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The Effect of Ultrasonic Alternating Loads on Restoration of Permeability of Sedimentary Rocks during Crude Paraffinic Oil Flow

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Featured Application: The results obtained during this study may be applied to the development of a technology for intensifying oil inflow to production wells in conditions of paraffin flocculation.

Abstract: This paper presents the results of experimental studies on the filtration of reservoir fluid through the rocks under the influence of nonlinear loads. A laboratory rig is assembled that allows for modeling the flow of fluid from the reservoir into the well during the propagation of elastic waves from the well. It is shown that depending on the permeability of the rock matrix as well as on the concentration of paraffins and asphaltenes in crude oil, the effect of the nonlinear load is different. Three types of sandstone are studied: low, medium, and high permeability. The greatest influence of nonlinear loads is observed in high-permeability sandstone. The effect manifests itself in fully unblocking the pore space from paraffins and asphaltenes accumulated in pore throats and restoring the oil permeability to its original value. In the case of medium-permeability sandstone subjected to nonlinear loads, blocking of the pore space is slow. In the case of low-permeability sandstone, the impact of nonlinear loads does not have a significant effect. When studying water filtration in the presence of residual oil saturation, the effect of nonlinear loads is observed as a mobilization of additional oil not previously involved in the filtration process, which also leads to an increase in the water permeability of the rock.

Keywords: ultrasonic vibrations; paraffinic oil flow; sandstone

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Citation: Riabokon, E.; Gladkikh, E.; Turbakov, M.; Kozhevnikov, E.; Guzev, M.; Yin, Q. The Effect of Ultrasonic Alternating Loads on Restoration of Permeability of Sedimentary Rocks during Crude Paraffinic Oil Flow. *Appl. Sci.* **2023**, *13*, 11821. https://doi.org/10.3390/app132111821

Academic Editor: Nikolaos Koukouzas

Received: 11 October 2023
Revised: 26 October 2023
Accepted: 27 October 2023
Published: 29 October 2023

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1. Introduction

The precipitation of paraffins during oil production is a widespread phenomenon that petroleum engineers struggle with. In addition to being precipitated inside the surface pipelines [1] and well tubing [2,3], paraffins and asphaltenes are also precipitated in the reservoir as a result of both a decrease in reservoir temperature due to cold water flooding [4] and a reservoir pressure drop [5]. Among the entire reservoir, the highest intensity of paraffin precipitation due to changes in reservoir pressure is observed near production wells, where there is a significant drop in reservoir pressure [6] caused by well performance. Paraffin flocculation blocks the pore channels of the rock, which is commonly called "formation damage" [7]. As a result, the rock permeability of the bottomhole formation zone deteriorates and the flowrate of the production well decreases, which can adversely affect production from the entire oil field.

In order to unblock the pore space, production engineers use bottom-hole formation treatments (for example, steam cycle, acid, and others). However, due to the constant

influx of fluid from the reservoir and new precipitations of paraffins and asphaltenes, such treatments have to be repeated, including shutting down the well and production. An alternative solution is nonlinear load treatment [8,9], which can be performed without shutting down the well [10]. Nonlinear load treatments use elastic wave generators of various types that produce vibrations propagating towards the productive formation.

A significant number of theoretical and experimental works are devoted to studying the effect of nonlinear loading on the filtration of single-phase and two-phase fluids in a porous medium, the mobilization of capillary-trapped oil, changes in the rheological characteristics of filtering fluids, and other phenomena (see reviews [11,12], as well as the development of downhole tools (see review of [13,14]). Treatment of low-permeability sandstone with ultrasonic vibrations increases the spontaneous capillary imbibition of water by the rock sample [15]. Treatment of coal samples in an experimental setup with an ultrasonic emitter demonstrates a significant improvement in their permeability [16]. To restore the permeability of rocks near the wellbore, many authors explore the ultrasonic method of removing the pore space of the rock from precipitation of inorganic substances (salts), drilling fluid, and well-killing fluid, as well as polymers. For example, ref. [17] has shown in the experimental installation for core flooding that ultrasonic vibrations remove calcium carbonate plugs at frequencies of 18–50 kHz. In the work of [18] on an experimental set-up, the authors restored the permeability of artificial rock samples clogged with inorganic substances ($CaCO_3$), paraffin deposits, drilling fluid, fine-grained substances, in situ fines, and polymers using ultrasonic vibrations. Deposits of inorganic substances such as KCl and NaCl are also removed from samples under the action of ultrasonic vibrations with a frequency of 22 kHz [19,20]. Ultrasonic impact destroys and removes the drilling fluid and completion fluid that clogged the pore space [21]. The value of the restored permeability is significantly affected by such parameters as frequency, specific power, duration of ultrasonic treatment, and the initial permeability of the core. Treatment at 20 kHz, compared to 18 kHz and 25 kHz, best restores the permeability of quartz and epoxy rock samples degraded by brine injection [22].

Despite the results achieved in the study of pore space removal from inorganic substances, there are very few experimental data among laboratory studies that could demonstrate the effect of nonlinear loads on the intensity of paraffin and asphaltene precipitation in rock and on the permeability of rocks during crude oil filtration.

Existing studies indicate that high-frequency nonlinear loading has a positive effect on the permeability of the rock in the presence of paraffins. For example, the pore space of the rock was unblocked, and the permeability was restored to 51% [23]. Sonification was allowed to restore from 50% to 75% of the permeability of alloxite discs with paraffin deposits [24]. Microwave and ultrasonic treatments can keep asphaltenes in a dispersed state to prevent deposition on rock walls [25]. Ultrasonic treatment accelerates the removal of unconsolidated sand from asphaltenes and helps reduce the viscosity of the filtering fluid [26]. When filtering gas through artificial quartz rock samples in the field of elastic vibrations at a frequency of 40 kHz, the permeability of the samples was restored by 30% [27]. Mechanical mixing provided by 20 kHz acoustic waves re-disperses the wax and restores the effective permeability of Berea sandstone samples to their intact state [28]. Due to the decrease in oil viscosity, interfacial tension, and microstructural changes in the rock, elastic vibrations have a positive enhancing effect on oil recovery during waterflooding [29] samples. Ref. [30] proposes to use nonlinear loading in conjunction with the injection of gas, liquid, or other chemicals. On the large-scale experimental rig [31], it was found that the nonlinear loads increase the fluidity of oil by a factor of 2–3 and increase the oil filtration rate through the porous medium by a factor of 1.2–1.5, arguing that narrow channels in the rocks of the borehole are unblocked (removed) from waxes and asphaltenes, clay particles, and other compounds.

Among state-of-the-art studies, 2D micromodels gain ground due to the visibility of the process. Using such a model, ultrasonic waves with a frequency of 20 kHz are able to remove the pore space from deposited asphaltenes, and the amount of removed asphaltenes

increases with increasing treatment time (sonication) [32]. The authors also showed that the geometry of the pore space significantly affects the efficiency of ultrasonic treatment. Using a micromodel with an ultrasonic device, the oscillations reverse asphaltene deposition on the pore wall and remove asphaltenes from the pore channel, increasing oil production [33]. Micromodels allow one to visually demonstrate the influence of a nonlinear load in a flat, artificially porous medium. At the same time, the pore space of the rock is much more complicated, and therefore it is of particular interest to evaluate the effect of nonlinear loading on a conventional core sample.

To study the influence of nonlinear loads on the filtration of a liquid in a porous medium, it is always required to build an experimental set-up containing a source of elastic waves. To study the fluid flow through rock samples under nonlinear loads [34,35], we made an attempt to design an experimental set-up. In this work, a laboratory rig is built, and the dependence of rock permeability and the intensity of paraffin and asphaltene precipitation on ultrasonic treatment are investigated. Section 2 describes the materials and methods used in this study. Section 3 presents the results obtained and their discussion, followed by a conclusion.

2. Materials and Methods

2.1. Materials

In this study, samples of consolidated sandstones (clastic rock) confined to the Visean stage of the Lower Carboniferous deposits are used as a medium through which the fluid is filtered (Figure 1). The rock was extracted from a depth of 2 km during drilling with the coring of production wells at an oil field in the Perm Territory (Russia). The field has low reservoir pressure near the wells (below the saturation pressure of oil with gas), as a result of which oil degassing already occurs in the reservoir. The consequence of this is also the release of paraffins and asphaltenes from the oil, which block the rock in the near-wellbore zone of the reservoir during oil filtration into the well. When preparing the plugs, the API [36] standard was used, according to which the samples were drilled perpendicular to the core, i.e., parallel to the bedding, extracted on a Soxhlet apparatus, and dried.

