

Experimental and Theoretical Evaluation of Hydrodynamic-Acoustic Stimulation for Injectivity Recovery in Uranium ISL Wells

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Abstract

A decrease in the permeability of the filter and near-filter zone of technological wells is one of the main factors reducing the efficiency of uranium in-situ leaching in hydrogenic deposits. This study proposes a technological scheme for hydrodynamic-acoustic stimulation of the near-filter zone based on the use of a flow-pulsation emitter equipped with a self-rotating valve. The Sabyrsai, Ketmenchi, and Sugraly uranium deposits were considered as objects for the computational adaptation of the proposed technology, as they represent different geotechnological conditions: repeated development of an infiltration-type deposit, pilot in-situ leaching cells with known filter-interval parameters, and complex carbonate-bearing conditions of a sandstone-hosted deposit. Based on Biot's poroelasticity theory, Darcy's law, a radial acoustic pressure attenuation model, and a safe-stimulation criterion, the mechanisms responsible for the recovery of filtration properties were substantiated. These mechanisms include the disintegration of weakly cemented clogging material, mobilization of fine dispersed particles, reduction of the skin factor, reactivation of existing microchannels, and intensification of mass transfer between the leaching solution and the ore-bearing rock. It is shown that the low-frequency range of 10–50 Hz is the primary range for deformation–filtration effects in water-saturated porous media, whereas frequencies above 500 Hz may be regarded as a local mechanism for filter cleaning and near-wellbore stimulation. A technological scheme, calculation dependencies, a parameter matrix for hydrogenic uranium deposits, a pilot-scale validation program, and digital algorithms for graph generation were developed. The obtained results provide a scientific and methodological basis for subsequent laboratory and field verification of hydrodynamic-acoustic stimulation of uranium in-situ leaching wells.

1. Introduction

Uranium in-situ leaching is one of the most technologically significant methods for developing hydrogenic deposits, as it enables metal recovery without conventional ore extraction to the surface. The technological efficiency of this process is determined by the stability of leaching-solution circulation within the “injection well–productive formation–production well” system, preservation of the hydrodynamic contour of the operational block, and stability of the filtration properties of the ore-bearing horizons [1, 2].

During long-term operation of in-situ leaching wells, the filtration capacity of the near-filter zone gradually deteriorates. The main causes include mechanical particle migration, precipitation of secondary mineral phases, changes in acid–base and redox conditions, and the formation of ferruginous, carbonate, sulfate, and biogenic deposits [3–7]. Clogging increases hydraulic resistance, raises injection pressure, reduces the injectivity of injection wells, decreases the flow rate of production wells, and worsens the uniformity of leaching-solution coverage within the ore body.

Various methods are used to restore filtration properties, including chemical treatment, hydrodynamic flushing, airlift cleaning, impulse, electro-discharge, vibration, and acoustic methods. Chemical methods are effective for soluble deposits; however, they require precise reagent selection and may be

accompanied by secondary precipitation. High-energy impulse methods can rapidly destroy clogging material, but they require strict pressure control to prevent filter damage and uncontrolled fracture development. In this context, acoustic stimulation occupies an intermediate position: it is more intensive than conventional flushing, but gentler than explosive and hydraulic-fracturing-type treatments [9–13].

Recent field evidence for uranium ISL wells confirms that physical stimulation of the filter and near-filter zone can substantially restore well injectivity when the treatment energy is controlled. Zairov et al. [8] experimentally demonstrated that optimized multi-strand detonation cord charges can disrupt clogging deposits while preserving filter integrity; injectivity increased from 0.6–0.9 m³/h before treatment to 1.5–2.3 m³/h after treatment. These results support the technological relevance of physical near-filter-zone stimulation, although high-energy shock-wave methods require strict control of dynamic loads.

Acoustic and ultrasonic stimulation has been extensively investigated in the oil and gas industry for improving well productivity, reducing oil viscosity, enhancing fluid mobility, and intensifying mass transfer [9–13]. A separate research direction concerns coal seams, where acoustic and ultrasonic methods have been applied to increase permeability, activate natural fractures, and enhance gas drainage [14–18]. Experimental studies on porous media confirm that acoustic waves can modify fluid-flow behavior, enhance dispersion, mobilize trapped particles, and reduce local filtration resistance [19–23].

However, the direct transfer of results obtained in oil, gas, and coal formations to uranium deposits is not straightforward. In uranium in-situ leaching, the primary objective is not to create new extended fractures, but to restore the existing pore conductivity of the filter and near-filter zone without disturbing the hydrodynamic isolation of the operational block. Therefore, a dedicated technological scheme is required that accounts for the water-saturated porous medium, chemical activity of leaching solutions, design of filter intervals, and environmental safety requirements.

