050125

35. Khimulia V., Karev V., Kovalenko Y., Barkov S. Changes in filtration and capacitance properties of highly porous reservoir in underground gas storage: CT-based and geomechanical modeling. *Journal of Rock Mechanics and Geotechnical Engineering*, 2024, no. 16, pp. 2982-2995. DOI: 10.1016/j.jrmge.2023.12.015

36. Hofmann H., Blöcher G., Milsch H., Babadagli T., Zimmermann G. Transmissivity of aligned and displaced tensile fractures in granitic rocks during cyclic loading. *International Journal of Rock Mechanics and Mining Sciences*, 2016, no. 87, pp. 69-84. DOI: 10.1016/j.ijrmms.2016.05.011

37. Stanton-Yonge A., Mitchell T.M., Meredith P.G. The Hydro-Mechanical Properties of Fracture Intersections: Pressure-Dependant Permeability and Effective Stress Law. *J. Geophys. Res. Solid Earth*, 2023, no. 128. DOI: 10.1029/2022JB025516

38. Ma J., Wang J. A Stress-Induced Permeability Evolution Model for Fissured Porous Media. *Rock Mech. Rock Eng.*, 2016, no. 49, pp. 477-485. DOI: 10.1007/s00603-015-0760-8

39. Biyoghé A.T., Leroy Y.M., Pimienta L., Zimmerman R.W. Stress-strain hysteresis during hydrostatic loading of porous rocks. *J. Mech. Phys. Solids*, 2024, no. 193, 105861 p. DOI: 10.1016/j.jmps.2024.105861

40. Zhang J., Zhou X., Liu X., Fang L., Liu Y., Wang Y. Deformation and permeability of fractured rocks using fluid-solid coupling under loading-unloading conditions. *Journal of Rock Mechanics and Geotechnical Engineering*, 2024. DOI: 10.1016/j.jrmge.2024.09.048

41. Selvadurai A.P.S., Głowacki A. Permeability Hysterisis of Limestone During Isotropic Compression. *Groundwater*, 2008, no. 46. DOI: 10.1111/j.1745-6584.2007.00390.x

42. Kozhevnikov E.V., Turbakov M.S., Riabokon E.P., Gladkikh E.A., Poplygin V.V. Cyclic confining pressure and rock permeability: Mechanical compaction or fines migration. *Heliyon*, 2023, no. 9, e21600 p. DOI: 10.1016/j.heliyon.2023.e21600

43. Lim S.S., Martin C.D. Core disking and its relationship with stress magnitude for Lac du Bonnet granite. *International Journal of Rock Mechanics and Mining Sciences*, 2010, no. 47, pp. 254-264. DOI: 10.1016/j.ijrmms.2009.11.007

44. Li X., Chen Y.-F., Wei K., Hu R., Yang Z.-B. A threshold stresses-based permeability variation model for microcracked porous rocks. *European Journal of Environmental and Civil Engineering*, 2020, no. 24, pp. 787-813. DOI: 10.1080/19648189.2018.1424650

45. Bedrikovetsky P., Siqueira F.D., Furtado C.A., Souza A.L.S. Modified Particle Detachment Model for Colloidal Transport in Porous Media. *Transp. Porous Media*, 2011, no. 86, pp. 353-383. DOI: 10.1007/s11242-010-9626-4

Список литературы

1. CO_2-brine-rock interactions altering the mineralogical, physical, and mechanical properties of carbonate-rich shale oil reservoirs / S. Li, S. Zhang, H. Xing, Y. Zou // Energy. – 2022. – No. 256. – P. 124608. DOI: 10.1016/j.energy.2022.124608

2. Use closed reservoirs for CO_2 storage and heat recovery: A two-stage brine-extraction and CO_2-circulation strategy / M. Chen, A. Al-Maktoumi, A. Izady, J. Cai, Y. Dong // Sustainable Energy Technologies and Assessments. – 2022. – No. 52. – P. 102346. DOI: 10.1016/j.seta.2022.102346

3. Study of the influence of nonlinear dynamic loads on elastic modulus of carbonate reservoir rocks / E. Riabokon, M. Turbakov, E. Kozhevnikov, V. Poplygin, M. Guzev // Energies. – 2021. – Vol. 14, no. 24. DOI 10.3390/en14248559

4. Nonlinear Young's Modulus of New Red Sandstone: Experimental Studies / E. Riabokon, E. Kozhevnikov, M. Wiercigroch, E. Kozhevnikov, D. Kobiakov, M. Guzev, M. Wiercigroch // Acta Mechanica Solida Sinica. – 2021. – Vol. 34, no. 6. – P. 989–999. DOI 10.1007/s10338-021-00298-w

5. Турбаков, М. С. Анализ эффективности технологий предупреждения образования асфальтосмолопарафиновых отложений на месторождениях Пермского Прикамья / М.С. Турбаков, С.Е. Чернышов, Е.Н. Устькачкинцев // Нефтяное хозяйство. – 2012. – № 11. – С. 122–123.