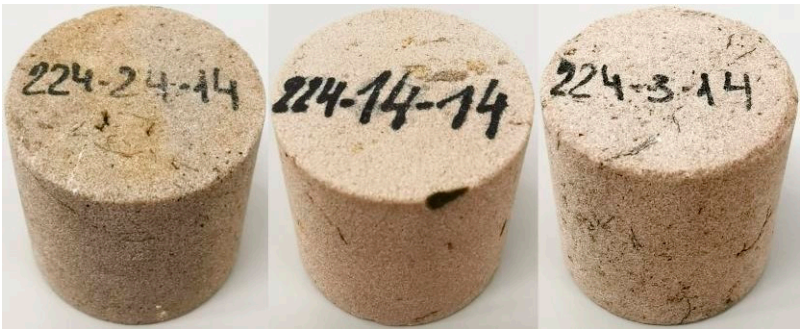


Figure 1. Sandstone plugs used in this study as filtering materials: medium permeability (224-24-14), high permeability (224-14-14), low permeability (224-3-14).

In order to evaluate the mineralogical composition of the rock under study, an ample sample from the same collection was used to prepare a powder sample and a thin section that were then used for an X-ray phase analysis performed on a D2 Phaser Bruker diffractometer and for a petrographic analysis performed on a polarizing microscope, the Olympus BX51, respectively. In terms of X-ray phase determination, in the bulk composition of the rock, quartz predominates, potassium feldspar is dominant among minor minerals, and kaolinite is present among clay minerals. In terms of petrography, the rock is fine- to medium-grained. The clastic part of the sandstone is dominated by well-sorted quartz grains of 0.2–0.5 mm; less common are rock fragments (quartzites and single fragments of clayey rocks) and pelitized feldspars. The cement is predominantly regeneration quartz with the formation of conformal structures. Kaolinite is developed unevenly in the pores, poorly crystallized, and with an admixture of hydromica. The rock is dominated by

indentation cementation, which is a cementless contact joint of grains, and a regeneration quartz joint of grains, which is characterized by a conformal structure. The pore space of the sandstone is unevenly represented by intergranular isolated and partially open hollow pores, presumably of secondary origin (formed by partial dissolution of a part of clastic fragments) of irregular shape, 0.08–0.5 mm in size. The mineralogical composition of the rock is given in Table 1. The microstructure of the rock is given in Figure 2.

Table 1. Mineralogical composition of the sandstone.

Mineral	Share on X-ray Diffraction	Share on Microscopic Analysis
Quartz	91.8%	92%
Potassium feldspar	6.6%	3%
Quartzite debris	-	4%
Kaolinite	1.6%	1%

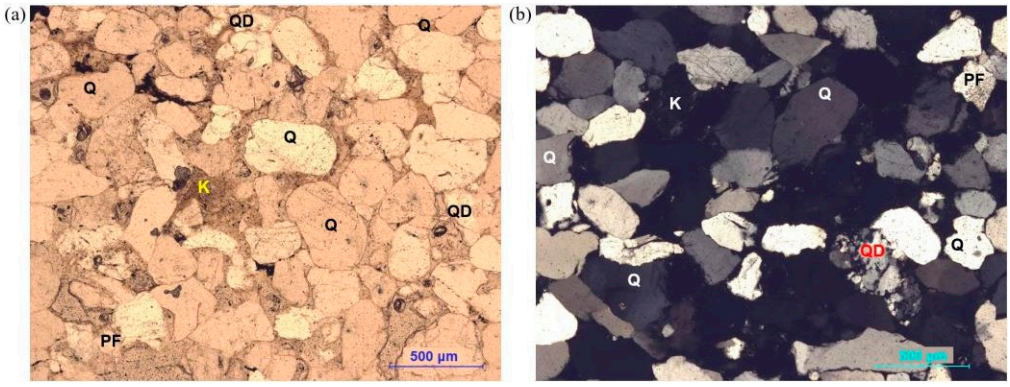


Figure 2. The microstructure of the sandstone obtained in transmitted light using crossed-nicol methods: (**a**) a fragment of a thin section with no analyzer used; (**b**) a fragment of a thin section with an analyzer used; Q is denoted to quartz, PF is denoted to potassium feldspar, QD is denoted to quartzite debris, and K is denoted to kaolinite.

The primary reservoir properties of the rock matrix were determined. Porosity was measured by weighing a dry and a water-saturated sample in air and water, and permeability was measured by gas using the Darcy method on a filtration system. The characteristics of the samples are shown in Table 2.

Table 2. Characteristics of the samples.

Parameter	224-24-14	224-14-14	224-3-14
Lithology	Sandstone	Sandstone	Sandstone
Permeability, mD	117	606	35
Porosity, %	16.9	17.5	16.7
Pore volume, cm^3	3.7	3.8	3.6
Plug size, mm	⌀30 *l*30	⌀30 *l*30	⌀30 *l*30

Crude oil containing paraffins and asphaltenes, obtained from wells in the same field as the samples, was used as a filtered liquid (Figure 3). The oil was additionally mixed to release residual associated gas. The density and dynamic viscosity of oil, measured at room temperature at 22 °C, were 836 kg/m3 and 3.3 mPa × s, respectively, which is generally regarded as relatively light. The black color of oil is a characteristic of the majority of mature oil and gas fields in the Volga-Ural oil-bearing province and is associated with the presence of oil resins in addition to paraffins and asphaltenes.



Figure 3. Crude reservoir oil sample before experiments.

The weight content of paraffins and asphaltenes in crude oil is 4.57% and 0.56%, respectively. The presence of paraffins and asphaltenes in the crude oil was established in the laboratory of chemical analysis as well as by light microscopy, according to which paraffin substances combine and reach 40 µm. Paraffin formations 15 µm in size are distinguished, as marked in Figure 4.

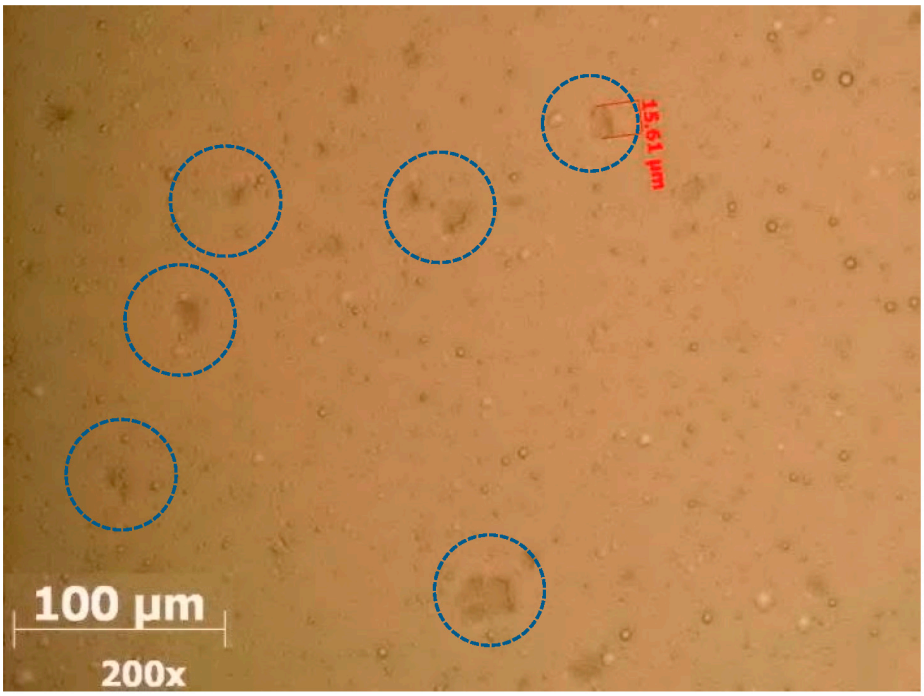


Figure 4. A microphotograph depicts the crude oil containing paraffin matter. The image was taken on an Axio Imager light microscope with an M2M tripod at 200× magnification.

2.2. Methods

The laboratory rig is a modified Auto Flood Reservoir Conditions Coreflooding System (AFS-300). The modification was made in the part of the liquid receiving chamber at the exit from the core holder. Such parts as a sleeve, a chamber, and a cover were manufactured for this study. The sleeve is installed in the core holder and pressed against the rock

sample. The sleeve is hollow and allows fluid to filter out of the rock plug into the chamber. The chamber is a hollow, conical part that is connected to the sleeve. The chamber has two nozzles, such as the upper one for the outlet of the filtered liquid to the back pressure regulator and then to the flow meter, and the lower one for emptying the chamber. The chamber is filled with the liquid coming from the plug. The chamber has a sealing cap at the end. An emitter of elastic waves is screwed onto the cap. The experimental method is as follows: First, the liquid filtered through the rock sample passes through the sample into the chamber. Then, due to the relatively large volume of 600 mL, to save time for the experiment, the chamber is manually replenished with the same liquid (crude oil). Next, at least three pore volumes are filtered, and a trend is set for a decrease in the permeability of the rock due to blocking the pore space of the sample by paraffins and asphaltenes.