This study considers a hydrodynamic acoustic emitter that generates flow pulsations through a self-rotating valve. When compressed air or a working fluid is supplied, the flow induces valve rotation, periodic variation of the flow cross-section, and generation of pressure oscillations. Experimental data for similar generators indicate the presence of two regions of increased acoustic activity: a low-frequency region of 10–50 Hz and a high-frequency region above 500 Hz. The former is of interest for deformation–filtration effects in the formation, whereas the latter is relevant to local disintegration of clogging material near the filter.

The aim of this study is to develop and physicomathematically justify a technological scheme for applying a hydrodynamic acoustic emitter to restore the permeability of the near-filter zone of technological wells during uranium in-situ leaching.

2. Materials and Methods

2.1. Objects of Study

The Sabysai, Ketmenchi, and Sugrally uranium deposits were considered as representative objects for adapting the proposed hydrodynamic-acoustic stimulation technology. These deposits were selected because they reflect different geotechnological conditions of uranium in-situ leaching and provide a basis for evaluating the applicability of acoustic stimulation to the recovery of near-filter-zone permeability.

The Sabysai deposit is an infiltration-type uranium deposit hosted mainly in permeable sandy, sandy-gravel, sandstone, and aleurolitic horizons. Its technological relevance is associated with the repeated development of residual uranium reserves, where the restoration of filtration conductivity in previously operated zones becomes particularly important [33]. Under such conditions, hydrodynamic-acoustic stimulation may be considered as a local method for reactivating residual permeability in the near-filter zone.

The Ketmenchi deposit was selected as the main computational object of the study because published data provide key parameters of a pilot in-situ leaching cell, including the well depth, filter interval, effective thickness, porosity, pore volume, and solution chemistry [32]. In particular, the available filter interval of 162–170 m makes this object suitable for testing the concept of sectional acoustic treatment of the lower, middle, and upper parts of the filter.

The Sugrally deposit represents a sandstone-hosted uranium deposit with more complex mining and geological conditions and an increased carbonate background. For this type of object, the main technological concern is the potential development of carbonate and mixed clogging in the filter and near-filter zone. Therefore, the application of hydrodynamic-acoustic stimulation to Sugrally requires a more cautious selection of operating parameters and mandatory geochemical control of the leaching solution [34].

Thus, the selected deposits provide three complementary scenarios for evaluating the proposed technology: Sabysai as an object of repeated development and residual permeability recovery, Ketmenchi as the main computational object with available pilot-cell parameters, and Sugrally as an object for adapting the method to carbonate-bearing and geologically complex conditions.

Table 1
Initial parameters of the study objects for computational adaptation of the method

Object	Geotechnological characteristics	Parameters used in the calculation	Priority task of acoustic treatment
Sabyrsai	Infiltration-type uranium deposit; sands, sandstones, gravelites, and aleurolites; repeated development	Thickness of the ore-bearing horizon: 12–15 m; Meso-Cenozoic sedimentary cover up to 500–600 m; ores with (CO ₂ <2%) and (CO ₂ >2%)	Recovery of residual filtration conductivity during repeated development
Ketmenchi	In-situ leaching object with pilot wells and cells	Well depth: 174 m; filter interval: 162–170 m; filter length: 8 m; effective thickness: 9 m; porosity: 0.20; pore volume: 3240 m ³	Main computational object for sectional acoustic treatment of the filter interval
Sugrally	Large sandstone-hosted uranium deposit with complex conditions and a carbonate background	Qualitative adaptation of the treatment regime; accurate well parameters require field data	Reduction of carbonate and mixed clogging under mandatory chemical control

For the Ketmenchi deposit, the following additional pilot-cell parameters were also considered: an area of 1800 m², an ore-bearing rock mass volume of 16,200 m³, a linear configuration with eight injection wells and two production wells, an injection-well spacing of 30×30 m, formation productivity of 14.2–17.5 kg/m², formation thickness of 2.9–3.05 m, initial uranium concentration in solution of 12–33 mg/L, pH during acidification of approximately 1.1–1.5, and oxidation–reduction potential of approximately 480–510 mV [32].

2.2. Hydrodynamic Acoustic Emitter and Its Operating Principle

In this study, a hydrodynamic acoustic emitter is considered as the technical basis for acoustic stimulation. The device represents a flow-pulsation generator based on a self-rotating valve. Its design enables the conversion of the energy of compressed air or working-fluid flow into periodic pressure oscillations that can be transmitted through the liquid medium to the filter and near-filter zone of a technological well.