6. Щербаков, А. А. Оценка эффективности мероприятий по интенсификации добычи нефти (на примере месторождений Соликамской депрессии) / А.А. Щербаков, Г.П. Хижняк, В.И. Галкин // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2019. – № 2. – С. 70–73. DOI 10.30713/2413-5011-2019-2-70-73

7. Effects of ultrasonic oscillations on permeability of rocks during the paraffinic oil flow / E. Riabokon, E. Gladkikh, M. Turbakov, E. Kozhevnikov, M. Guzev, N. Popov, P. Kamenev // Géotechnique Letters. – 2023. – No. 13. – P. 1–20. DOI: 10.1680/jgele.22.00137

8. Apparent Permeability Evolution Due to Colloid Migration Under Cyclic Confining Pressure: On the Example of Porous Limestone / E.V. Kozhevnikov, M.S. Turbakov, E.P. Riabokon, E.A. Gladkikh // Transp Porous Media. – 2023. DOI: 10.1007/s11242-023-01979-5

9. Газожидкостные промывочные смеси для первичного вскрытия пластов в условиях аномально низких пластовых давлений / М.В. Турицына [и др.] // Нефтяное хозяйство. – 2012. – № 9. – С. 58–59.

10. The Stress-Memory Effect of Fracture Stiffness During Cyclic Loading in Low-Permeability Sandstone / C. Kluge, G. Blöcher, H. Hofmann, A. Barnhoorn, J. Schmittbuhl, D. Bruhn // J. Geophys. Res. Solid Earth. – 2021. – No. 126. DOI: 10.1029/2020JB021469

11. Experimental Study on the Porosity and Permeability Change of High-Rank Coal under Cyclic Loading and Unloading / L. Li, D. Yang, W. Liu, X. Zhang, L. Zhao, X. Zhu // ACS Omega. – 2022. – No. 7. – P. 30197–30207. DOI: 10.1021/acsomega.2c03304

12. Experimental Investigation on Post-Peak Permeability Evolution Law of Saturated Sandstone under Various Cyclic Loading–Unloading and Confining Pressure / L. Chen, D. Zhang, W. Zhang, J. Guo, N. Yao, G. Fan, S. Zhang, X. Wang, P. Wu // Water (Basel). – 2022. – No. 14. – P. 1773. DOI: 10.3390/w14111773

13. The Effect of Dynamic Loads on the Creep of Geomaterials / A.M. Golosov, E.P. Riabokon, M.S. Turbakov, E.V. Kozhevnikov, V.V. Poplygin, M.A. Guzev, H. Jing // IUTAM: IUTAM Symposium Creep in Structures. – 2023. – P. 143–150. DOI: 10.1007/978-3-031-39070-8_9

14. Civan, F. Effective-Stress Coefficients of Porous Rocks Involving Shocks and Loading/Unloading Hysteresis / F. Civan // SPE Journal. – 2021. – No. 26. – P. 44–67. DOI: 10.2118/200501-PA

15. Deb, D. Colloid and colloid-facilitated contaminant transport in subsurface ecosystem – a concise review / D. Deb, S. Chakma // International Journal of Environmental Science and Technology. – 2022. DOI: https://doi.org/10.1007/s13762-022-04201-z

16. Direct pore scale numerical simulation of colloid transport and retention. Part I: Fluid flow velocity, colloid size, and pore structure effects / M. Samari Kermani, S. Jafari, M. Rahnama, A. Raoof // Adv. Water Resource. – 2020. – No. 144. DOI: 10.1016/j.advwatres.2020.103694

17. Colloid Migration as a Reason for Porous Sandstone Permeability Degradation during Coreflooding / E.V. Kozhevnikov, M.S. Turbakov, E.A. Gladkikh, E.P. Riabokon, V.V. Poplygin, M.A. Guzev, C. Qi, A.A. Kunitskikh // Energies (Basel). – 2022. – No. 15. – P. 2845. DOI: 10.3390/en15082845