Then, to observe the effect of the nonlinear load during filtering, the actuator of elastic waves (nonlinear load) is activated. As a result of the reciprocating motion of the actuator elements, a nonlinear load of a given frequency is created on the chamber cap. Cap vibrations are transmitted through the fluid filling the cone chamber through the sleeve to the end of the rock sample, after which the vibrations (elastic waves) further propagate through the matrix and fluid into the pore channels (the effect of a solid and liquid piston) [37]. The activation of nonlinear loads leads to a change in the permeability of the rock plug. The modernized design of the rig simulates the inflow of fluid from the formation into the well, in which the actuator for elastic waves is installed, which sends nonlinear loads to the near-wellbore formation zone towards the filtering oil. Improvements are shown in Figure 5. The principle of operation of the Langevin emitter is based on the ability of the material (crystals) of a piezoceramic element to change its dimensions in an electric field (also known as the inverse piezoelectric effect and similarly used as in the experiments by [38]). The actuator is characterized by one dominant frequency, at which it produces the maximum amplitude of reciprocating motion (enters into a resonance state). Therefore, the cap is made in such a way that it allows the actuator to be changed to study the filtration at different frequencies of a nonlinear load. The nonlinear signal is modulated on a Rigol DG1022 oscillator. Due to the low amplitude of the signal from the generator, a custom-built amplifier is used, which increases the signal amplitude to the maximum possible at the resonant frequency. The control of the frequency and amplitude of the signal received after the amplifier and coming to the actuator is carried out using the Hantek6204BD oscilloscope and a workstation.

In the experiments, the rock sample is in a state of all-round compression. With the help of a rubber cuff, an overburden stress is created in the core holder, simulating the rock pressure of 1000 psi (or 6.9 MPa). With the help of pumps supplying liquid to the ample inlet, a pore pressure of 100–150 psi (or 0.7–1.0 Mpa) is created, while the back pressure regulator maintains pressure at the sample outlet. To determine the ermeability in laboratory conditions on a flooding system, it is customary to use Darcy's law [39], which defines permeability as the area of pores in a section S of a sample l long, occupied by a liquid with dynamic viscosity μ, when it is filtered with a flow rate Q through a rock sample, at the ends of which a pressure difference is created between the pressure at the inlet to the sample and the pressure at the outlet of the sample ΔP

$$k = \frac{Q \times \mu \times l}{S \times \Delta P}, [D] \quad (1)$$

In experiments, the liquid flow rate Q at the inlet to the sample is set, and the pumps maintain it at a set level. As a result of hydraulic resistances, the pressure at the sample outlet P_{out} is lower than the pressure at the input P_{in} into the sample. The differential pressure gauge registers the difference between pressures $\Delta P = P_{in} - P_{out}$, which is used to calculate the current permeability k of the sample on the filtering liquid.

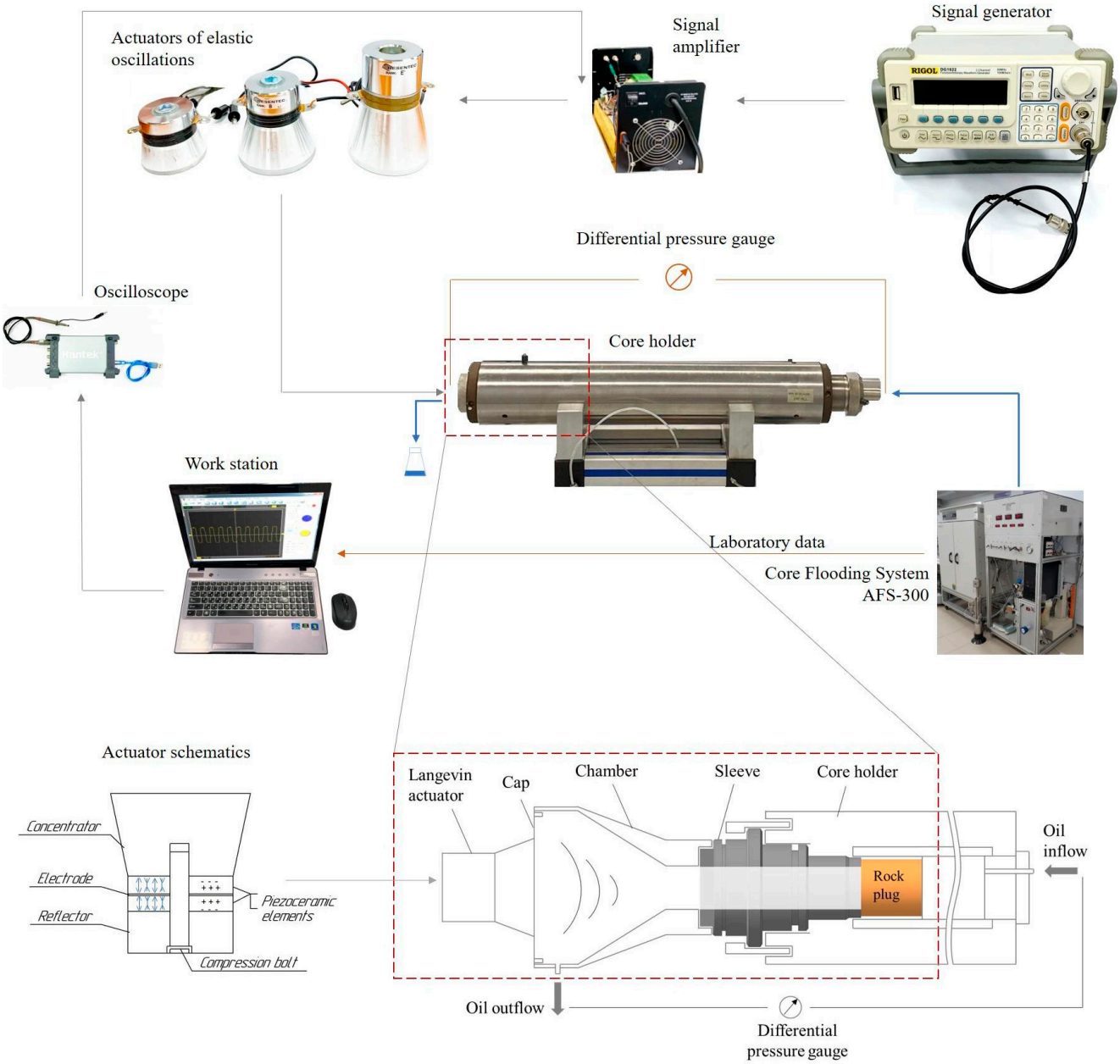


Figure 5. The schematics of the modified core flooding system.

One of the tasks during the experiment is to prevent the bleeding of liquid from the chamber into the outlet when creating a nonlinear load from the actuator. For this purpose, the back pressure regulator is used, which is a membrane on one side of which pressure is injected, preventing the penetration of liquid into the outlet pipe. Thus, most of the energy from elastic waves is transferred to the sample along with the filtering liquid, which has a greater effect on the permeability of the rock. Before the start of each experiment, three pore volumes are pumped through the sample to establish the filtration regime. Further, during the experiment, the flow rate was maintained constant. The experiment on each sample lasts up to two hours, during which there are stages of activation and deactivation of the actuator as well as changes in the frequency of exposure to elastic vibrations.

A general view of the experimental rig located in the laboratory of the Department of Oil and Gas Technologies of the Perm National Research Polytechnic University is shown in Figure 6.