Structurally, the emitter consists of a housing, an internal channel, a working chamber, a self-rotating valve freely rotating on an axis, an inlet fitting, and an outlet nozzle. When compressed air is supplied into the internal cavity of the device, a flow is formed that induces rotation of the valve. As a result of periodic variation in the flow cross-section, pressure pulses and flow pulsations are generated. This operating mode enables the generation of acoustic oscillations with different spectral compositions depending on the supply pressure, channel geometry, valve position, and hydrodynamic characteristics of the flow.

During laboratory tests, compressed air was supplied to the device inlet at pressures ranging from 0.2 to 3.0 atm. The purpose of the tests was to evaluate the spectral and vibroacoustic characteristics of the emitter and to identify frequency ranges potentially suitable for geotechnological application in restoring the filtration properties of the near-filter zone.

From a physical standpoint, the operation of the emitter is based on a periodic modification of the flow structure accompanied by local oscillations in pressure, velocity, and turbulence. Unlike conventional vibration-based and ultrasonic systems, the acoustic field in this case is generated hydrodynamically. Similar approaches to acoustic and ultrasonic stimulation have previously been considered for porous media, oil and gas reservoirs, and coal seams, where wave воздействие promoted changes in filtration properties and mobilization of fluids [9–22].

For uranium in-situ leaching conditions, it is fundamentally important that the hydrodynamic acoustic emitter can operate in a controlled pulsed mode without generating the extreme dynamic loads characteristic of high-energy stimulation methods. This is particularly significant for the treatment of technological wells, where the objective is to restore the permeability of the filter and near-filter zone while avoiding filter damage, sand production, and disturbance of the hydrodynamic isolation of the operational block [1–4].

Within the framework of the present study, the hydrodynamic emitter performs a dual function. On the one hand, it generates low-frequency pulsations capable of producing deformation–filtration effects in a water-saturated porous medium. On the other hand, under an appropriate operating regime, it generates high-frequency components that may contribute to local filter cleaning and disintegration of thin clogging deposits in the near-wellbore zone. Such a distinction between the two mechanisms is consistent with current understanding of the frequency-dependent attenuation of acoustic waves in saturated porous media and the influence of oscillations on filtration flow [19–24].

2.3. Method for Investigating Vibroacoustic Characteristics

To evaluate the operating parameters of the hydrodynamic acoustic emitter, its vibroacoustic characteristics were investigated at different inlet pressures. The main objective of this stage was to identify the frequency ranges in which the emitter generates stable pressure pulsations potentially suitable for acting on the filter and near-filter zone of uranium in-situ leaching wells.

During the tests, compressed air was supplied to the device inlet at pressures ranging from 0.2 to 3.0 atm. Variation in the inlet pressure made it possible to change the flow velocity, turbulence intensity, and rotation frequency of the self-rotating valve. Since the acoustic field in the considered device is formed due to periodic variation of the flow cross-section, the valve rotation frequency was considered one of the key factors determining the fundamental frequency of flow pulsations.

Spectral analysis was performed over a wide frequency range to identify regions of increased acoustic activity. Particular attention was paid to two frequency zones: the low-frequency range of 10–50 Hz, which is of interest for deformation–filtration effects in water-saturated porous media, and the high-

frequency range above 500 Hz, which is mainly associated with jet-induced turbulent flow. This separation of frequency regions is consistent with the distinction between low-frequency wave stimulation and high-frequency local acoustic cleaning mechanisms in porous media [19–22].

When interpreting the results, attention was focused on two aspects: identifying the ranges of increased acoustic activity and assessing the possibility of controlling the fundamental frequency of flow pulsations by changing the pressure and direction of the working-fluid supply. This approach makes it possible not only to describe the device from an engineering standpoint, but also to assess its potential applicability for acting on the ore-bearing horizons of uranium deposits.

Table 2
Interpretation of the frequency ranges of the hydrodynamic acoustic emitter

Frequency range	Formation mechanism	Expected technological significance
10–50 Hz	Self-rotation of the valve and periodic variation of the flow cross-section	Deformation–filtration effect on the near-filter zone, mobilization of clogging material, and permeability recovery
> 500 Hz	Jet flow and flow turbulization	Local filter cleaning, destruction of fine deposits, and disaggregation of clogging material
Combined mode	Combination of low- and high-frequency oscillations	Simultaneous recovery of pore conductivity and cleaning of the filter surface

The obtained frequency intervals were further used to select computational regimes for hydrodynamic-acoustic stimulation. The low-frequency range was considered the main range for acting on the near-filter zone, whereas the high-frequency component was treated as an auxiliary mechanism for local filter cleaning.