18. Colloid transport through soil and other porous media under transient flow conditions: a review / C. Wang, R. Wang, Z. Huo, E. Xie, H.E. Dahlke // WIREs Water. – 2020. – No. 7. DOI: 10.1002/wat2.1439

19. pH-responsive phenol–formaldehyde resin: aggregation mechanism and plugging science / D. Zhao, H. Yang, Y. Wei, Z. Li, W. Yang, G. Shen, Z. Tang, L. Wang, J. Li, J. Chen, H. Feng // Colloid Polym. Sci. – 2023. DOI: 10.1007/s00396-023-05144-8

20. Hu, C. Porosity and Permeability Evolution with Deviatoric Stress of Reservoir Sandstone: Insights from Triaxial Compression Tests and In Situ Compression CT / C. Hu, F. Agostini, Y. Jia // Geofluids. – 2020. – No. 2020. – P. 1–16. DOI: 10.1155/2020/6611079

21. Transport property evolution during hydrostatic and triaxial compression of a high porosity sandstone / C. Hu, F. Agostini, F. Skoczylas, L. Jeannin, P. Egermann, Y. Jia // European Journal of Environmental and Civil Engineering. – 2020. – P. 1–14. DOI: 10.1080/19648189.2020.1763854

22. Kozhevnikov, E. A Model of Reservoir Permeability Evolution during Oil Production / E. Kozhevnikov, E. Riabokon, M. Turbakov // Energies (Basel). – 2021. – No. 14. – P. 2695. DOI: 10.3390/en14092695

23. Colloidal-induced permeability degradation assessment of porous media / E.V. Kozhevnikov, M.S. Turbakov, E.A. Gladkikh, E.P. Riabokon, V.V. Poplygin, M.A. Guzev, C. Qi, H. Jing // Géotechnique Letters. – 2022. – No. 12. – P. 217–224. DOI: 10.1680/jgele.22.00017

24. Anyim, K. Fault zone exploitation in geothermal reservoirs: Production optimization, permeability evolution and induced seismicity / K. Anyim, Q. Gan // Advances in Geo-Energy Research. – 2020. – No. 4. – P. 1–12. DOI: 10.26804/ager.2020.01.01

25. Stress dependent gas-water relative permeability in gas hydrates: A theoretical model / G. Lei, Q. Liao, Q. Lin, L. Zhang, L. Xue, W. Chen // Advances in Geo-Energy Research. – 2020. – No. 4. – P. 326–338. DOI: 10.46690/ager.2020.03.10

26. The mechanism of porous reservoir permeability deterioration due to pore pressure decrease / E. Kozhevnikov, M. Turbakov, E. Riabokon, E. Gladkikh, M. Guzev, C. Qi, X. Li // Advances in Geo-Energy Research. – 2024. – No. 13. – P. 96–105. DOI: 10.46690/ager.2024.08.04

27. Raziperchikolaee, S. Impact of stress dependence of elastic moduli and poroelastic constants on earth surface uplift due to injection / S. Raziperchikolaee // Advances in Geo-Energy Research. – 2023. – No. 10. – P. 56–64. DOI: 10.46690/ager.2023.10.06

28. Effect of fines migration on oil recovery from carbonate rocks / A. Almutairi, S. Saira, Y. Wang, F. Le-Hussain // Advances in Geo-Energy Research. – 2023. – No. 8. – P. 61–70. DOI: 10.46690/ager.2023.04.06

29. Rock permeability evolution during cyclic loading and colloid migration after saturation and drying / E. Kozhevnikov, M. Turbakov, E. Riabokon, E. Gladkikh, M. Guzev, A. Panteleeva, Z. Ivanov // Advances in Geo-Energy Research. – 2024. – No. 11. – P. 208–219. DOI: 10.46690/ager.2024.03.05

30. Ramachandran, V. Plugging by hydrodynamic bridging during flow of stable colloidal particles within cylindrical pores / V. Ramachandran, H.S. Fogler // J. Fluid Mech. – 1999. – No. 385. – P. 129–156. DOI: 10.1017/S0022112098004121

31. Chen, C. Pore-scale analysis of permeability reduction resulting from colloid deposition / C. Chen, A.I. Packman, J.F. Gaillard // Geophys. Res. Lett. – 2008. – No. 35. DOI: 10.1029/2007GL033077