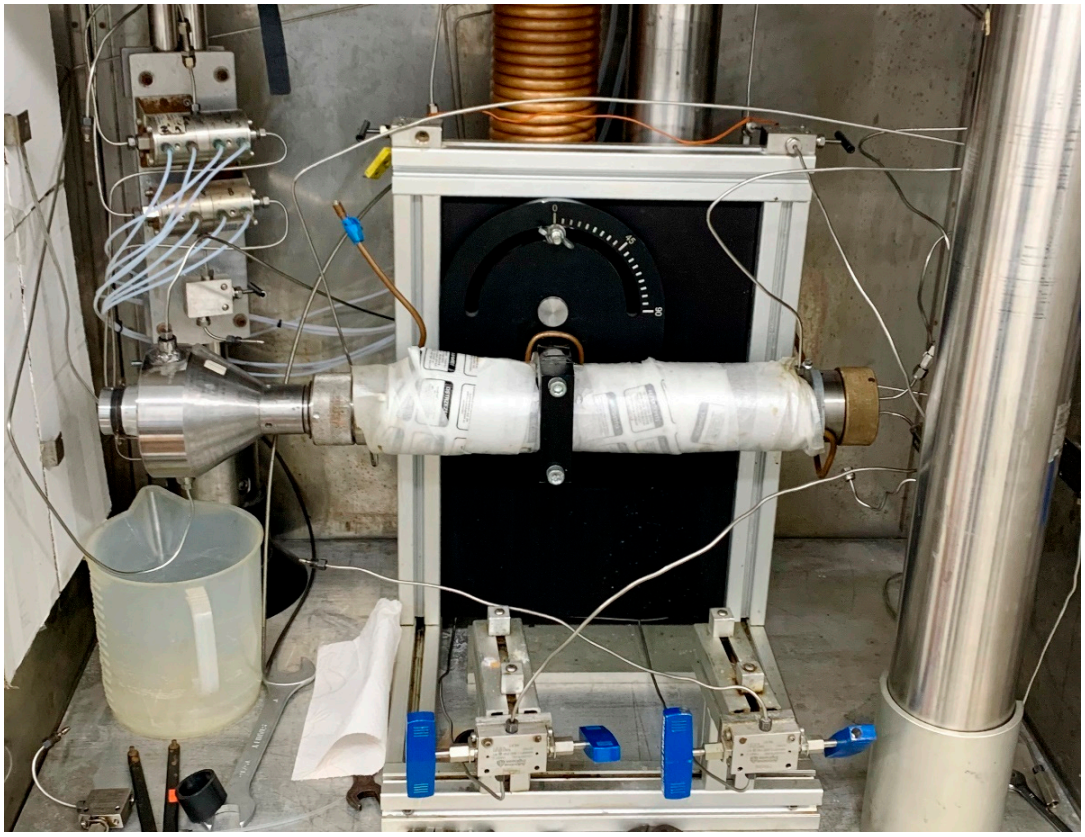


Figure 6. A photograph depicting a general view of the experimental rig.

For the experiment on the filtration of distilled water in the presence of residual oil, the sample is first saturated with kerosene by the vacuum method. After filling the open pores with kerosene, the sample is placed in the AFS-300 core flooding system, and oil begins to filter through it. When injected, oil first dissolves in kerosene and then completely replaces it. An indicator of the complete replacement of kerosene by oil is the stabilization of the permeability of the sample. Further, as a result of the long-term filtration (displacement) of water, residual oil saturation is created. An indicator of the formation of residual oil saturation in the plug is the absence of oil at the outlet of the sample (watering of the flow of the outgoing liquid). The developed rig can also be used to study the effect of nonlinear load on the filtration of other fluids, including changes in rock permeability during colloid migration [40,41].

3. Results and Discussion

Laboratory experiments included two types of studies. The first experiment is aimed at studying the effect of a nonlinear load on water filtration in the presence of residual oil saturation in the sample. The second experiment is aimed at studying the effect of a nonlinear load on single-phase oil filtration.

3.1. Residual Oil Mobilization

A medium-permeability sample was used to study the effect of nonlinear loading on water seepage in the presence of residual oil. When actuators are activated, the permeability of the rock increases linearly (Figure 7). The most intensive permeability increase Δk from the initial value k_0 is observed when treating the sample with an ultrasonic frequency ω of 28 kHz (slope or tan β = 2.22). In comparison with other frequencies at 28 kHz, the permeability reaches its maximum value, and the increase in permeability reaches 14% (see Table 3).

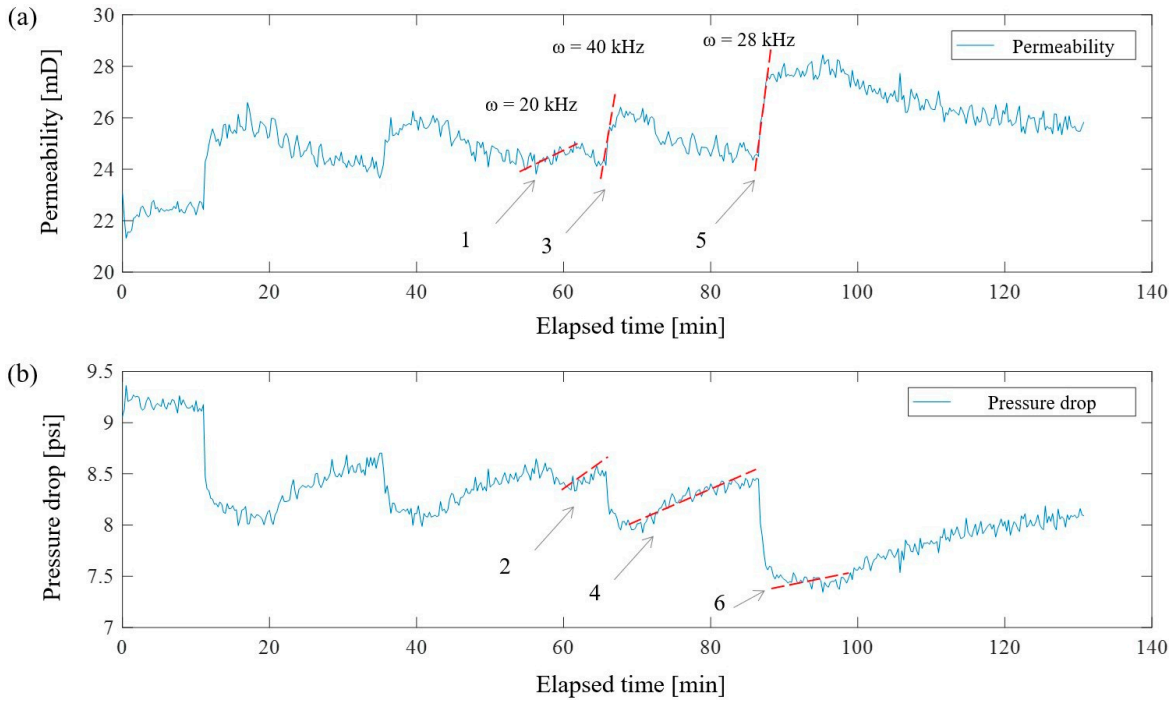


Figure 7. Graphs of changes in filtration parameters during the use of distilled water in the presence of residual oil: (**a**) permeability; (**b**) pressure drop. Segments 1, 3, and 5 correspond to sample treatment at 20 kHz, 40 kHz, and 28 kHz; sections 2, 4, and 6 correspond to turning of treatment and restoring filtration.

Table 3. Results of experimental data processing.

ω, kHz	tan β	angle β	k_0, mD	Δk, mD	%
40	0.87	41	24	2.2	8.4
20	0.13	7.4	24	1	4
28	2.22	65.8	24	4	14

Figure 7 shows that a linear increase in permeability corresponds to a linear decrease in pressure drop (since the Darcy filtration law is linear). After turning off the actuator, the filtration regime is restored; however, the permeability and pressure drop no longer return to their previous values; the permeability now remains at a value higher than it was before the activation of the nonlinear load, and the pressure difference has a value lower than before the activation of the actuator. In the time interval after the second hour of the experiment, these parameters reach asymptotic values, which indicates the opening of new filtration channels in the sample.

After nonlinear loading, an additional amount of oil was released from the sample (Figure 8), which indicates an increase in displacement efficiency and a decrease in residual oil saturation in the sample. Distilled water, which was clear before treatment, has taken on an oily hue. Also, drops of oil are observed in distilled water, which most likely formed (dispersed) as a result of cavitation in the cone. In order to study the highest permeability achievable, the experiment was continued the next day under the same conditions. During the treatment, the permeability of the sample increased from 26 mD to 32.5 mD (20%), and in total, the permeability increased by almost 10 mD compared to the initial value of permeability (see Figure 7a) obtained after a long displacement of crude oil by distilled water without nonlinear effect (Figure 9). At the same time, the peak permeability reaches 34 mD at a pore pressure of 98.6 psi (or 0.68 Mpa).

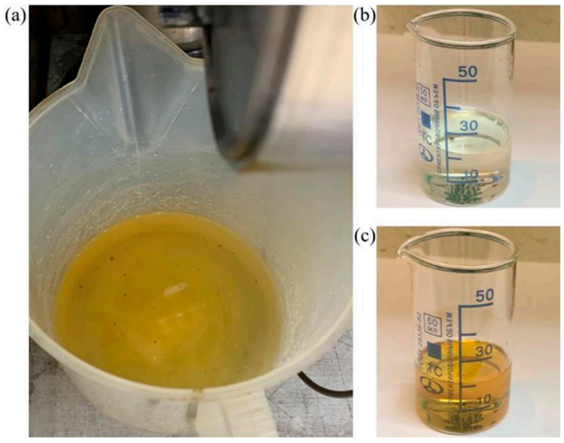


Figure 8. Displaced residual oil from the sample during water injection: (**a**) colored distilled water and oil droplets at the outlet of the sample; (**b**) a solvent (gasoline) before washing the rig parts; (**c**) a solvent after washing the rig parts.