2.4. Physicomathematical Model

The theoretical basis for describing acoustic effects in a water-saturated uranium-bearing formation is Biot’s poroelasticity theory, according to which a saturated porous medium is considered as a system consisting of a deformable solid skeleton and pore fluid [23, 24]. During wave propagation, relative motion between the fluid and solid phases, viscous friction, pore-pressure variation, and energy attenuation occur.

The variable acoustic pressure is expressed as:

$$p_a(t) = p_a \sin(2\pi ft)$$

where $p_a(t)$ is the instantaneous acoustic pressure, p_m is the pressure amplitude, f is the excitation frequency, and t is time.

The acoustically induced filtration component can be written based on Darcy's law [25, 27]:

$$u_a = -\frac{k}{\mu} \nabla p_a$$

2

where u_a is the additional filtration velocity, k is permeability, μ is the dynamic viscosity of the solution, and ∇p_a is the acoustic pressure gradient.

The radial attenuation of pressure amplitude is described by:

$$p(r) = p_0 \left(\frac{r_w}{r} \right)^n \exp[-\alpha(f)(r - r_w)]$$

3

where p_0 is the pressure amplitude at the well wall, r_w is the well radius, r is the distance from the well axis, n is the geometric spreading exponent, and $\alpha(f)$ is the frequency-dependent attenuation coefficient.

The effective stimulation radius is determined from the condition:

$$p(r_{eff}) \geq p_{mob}$$

4

where p_{mob} is the threshold pressure required for the mobilization of clogging material and reactivation of existing microchannels.

For uranium-bearing formations, not only stimulation efficiency but also operational safety is of fundamental importance. The acoustic pressure must be sufficient to disturb clogging structures, but it must not cause filter damage, sand production, uncontrolled fracture development, or disturbance of the hydrodynamic isolation of the operational block. Therefore, the operating regime can be described by the inequality:

$$p_{mob} < p_a < p_{fail}$$

5

where p_{fail} is the limiting pressure at which macrofailure of the rock or structural elements of the well may occur.

For technological evaluation, a dimensionless acoustic activation criterion can be introduced:

$$P_a = \frac{p_m^2 T}{\rho c^2 \mu} \bullet \frac{k_0}{r_w^2} \bullet \eta_f$$

6
,

where T is the total stimulation time, ρ is the solution density, c is the wave propagation velocity in the saturated medium, μ is the initial permeability of the near-filter zone, and η_f is the frequency-matching coefficient.

The frequency-matching coefficient can be expressed as:

$$\eta_f = \exp \left[-\frac{(f - f_{opt})^2}{2\sigma_f^2} \right]$$

7
,

where f_{opt} is the optimal stimulation frequency and, σ_f is the width of the effective frequency range.

Permeability recovery after acoustic treatment can be represented by the following saturation-type relationship:

$$\frac{k_1}{k_0} = 1 + A (1 - \exp [-mP_a])$$

8
,

where k_1 is the permeability after treatment, A is the maximum achievable relative increase, and m is an empirical coefficient describing the sensitivity of the medium to acoustic stimulation.

2.5. Digital Modeling Methodology

Digital modeling of hydrodynamic-acoustic stimulation was performed to evaluate acoustic pressure propagation in the near-filter zone, determine the effective stimulation radius, and predict permeability changes after treatment. The model is intended for the preliminary selection of a safe and technologically justified operating regime for the hydrodynamic acoustic emitter.

The calculation procedure includes the following sequential stages:

1. input of the initial parameters of the well, filter interval, and ore-bearing horizon;
2. selection of the stimulation frequency regime: the low-frequency range of 10–50 Hz, the high-frequency range above 500 Hz, or a combined regime;
3. assignment of the acoustic pressure amplitude at the filter wall;
4. calculation of acoustic pressure attenuation with radial distance from the well axis;
5. determination of the effective stimulation radius r_{eff} based on the condition that the clogging-material mobilization threshold is exceeded;
6. calculation of the dimensionless acoustic activation criterion;
7. prediction of the relative permeability change k_1/k_0 ;
8. construction of sensitivity plots as a function of frequency, pressure, attenuation coefficient, and stimulation time.

The main parameters of the model are presented in Table 3.