32. Coal fines migration: A holistic review of influencing factors / F.U.R. Awan, M. Arif, S. Iglauer, A. Keshavarz // Adv. Colloid Interface Sci. – 2022. – No. 301. – P. 102595. DOI: 10.1016/j.cis.2021.102595

33. Pimienta, L. Hydro-mechanical coupling in porous rocks: hidden dependences to the microstructure? / L. Pimienta, B. Quintal, E. Caspari // Geophys. J. Int. – 2020. – No. 224. – P. 973–984. DOI: 10.1093/gji/ggaa497

34. Karev, V.I. Experimental Studies of the Deformation, Destruction and Filtration in Rocks: A Review / V.I. Karev, V.V. Khimulia, N.I. Shevtsov // Mechanics of Solids. – 2021. – No. 56. – P. 613–630. DOI: 10.3103/S0025654421050125

35. Changes in filtration and capacitance properties of highly porous reservoir in underground gas storage: CT-based and geomechanical modeling / V. Khimulia, V. Karev, Y. Kovalenko, S. Barkov // Journal of Rock Mechanics and Geotechnical Engineering. – 2024. – No. 16. – P. 2982–2995. DOI: 10.1016/j.jrmge.2023.12.015

36. Transmissivity of aligned and displaced tensile fractures in granitic rocks during cyclic loading / H. Hofmann, G. Blöcher, H. Milsch, T. Babadagli, G. Zimmermann // International Journal of Rock Mechanics and Mining Sciences. – 2016. – No. 87. – P. 69–84. DOI: 10.1016/j.ijrmms.2016.05.011

37. Stanton-Yonge, A. The Hydro-Mechanical Properties of Fracture Intersections: Pressure-Dependant Permeability and Effective Stress Law / A. Stanton-Yonge, T.M. Mitchell, P.G. Meredith // J. Geophys. Res. Solid Earth. – 2023. – No. 128. DOI: 10.1029/2022JB025516

38. Ma, J. A Stress-Induced Permeability Evolution Model for Fissured Porous Media / J. Ma, J. Wang // Rock Mech. Rock Eng. – 2016. – No. 49. – P. 477–485. DOI: 10.1007/s00603-015-0760-8

39. Stress-strain hysteresis during hydrostatic loading of porous rocks / A.T. Biyoghé, Y.M. Leroy, L. Pimienta, R.W. Zimmerman // J. Mech. Phys. Solids. – 2024. – No. 193. – P. 105861. DOI: 10.1016/j.jmps.2024.105861

40. Deformation and permeability of fractured rocks using fluid-solid coupling under loading-unloading conditions / J. Zhang, X. Zhou, X. Liu, L. Fang, Y. Liu, Y. Wang // Journal of Rock Mechanics and Geotechnical Engineering. – 2024. DOI: 10.1016/j.jrmge.2024.09.048

41. Selvadurai, A.P.S. Permeability Hysterisis of Limestone During Isotropic Compression / A.P.S. Selvadurai, A. Głowacki // Groundwater. – 2008. – No. 46. DOI: 10.1111/j.1745-6584.2007.00390.x

42. Cyclic confining pressure and rock permeability: Mechanical compaction or fines migration / E.V. Kozhevnikov, M.S. Turbakov, E.P. Riabokon, E.A. Gladkikh, V.V. Poplygin // Heliyon. – 2023. – No. 9. – P. e21600. DOI: 10.1016/j.heliyon.2023.e21600

43. Lim, S.S. Core disking and its relationship with stress magnitude for Lac du Bonnet granite / S.S. Lim, C.D. Martin // International Journal of Rock Mechanics and Mining Sciences. – 2010. – No. 47. – P. 254–264. DOI: 10.1016/j.ijrmms.2009.11.007

44. A threshold stresses-based permeability variation model for microcracked porous rocks / X. Li, Y.-F. Chen, K. Wei, R. Hu, Z.-B. Yang // European Journal of Environmental and Civil Engineeringю – 2020. – No. 24. – P. 787–813. DOI: 10.1080/19648189.2018.1424650

45. Modified Particle Detachment Model for Colloidal Transport in Porous Media / P. Bedrikovetsky, F.D. Siqueira, C.A. Furtado, A.L.S. Souza // Transp. Porous Media. – 2011. – No. 86. – P. 353–383. DOI: 10.1007/s11242-010-9626-4

Финансирование. Исследования выполнены при финансовой поддержке Министерства образования и науки Пермского края (проект № СЭД-26-08-08-28).

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Вклад авторов равноценен.