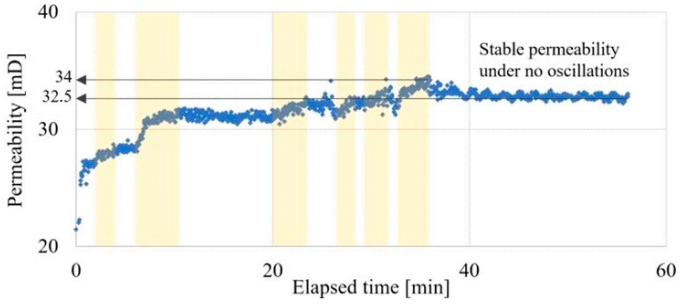


Figure 9. Graph of the water permeability of a rock sample increasing under nonlinear loading in the presence of residual oil inside the rock sample. The six stages of nonlinear load activation are highlighted in yellow. After activation stages, the permeability tends to decrease, and it stabilizes after the final stage of activation, corresponding to the removal of the maximum amount of trapped residual oil able to be moved by the effect of nonlinear loads.

The results of the experiment demonstrate the effect of nonlinear loading on the involvement of previously undrained oil in filtration. It can be seen that the impact of an onlinear load contributes to an increase in the mobilization of capillary-trapped oil and an increase in water permeability.

3.2. Intensification of Single-Phase Filtration

In their work, ref. [42] distinguishes three forms of rock deterioration in the near wellbore zone: physical blocking of the pore space (damage to permeability), change in wettability, and increase in viscosity (formation of emulsion). Given that in our experiment there was no fluid replacement but single-phase filtration was performed at a constant temperature and relatively constant pressure, a change in the wettability of the sample during the experiment is unlikely. Due to the filtration of single-phase oil during the experiment, the occurrence of an emulsion in the sample itself is also unlikely. In this connection, the physical blocking of pore channels by particles of asphaltene and paraffin is considered the main form of permeability deterioration. Despite the fact that some papers indicate that the increase in permeability is associated with the development of internal cracks and deformations in the rock [16], it seems to us that such an effect on consolidated rock samples is unlikely. Given that the sample in the rig is in a compressed (by cuff) state, it is possible that new cracks will not be able to open. In this study, the nonlinear load is not characterized by high amplitudes; therefore, deformation of consolidated rock samples is hardly possible, and the main mechanism for restoring permeability is unblocking of the pore space.

3.2.1. Medium-Permeability Sandstone

In the experiment, a liquid of one phase (oil) is filtered through a sandstone plug of medium permeability. The oil contains paraffins and asphaltenes, which block the pore channels of the sample. During the experiment, a number of activations and deactivations of the nonlinear load were performed. In this case, depending on the moment of time when activation is performed, the effect of nonlinear loads is different. Figure 10 shows graphs of changes in experimental data.

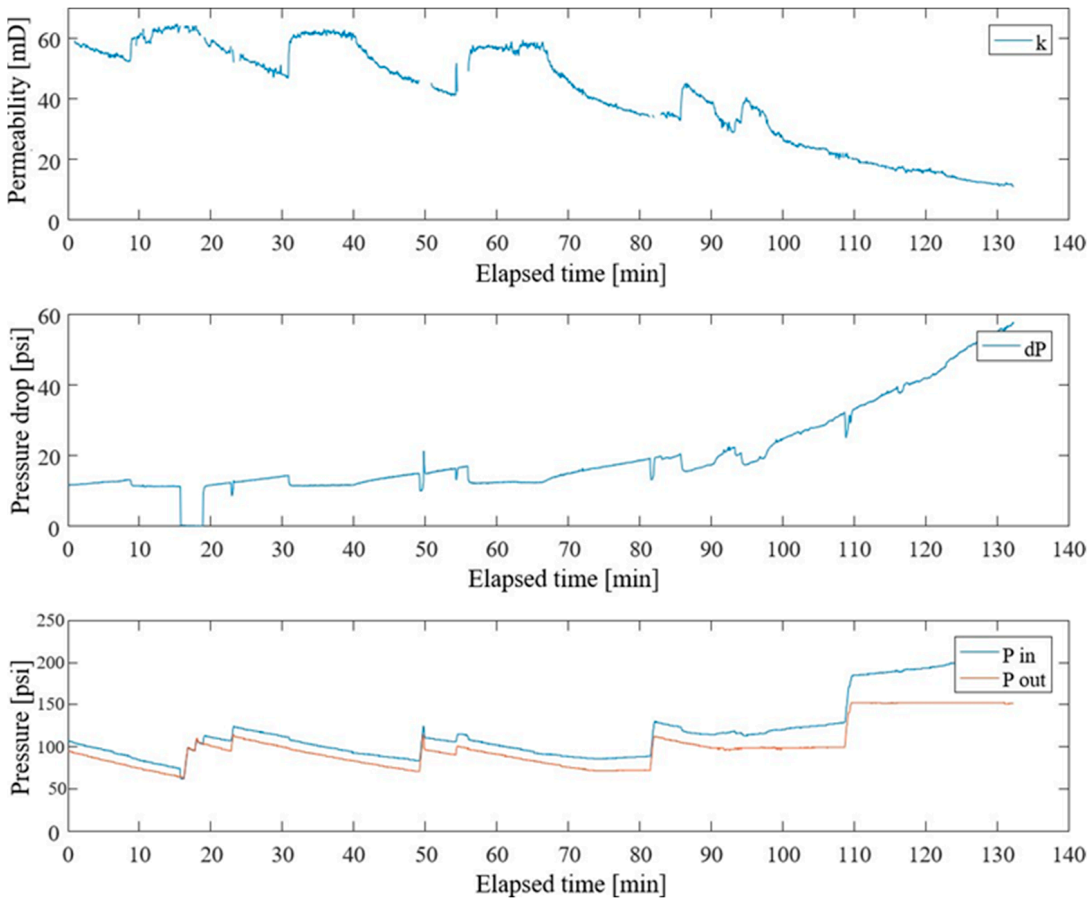


Figure 10. Graphs of experimental parameters during crude oil filtration (medium permeability sandstone).

Figure 10 shows that the permeability changes in proportion to the pressure drop. In turn, the pressure drop is caused by the difference between the pressure at the inlet of the sample and the pressure at the outlet of the sample, as shown in the bottom panel of Figure 10. Looking at the moments of activation of the emitter, for example, at the 31st minute (second activation), one can see that permeability increases sharply by 25%. This jump is due to the fact that the pressure at the inlet of the sample and the pressure at the outlet of the sample do not change in the same way. At the moment of activation of the nonlinear load, the pressure at the inlet of the sample decreases more significantly than at the outlet of the sample (Figure 11).

By lowering the pressure more significantly at the inlet than at the outlet, the pressure drop is reduced. Reducing the fluid pressure at the sample inlet seems logical. It can be assumed that the nonlinear load contributes to the unblocking of the pore space from accumulations of paraffins and asphaltenes in the narrowing of the pore channels (pore throats), i.e., more space is opened up for fluid filtration at the same flow rate, resulting in fluid filtration not requiring the initial high inlet pressure to be maintained.