Table 3
Calculation parameters of the hydrodynamic-acoustic stimulation model

Parameter	Symbol	Unit of measurement	Role in the model
Well radius	r_w	m	Geometric basis for calculating radial pressure propagation
Filter length	L_f	m	Determines the number of treatment sections and stimulation duration
Initial permeability	k_0	m^2 or mD	Characterizes the degree of clogging in the near-filter zone before treatment
Permeability after treatment	k_1	m^2 or mD	Used to evaluate the efficiency of acoustic stimulation
Acoustic pressure amplitude	p_m	MPa	Main energy parameter of acoustic stimulation
Pressure at the well wall	p_0	MPa	Initial pressure value for calculating radial attenuation
Stimulation frequency	f	Hz	Determines the stimulation mechanism: low-frequency deformation or high-frequency local effect
Optimal frequency	f_{opt}	Hz	Used to calculate the frequency-matching coefficient
Stimulation time	T	S	Determines the total duration of energy transfer to the near-filter zone
Attenuation coefficient	$\alpha(f)$	m^{-1}	Describes acoustic energy losses during propagation in a saturated porous medium
Geometric spreading exponent	n	–	Accounts for amplitude reduction due to radial wave propagation
Clogging-material mobilization threshold	p_{mob}	MPa	Minimum pressure required to destroy or displace clogging formations
Failure pressure limit	p_{fail}	MPa	Upper limit preventing filter damage and macrofailure of the formation
Effective stimulation radius	r_{eff}	m	Boundary of the zone within which acoustic pressure remains technologically effective
Solution density	ρ	kg/m^3	Considered in the calculation of acoustic energy in the saturated medium
Wave propagation velocity	c	m/s	Characterizes the acoustic properties of the water-saturated porous medium
Dynamic viscosity of the solution	μ	Pa·s	Accounts for resistance to filtration flow of the solution

Parameter	Symbol	Unit of measurement	Role in the model
Acoustic activation criterion	P_a	–	Integrally evaluates the adequacy of acoustic stimulation for permeability recovery

For the initial computational assessment under the conditions of the Ketmenchi deposit, the following input parameters were used: well depth of 174 m, filter interval of 162.0–170.0 m, filter length of 8 m, effective thickness of 9 m, porosity coefficient of 0.20, and pore volume of 3240 m³ [31]. These data make it possible to perform preliminary segmentation of the filter interval and to determine treatment regimes for the lower, middle, and upper sections of the filter.

Digital modeling was performed as a preliminary engineering stage aimed at defining the permissible range of stimulation parameters. The obtained computational dependencies were further used to construct plots of pressure attenuation, variation in effective stimulation radius with frequency, and predicted permeability recovery.

2.6. Pilot-Scale Validation Methodology

To verify the proposed technology under field conditions, a sequential pilot-scale validation program was developed. It logically extends the computational methodology presented in Section 2.5 and is intended to support the transition from model-based assessment of stimulation parameters to their verification in technological wells used for uranium in-situ leaching. The program includes well selection, initial hydrodynamic and geochemical diagnostics, spectral tuning of the emitter, sectional treatment of the filter interval, post-treatment pumping, repeated diagnostics, and evaluation of the long-term stability of the treatment effect.

At the first stage, wells with reduced injectivity or flow rate, but without signs of structural damage, are selected. This selection criterion makes it possible to exclude cases in which productivity decline is associated not with clogging of the filter and near-filter zone, but with an emergency well condition, filter-structure failure, or depletion of the hydrodynamic potential of the operational block [1–4].

At the second stage, initial diagnostics are performed. The measured parameters include flow rate or injectivity Q_0 , injection pressure, pH, Eh, turbidity, suspended solids content, and concentrations of U, Fe, Ca, Mg, SO_4^{2-} , and HCO_3^- . These data make it possible to determine the initial condition of the well, evaluate the degree of filtration-property degradation, and preliminarily identify the possible clogging type: mechanical, chemical, biogenic, or mixed [3, 4, 7, 29–31].

At the third stage, spectral tuning of the hydrodynamic acoustic emitter is carried out. The ratio between the low-frequency range of 10–50 Hz and the high-frequency range above 500 Hz is determined. For primary treatment, the low-frequency mode is preferred as the main stimulation regime, whereas the

high-frequency component is considered an auxiliary factor for local cleaning of the filter and the adjacent near-filter zone [9–13, 19–22].

At the fourth stage, sectional treatment of the filter interval is performed. For the Ketmenchi object, treatment of the 162–170 m interval in three sections—the lower, middle, and upper parts—is recommended. For each section, the frequency, amplitude, treatment duration, and technological pauses are specified. This approach enables a more uniform distribution of acoustic energy along the filter length and reduces the risk of local structural overload.