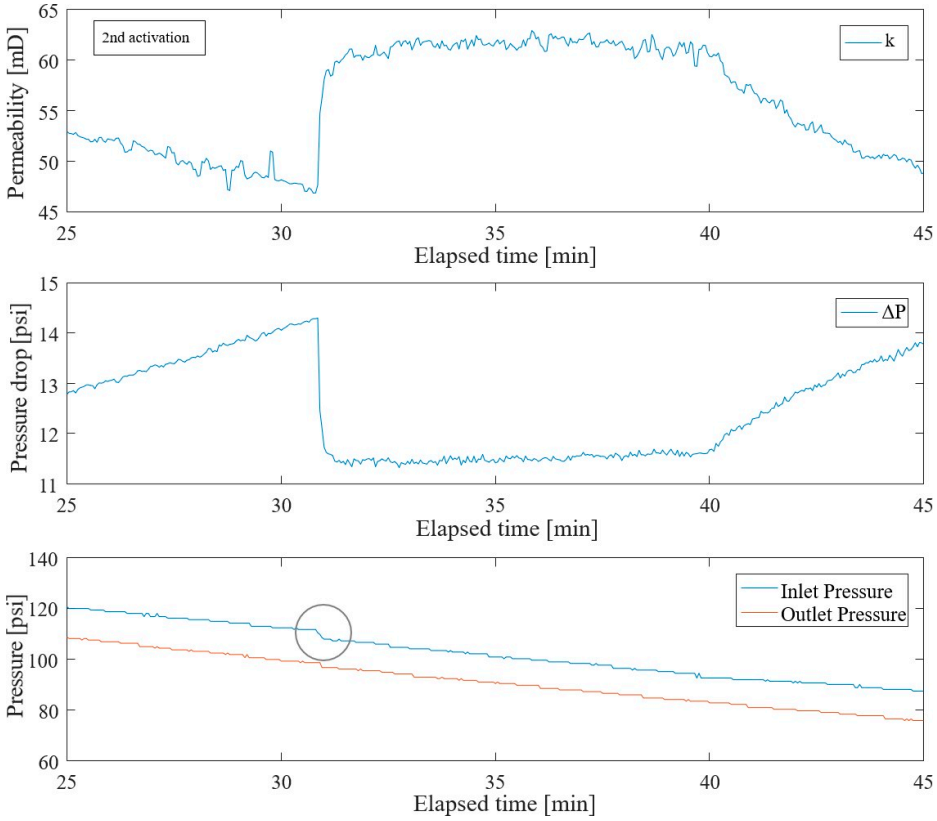


Figure 11. Graphs of experimental parameters at the 31st minute.

Figure 12 shows a plot of the change in permeability throughout the experiment. Analysis of the graph provides three observations that can be distinguished, as described below.

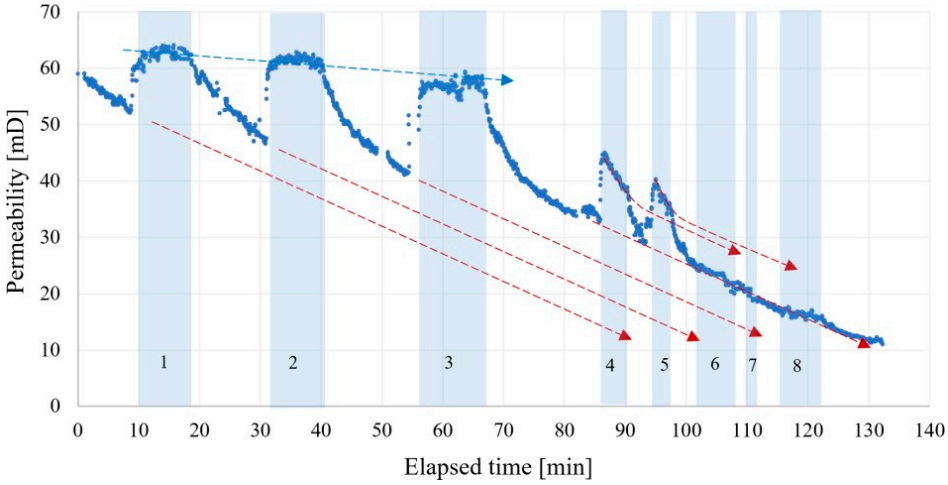


Figure 12. Graphs of change in sample permeability during crude oil filtration (medium-permeability sandstone). The red arrows show the general trend towards a decrease in the permeability of the sample as a result of blocking the pore space. The periods of activation of the nonlinear action are highlighted in blue.

Observation 1: When oil containing paraffins and asphaltenes is filtered, the permeability deteriorates.

From the start of the experiment to the end of the experiment, the permeability decreased six times from 60 mD to 10 mD. It is interesting to note that elastic fluctuations affect the permeability decrease trend only at the beginning, where the permeability de-

creases in accordance with the exponential law. In the future, the graph will become linear with each activation and deactivation of elastic vibrations (this is most noticeable after 1–5 deactivations). The decrease in permeability is most likely due to the deposition of paraffins and asphaltenes in the pore space throats, as a result of which it is more difficult for oil to enter the pore channel, which eventually becomes completely blocked and fluid filtration in it stops. Further, it will be shown that with longer filtration, the pore space of the sample becomes completely blocked.

Observation 2: The activation of a nonlinear load during the filtration of oil containing paraffins and asphaltenes contributes to the restoration of permeability.

From the point of view of the nature of the change in permeability upon activation of a nonlinear load, three observed effects can be distinguished. The first effect is the restoration of the permeability to some value close to the initial value and its maintenance at a constant level. The first three activations correspond to this effect. Despite the decrease in the permeability of the sample deposited in the pore space of paraffins and asphaltenes, before the third (as well as before the 1st and 2nd) activations, the permeability in the presence of nonlinear loading is restored from the current value k_b (permeability before) to the value k_a (permeability after), which is almost the original value of 60 mD. This effect can be explained by what happens in the pore space. At the beginning, when filtration proceeds without the nonlinear load applied, part of the paraffins and asphaltenes are deposited in the constrictions between the grains that make up the rock. After a nonlinear load is activated, these accumulated paraffins and asphaltenes, as a result of the relative displacements of the matrix and the liquid, are separated and carried away by the flow of the filtering liquid, which leads to the restoration of the permeability Δk to its initial value. A similar mechanism is also described in [11]. At the same time, due to the underrecovery of permeability, there is still a trend towards its decrease. This is primarily due to the duration of the previous filtration without nonlinear loading t_b. Table 4 shows that with an increase in the duration of the previous filtration without treatment, the achievable value of the restored permeability decreases, despite the fact that the permeability returns from a deeper drop (permeability gain increases).

Table 4. Results on increased permeability of the first effect.

t_b, min	$k_b \ldots k_a$, mD	Δk, mD	ω, kHz
9	from 52 to 62	10	20
12	from 48 to 61	13	20
15	from 40 to 58	18	20

At the same time, the duration of activation does not affect the oil permeability k = const. Permeability fluctuations in the second half of the shelf of the 3rd activation are related to the search for the most effective frequency (20 kHz, 2 kHz) to try to increase the permeability (which did not happen). With a further increase in the filtration time without 4 linear loads applied, a certain threshold value of permeability is reached, after which non-linear loading is no longer able to restore and maintain the permeability. It can be seen that after the injection of a significant amount of pore volume in the interval of 67 to 85 min, the nonlinear load is not able to unblock the pore space of the rock. The effect of permeability reduction during filtration in the presence of nonlinear loading is the second observed effect, which corresponds to the 4th and 5th activations of the actuator. Apparently, by this moment, the pore space was blocked quite strongly, and, during liquid filtration, paraffins and asphaltenes continued to accumulate in intergranular channels, but part of the paraffins and asphaltenes, due to the resulting oscillations of the matrix, still came off and was carried away in the liquid flow, as a result of which an increase in permeability of 12 mD was observed (Table 5).

Table 5. Results on increased permeability of the second effect.

t_b, min	$k_b \ldots k_a$, mD	Δk, mD	ω, kHz
19	from 33 to 45	12	28
4	from 30 to 40	10	20

The subsequent 5th activation led to an increase in permeability of only 10 mD, although the previous filtration without a nonlinear load applied was only four minutes. If we extend the curve of permeability reduction during artificial nonlinear loading, we will see that soon the permeability will reach a very low value (as it happened in the 130th minute) and then might stop completely due to blockage.

The third effect is characterized by minimal restoration of permeability under nonlinear loading by an actuator from 20 to 40 kHz. It seems to be due to the fact that paraffins and asphaltenes accumulated in constrictions create a sufficiently strong structure in the pore space, and the combined effect of the energy of the fluid flow and the energy of vibration of the pore wall under nonlinear loading is not enough to overcome the strength of paraffins and asphaltenes and push it through. Permeability was also not sensitive to a 50 psi increase in pore pressure.

Observation 3: Delaying the activation of a nonlinear load does not restore the permeability to its original value.

Figure 12 demonstrates the inevitable decrease in permeability once the filtration of oil is performed without elastic vibrations. If elastic vibrations are imposed on the rock and liquid at the initial moment of filtration, then the porous space of the rock will be preserved from the deposition of paraffins and asphaltenes. This means that the permeability would remain at 60 mD throughout the entire run. This assumption requires laboratory confirmation, for which an additional experiment will be carried out. However, already from the current experiment, it is clear that the permeability is constant up to 12 min.

3.2.2. Low-Permeability Sandstone

In an experiment on a rock of low permeability, the nonlinear loading was less effective. The initial permeability of the sample was 35 mD. Despite periodic recovery, the permeability still decreased to 30 mD (Figure 13). At the beginning of the experiment (up to 20 min), the flow rate was set on a sample of medium permeability, and an intense decrease in permeability was observed. The explanation for this effect was a more intense blocking of the pore space of the sample, associated with a smaller cross section and the number of pore channels, at the same linear rate of oil filtration through the sample. To create conditions similar to those of the medium permeability sample, the oil flow rate was reduced to 0.28 mL/min, so the linear oil filtration rate was proportional to the oil filtration rate in the high permeability sample.

In comparison with the experiment on a high-permeability sample, the greatest effect on a low-permeability sample was achieved at a frequency of 40 kHz. A possible reason is that with increasing frequency, the wavelength decreases and the impact begins to be exerted on grains with a smaller size, resulting in a more intense pushing of paraffins and asphaltenes between the oscillating walls of the matrix.

3.2.3. High-Permeability Sandstone

In the experiment on a high-permeability sandstone sample, the oil flow rate was 2 mL/min. When conducting experiments in the absence of nonlinear loading, a trend of increasing pressure gradient is clearly distinguished (for example, in the range from 0 to 10 min) (see Figure 14a). This corresponds to the gradual accumulation of paraffins and asphaltenes in the narrowing of the pore channels.

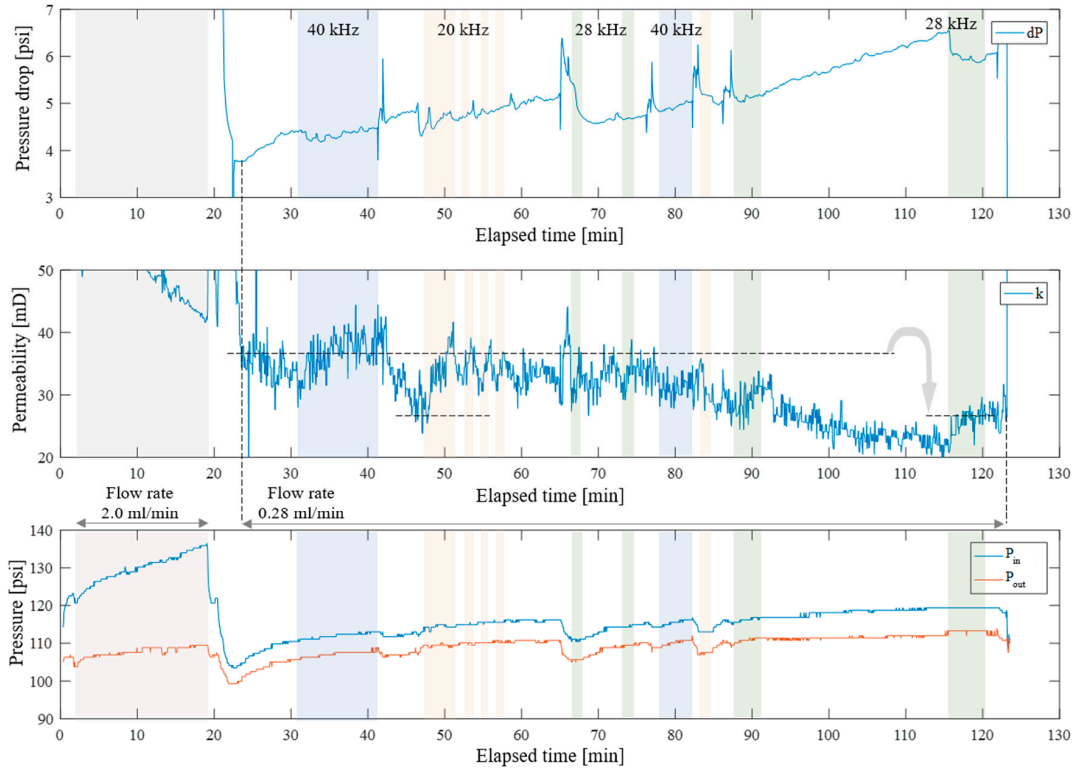


Figure 13. Graphs of experimental parameters during filtration of crude oil containing paraffins and asphaltenes (low permeability sample). Despite a series of different frequency activations of nonlinear loading, permeability decreased.

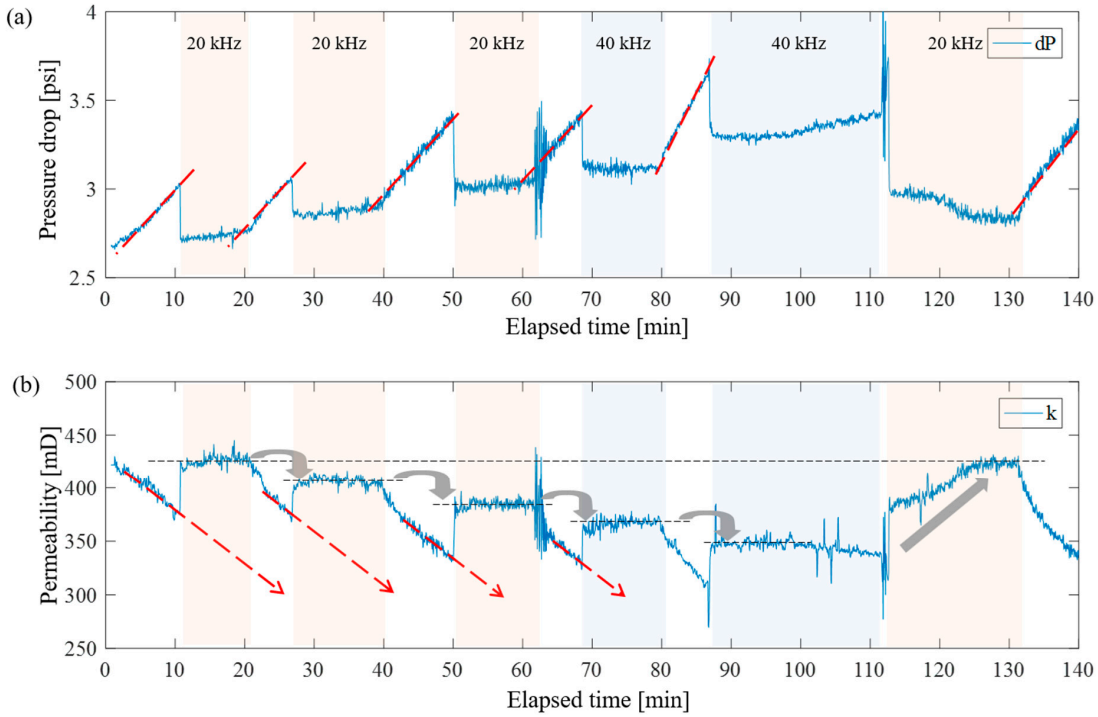


Figure 14. Graphs of experimental parameters during filtration of oil containing paraffins and asphaltenes (high permeability sample): (**a**) pressure drop; (**b**) permeability. The red arrows show the trend towards a decrease in permeability due to blocking of the pore space of the plug by para-ns and asphaltenes, corresponding to filtration without the impact of a nonlinear load. The permeability is restored to its original value.

During the transfer of oscillatory acceleration to the rock, the rock wall is displaced relative to the deposited (precipitated) paraffins and asphaltenes, as a result of which the energy of adhesion of paraffin and asphaltene particles between themselves and the wall occurs and the separation (pushing) of paraffins and asphaltenes through the pore channel occurs in the flow of oil.

It can be seen that artificial variable loading removes most of the pressure drop caused by pore blocking and restores permeability. At the same time, up to 110 min, a slight trend towards pore blocking is observed. The effect of changing the frequency from 40 kHz to 20 kHz on the filtering mechanism is clearly observed. Combining exposure at frequencies of 40 kHz and 20 kHz, a decrease in pressure drop and restoration of the sample permeability to the initial value of 420 mD (Figure 14b) were achieved, although during the experiment the permeability decreased to 340 mD.

Additionally, in this work, an experiment was set up to filter oil with a high content of paraffins and asphaltenes through a sample of medium permeability. In view of the large number of particles in oil, they combine and create large structures (Figure 15), which intensively block oil filtration channels in the pore space of the rock, as a result of which the permeability of the rock is reduced to zero (Figure 16). At the same time, the activation of a nonlinear load does not have any effect on the permeability.



Figure 15. There are large associations between paraffins and asphaltenes in crude oil and their high concentrations.

3.3. Model Interpretation

When filtering oil, paraffins, which are long molecular chains of a linear or branched form [43] capable of combining, are in a collapsed state. When they get into the pore throats, comparable to the size of paraffins and asphaltenes (or several linked molecules), they do not pass further but accumulate in front of the impassable area. This leads to a decrease in the flow area of the channel, an increase in the pressure of the injected oil at the entrance to the sample, and, accordingly, a decrease in the permeability of the rock. In the absence of a nonlinear load on the sample, paraffins and asphaltenes completely block channels of small diameter at first (comparable to the particle size of paraffins and asphaltenes and less), and then they can block channels of large diameter, which eventually leads to a filtration stop (Figure 17a).