At the fifth stage, the well is pumped to remove disintegrated and mobilized clogging material. During pumping, turbidity, suspended solids content, and changes in the chemical composition of the solution are monitored. This stage is necessary to prevent the re-deposition of fine dispersed material in less permeable parts of the near-filter zone.

At the sixth stage, repeated hydrodynamic diagnostics are performed to determine Q_1 , pressure, specific injectivity, the skin factor, and recovery coefficients:

$$\eta_Q = \frac{Q_1}{Q_0}, \quad \eta_k = \frac{k_1}{k_0}.$$

9

where η_Q is the recovery coefficient based on flow rate or injectivity, η_k is the permeability recovery coefficient, Q_0 and Q_1 are the flow rate or injectivity before and after treatment, respectively, and k_0 and k_1 are the permeability values before and after treatment, respectively.

At the final stage, the stability of the treatment effect is evaluated after 1, 7, and 30 days. If the increase in injectivity or flow rate is insufficient, the stimulation regime is adjusted by returning to the selection of frequency, amplitude, treatment duration, and number of treatment cycles.

Table 4
Minimum dataset for pilot-scale validation

Data group	Parameters	Purpose
Hydrodynamic data	Q_0 , Q_1 , pressure, skin factor	Evaluation of the increase in filtration conductivity
Geometrical data	Well depth, filter interval, filter length, well radius	Calculation of the stimulation zone and segmentation of treatment
Chemical data	pH, Eh, U, Fe, Ca, Mg, SO_4^{2-} , HCO_3^-	Control of the geochemical stability of the solution
Mechanical data	Turbidity, suspended solids, sand production	Assessment of clogging-material removal and technological risks
Acoustic data	Frequency, pressure amplitude, treatment duration, number of cycles	Optimization of the stimulation regime
Operational data	Effect after 1, 7, and 30 days	Verification of treatment-effect stability

The proposed methodology provides a transition from computational and methodological justification to a field-verifiable technology. It forms the basis for subsequent experimental validation of hydrodynamic-acoustic stimulation in uranium in-situ leaching wells using actual pre- and post-treatment data.

3. Results

3.1. Analysis of the Amplitude–Frequency Response of the Hydrodynamic Acoustic Emitter

The results of vibroacoustic measurements showed that the hydrodynamic acoustic emitter generates not a single-frequency signal, but a broadband acoustic field with a pronounced non-uniform amplitude–frequency response. As shown in Fig. 2, two regions of increased acoustic activity are observed in the spectrum: a low-frequency region within 0.01–0.05 kHz and a high-frequency region at frequencies above 0.5 kHz.

From a physical standpoint, stimulation in the 10–50 Hz range may be accompanied by periodic pore-pressure variations, weakening of adhesive bonds between clogging particles and pore surfaces, mobilization of fine dispersed material, and partial reactivation of existing filtration microchannels. Therefore, this range can be considered the primary interval for gentle acoustic stimulation of the filter and near-filter zone without generating critical dynamic loads on the ore-bearing horizon.

In the frequency interval of approximately 0.05–0.2 kHz, a relative decrease in the sound pressure level is observed. This zone can be interpreted as a transitional region, where the contribution of low-frequency pulsations decreases, while the jet-induced turbulent component has not yet become

dominant. From a technological perspective, this part of the spectrum is less preferable as the main operating range; however, it may be taken into account in a combined stimulation regime.

The second region of increased acoustic activity appears at frequencies above 0.5 kHz. In this range, the sound pressure level increases noticeably and reaches 50–60 dB in the high-frequency part of the spectrum. The formation of this region is mainly associated with the jet-like flow pattern inside the generator body and at the nozzle outlet. As the working-medium pressure increases, the flow velocity rises and turbulence intensifies, making the high-frequency component of the spectrum more pronounced.

For uranium in-situ leaching applications, the high-frequency region above 500 Hz has primarily local technological significance. Due to stronger attenuation in saturated porous media, it should not be regarded as the main mechanism for deep stimulation of the formation. At the same time, high-frequency pulsations may be useful for cleaning the filter surface, destroying thin mineral and mechanical deposits, and disaggregating weakly cemented clogging material in the immediate vicinity of the well wall.

Thus, analysis of the spectral response shows that the hydrodynamic acoustic emitter is capable of generating a combined effect: the low-frequency component of 10–50 Hz provides the main deformation–filtration effect in the near-filter zone, whereas the high-frequency component above 500 Hz enhances local filter cleaning. The possibility of regulating the supply pressure and flow direction makes it possible to change the rotation frequency of the self-rotating valve and, consequently, to control the fundamental frequency of flow pulsations. This is an important technological advantage, as the acoustic treatment regime can be adapted to the lithological features of the formation, the degree of clogging, and the design of the technological well.