In the case of the activation of variable loading, elastic vibrations propagate through the sample matrix and lead to its elastic deformation (high-frequency, low-amplitude compression and expansion). The resulting vibration leads to the relative motion of the rock walls and the paraffins and asphaltenes located in the constrictions. As a result of relative motion, paraffins and asphaltenes are compacted and pushed by the flow of filtered

oil deep into the sample. On their further path, paraffins and asphaltenes enter new pore channels and can either block them (if the pore throat size is much smaller than the size of paraffins and asphaltenes) or be filtered without restrictions or influence on permeability (Figure 17b).

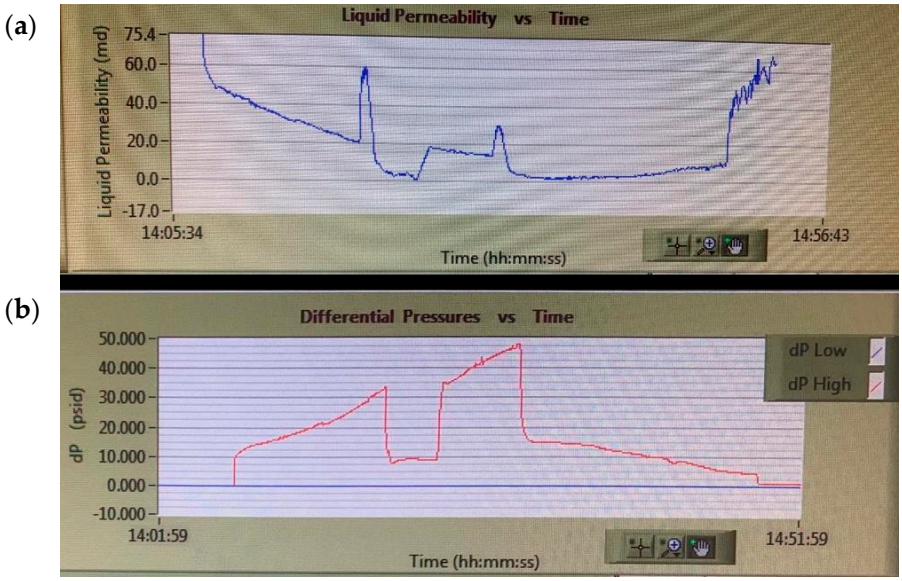


Figure 16. Experimental data in the filtration of crude oil with a high concentration of paraffins and asphaltenes: (**a**) permeability; (**b**) pressure drop.

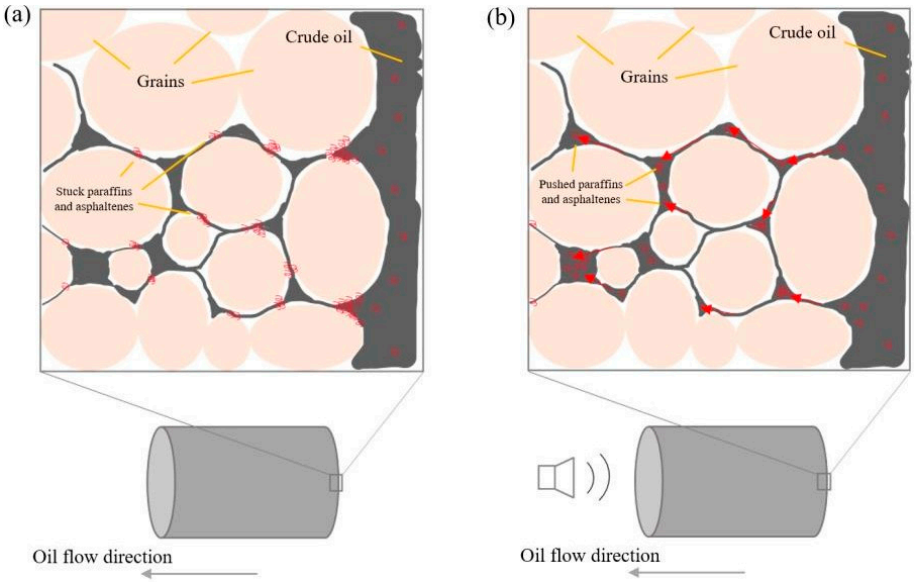


Figure 17. The nature of the removal of paraffins and asphaltenes in the pore channels (schematically): (**a**) accumulation of paraffins and asphaltenes stuck in pore throats during crude oil filtration with no nonlinear load applied; (**b**) pushing paraffins and asphaltenes through the pore throats with the oil ow with a nonlinear load applied.

The creation of a mathematical model that would describe the effect of a nonlinear load on the intensity of paraffin and asphaltene deposition during the filtration of crude oil through rocks is a task that would allow us to interpret the experimental results obtained in this work and transfer them to the scale of the near-wellbore formation zone (near the production well). To date, among the existing models, a work by [6] can be distinguished that proposes a mathematical model that describes the deterioration of permeability and porosity of rock near a production well due to the deposition of paraffins caused by a

decrease in reservoir pressure, as well as the effect of deterioration in permeability on the well flow rate. At the same time, models that would describe the effect of changing the permeability due to the impact of nonlinear loads are not widespread. Comparing with the Near Wellbore Formation Damage Model proposed by [6], the results of the present study suggest that the intensity of the paraffin and asphaltene flocculation and precipitation in the pore space of near-wellbore rocks would be decreased if the nonlinear load were applied to the wellbore surface. The degree of damage (DOD) to permeability would be lower, resulting in the restoration of permeability in eqn. (20). The skin factor would be lower accordingly, and reservoir pressure (see pressure profile in Figure 7) would be decreasing at a lower rate towards a production well (and would not fall sharply very near the well) if elastic waves, activated from a well, propagated towards a reservoir. Using the results obtained in the present paper and considering the radius of nonlinear load influence around the well, the mentioned model could be supplemented, describing the recovery of permeability and production rate by implementing nonlinear loads in the case of the production of crude oil containing paraffins and asphaltenes.

The potential application of the results obtained can be found in the field of oil production, especially to enhance oil recovery at wells with low formation pressure and paraffins presented in crude oil concentration. Those are usually the reasons for blockage of the pore space in the near-wellbore zone since there is a flocculation phenomenon observed near the well that degrades the permeability and decreases the well rate. The results obtained in the present study would be useful for understanding the effect of vibrations on rock permeability. In order to unblock the pore space, well tools may be developed that could help production engineers fight paraffin precipitation in near-wellbore rock.

4. Conclusions

Experimental studies on the influence of nonlinear rock loading on its permeability during fluid filtration are carried out. Three types of sandstone taken from the reservoir were used as a filtering medium: low, medium, and high permeability. Waxy oil from the same field was used as the filtered fluid. For this study, an experimental set-up was created that simulates the influx of fluid from the formation into the well, in which an elastic wave actuator is installed, which sends nonlinear loads to the near-wellbore formation zone towards the filtering oil. Based on the results of this study, the following conclusions can be drawn:

(1) The impact of a nonlinear load on the rock, through which crude oil containing paraffins and asphaltenes is filtered, contributes to a change in the permeability coefficient of the rock. In the case of samples of medium and high permeability, when elastic vibrations are activated, the permeability of the rock is restored.
(2) This paper developed the idea that during the filtration of paraffin and asphaltene-containing oil, particles block the pore space and are deposited in pore throats. To unblock the pore space, there is an artificial nonlinear loading, as a result of which an impulse is transferred to the rock sample by elastic vibrations, which leads to a relative displacement of the pore channel wall and paraffin and asphaltene accumulations. Having overcome the force threshold of adhesion of deposits to the wall, with the help of oscillatory acceleration, paraffin and asphaltene particles are torn off and carried away (pushed) further along the channel by the oil flow.
(3) In the case of irreversible deterioration of a part of the permeable channels, the impact of a variable load contributes to postponing the moment of blocking the remaining part of the channels and maintaining the oil flow at a constant level.
(4) The impact of nonlinear loading has no significant effect in the case of already existing strong blockage of permeable channels, high concentrations of paraffins and asphaltenes, or when the wax sizes are comparable to the size of the pore channels (rock of low permeability).

Author Contributions: Conceptualization, M.G.; methodology, E.R.; investigation, E.R. and E.G.; data curation, E.K.; writing—original draft preparation, E.R.; writing—review and editing, E.R.; visualization, Q.Y.; funding acquisition, M.T. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to acknowledge the generous financial support from the Russian Science Foundation (Project No. 23-19-00699, https://rscf.ru/project/23-19-00699/).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Research data are not available for sharing.

Conflicts of Interest: The authors declare no conflict of interest.

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