3.2. Technological Scheme of Hydrodynamic-Acoustic Stimulation

The proposed technological scheme for hydrodynamic-acoustic stimulation of the near-filter zone of a uranium in-situ leaching well is presented in Fig. 3. The scheme combines three major functional blocks: diagnostic–analytical, calculation–technological, and operational–control. Within these blocks, 12 sequential stages are distinguished, ensuring a transition from the initial assessment of well condition to the selection of the stimulation regime, implementation of treatment, post-treatment control, and engineering decision-making.

Note

The dashed arrow from the block “In case of insufficient recovery” to Stage 5 indicates a return to repeated selection of the stimulation regime if the filtration characteristics are not sufficiently restored after the primary treatment cycle.

At the first stage, the initial well data are collected, including flow rate or injectivity Q_0 , pressure P_0 , filter-interval thickness H_f , filter diameter d_f , initial permeability k_0 , solution salinity, well operating life, and the history of previous treatments. This is followed by primary hydrodynamic diagnostics using a step-rate test, pressure recovery analysis, and evaluation of specific injectivity q_0 . These data make it possible to determine the degree of degradation of filtration properties and to identify the dominant clogging mechanism, whether mechanical, chemical, biogenic, or mixed.

The calculation–technological block is associated with assessing the applicability of acoustic stimulation and selecting the treatment regime. At this stage, the skin factor S , pressure drop ΔP , expected ratios k_1/k_0 and Q_1/Q_0 , as well as energy-related and technological risks, are determined. The hydrodynamic-acoustic stimulation regime is then selected: the low-frequency range of 10–50 Hz, the high-frequency regime above 500 Hz, or a combined treatment mode. Subsequently, the parameters of the emitter and the stimulation zone are calculated, including the acoustic pressure amplitude p_a , frequency f , treatment duration T , emitter power N_L , effective stimulation radius r_{eff} , acoustic impulse I_a , and the safe-operation condition $p(r) \geq p_{crit}$, which prevents damage to the filter and the ore-bearing horizon.

The operational–control block includes equipment preparation and calibration, sealing, centering, pressure control, amplitude and frequency verification, lowering the emitter into the filter interval, and positioning it according to the filter thickness. This is followed by pulse-cyclic treatment of the near-filter zone, combining acoustic oscillations with hydrodynamic pulsation. The main expected effects are loosening of clogging formations, particle disaggregation, reduction of clogging-material adhesion to pore surfaces, and recovery of filtration conductivity.

After acoustic treatment, the well is pumped to remove clogging products, with monitoring of turbidity, suspended solids, Fe, Ca, SO_4^{2-} , pH and Eh. A repeated hydrodynamic test is then performed to determine Q_1 , P_1 , q_1 , the flow-rate or injectivity recovery coefficient $\eta_Q = Q_1/Q_0$, and the permeability recovery coefficient $\eta_k = k_1/k_0$. If the recovery of filtration characteristics is insufficient, the scheme provides for a return to the stage of stimulation-regime selection, with adjustment of frequency, amplitude, treatment duration, and cyclicity. At the final stage, an engineering decision is made: to complete the treatment, repeat the cycle, or combine acoustic stimulation with reagent treatment.

3.3. Well Configuration for Hydrodynamic-Acoustic Stimulation

The layout of the hydrodynamic acoustic emitter within the filter interval of a technological uranium in-situ leaching well is shown in Fig. 4. The configuration includes a surface control unit, a pump-compressor unit, a pressure-recording system, wellhead equipment, a flexible tubing string or cable-tubing line, casing, the technological filter interval, the downhole hydrodynamic acoustic emitter, and the sump section of the well.

The diagram shows that the emitter is positioned directly within the technological filter interval, where the main zone of acoustic stimulation is formed. This placement is fundamentally important because the maximum pulsation energy is transmitted to the most problematic area, namely the filter and the adjacent near-filter zone, where mechanical, chemical, and biogenic clogging products are usually concentrated.

The surface part of the system provides working-fluid supply, pressure regulation, control of the pulsation-generation regime, and recording of hydrodynamic parameters. The pump-compressor unit creates the flow required for operation of the hydrodynamic acoustic emitter, while the pressure recorder makes it possible to monitor pressure changes during treatment and prevent the regime from entering the range of hazardous dynamic loads.

In the downhole section, the emitter should be installed with regard to the filter thickness, the depth of the treatment interval, and the expected location of the zone of maximum clogging. For an extended filter interval, sectional treatment is advisable, with the lower, middle, and upper parts of the filter treated sequentially. This approach allows acoustic stimulation to be distributed more uniformly over the filter thickness and reduces the risk of local structural overstressing.

Figure 4 highlights two characteristic stimulation zones: the clogging-material disintegration zone r_c and the effective stimulation radius r_{eff} . The clogging-material disintegration zone corresponds to the area closest to the filter, where acoustic pressure and hydrodynamic pulsation are most intense. In this zone, loosening, disaggregation, and removal of clogging formations are expected. The effective stimulation radius r_{eff} characterizes the limiting distance within which acoustic pressure remains sufficient to exert a technologically significant effect on the porous medium.

Thus, the proposed configuration shows that hydrodynamic-acoustic stimulation should be regarded as a local method for restoring the filtration properties of the near-filter zone rather than as a technology for deep destruction of the productive formation. This is consistent with the requirements of uranium in-situ leaching, where it is necessary to preserve the hydrodynamic isolation of the operational block and to prevent uncontrolled fracture development.

3.4. Interpretation of the Results with Respect to Uranium-Bearing Formations

The obtained spectral characteristics and the proposed well configuration indicate that hydrodynamic-acoustic stimulation should be considered a local method for restoring filtration conductivity in the near-filter zone, rather than a technology for deep destruction of the productive horizon. For uranium in-situ leaching wells, this is of fundamental importance, since process efficiency is determined not only by permeability but also by preservation of the controlled hydrodynamic contour of the operational block [1–4].

The main expected effect of acoustic stimulation is associated with the conversion of pulsating-flow energy into cyclic variations in pore pressure and local stresses near the filter. In a water-saturated porous medium, such oscillations may weaken the bonds between clogging particles and pore surfaces, disturb weakly cemented aggregates, promote mobilization of fine dispersed material, and partially restore existing filtration channels [19–24]. Unlike hydraulic fracturing or high-energy impulse treatment, this mechanism is primarily aimed at reactivating the existing pore structure.

For uranium-bearing formations developed by in-situ leaching, it is particularly important to consider the chemical nature of clogging. Mechanical particles, products of secondary mineral formation, ferruginous, carbonate, and sulfate deposits, as well as biogenic formations, may accumulate in the near-filter zone [3, 4, 7]. Therefore, acoustic stimulation should not be regarded as a universal standalone operation, but rather as an element of integrated well rehabilitation that can enhance subsequent pumping and, if necessary, reagent treatment.

The technological effect of stimulation is manifested in reduced local hydraulic resistance, decreased skin factor, and increased specific injectivity or well flow rate. However, such an effect can be achieved only if the safe range of dynamic pressure, previously defined in the computational model, is maintained. Acoustic pressure must be sufficient to mobilize clogging material, but it must not enter the range associated with filter damage, sand production, loss of pore-skeleton stability, or disturbance of the hydrodynamic isolation of the operational block [14–18, 23, 24].

From a practical standpoint, a pulse-cyclic treatment regime is the most justified. This scheme makes it possible to alternate periods of acoustic stimulation with technological pauses and pumping, thereby reducing the risk of secondary re-deposition of fine dispersed particles. By contrast, prolonged continuous stimulation may produce an adverse effect, including redistribution of particles within the pore space and formation of new local clogging zones [4, 19–22].

Thus, under uranium in-situ leaching conditions, hydrodynamic-acoustic stimulation should be regarded as a controlled local technology for restoring the near-filter zone. Its application is most justified in wells where productivity decline is associated with clogging of the filter and adjacent porous medium, rather than with structural well damage or depletion of the hydrodynamic potential of the operational block. Practical implementation of the method requires mandatory hydrodynamic diagnostics before and after treatment, monitoring of solution chemistry, and evaluation of treatment-effect stability over time.

3.5. Mechanisms of Impact on the Near-Filter Zone

Based on the spectral characteristics of the emitter, the well configuration, and the computational scheme of acoustic stimulation, the main mechanisms by which hydrodynamic-acoustic stimulation affects the filter and near-filter zone of a technological well were identified. These mechanisms are associated with the combined action of pressure pulsations, local deformation of the pore skeleton, hydrodynamic mobilization of particles, and subsequent well pumping.

Table 5
Mechanisms of hydrodynamic-acoustic stimulation effects on the near-filter zone

Mechanism	Physical nature	Technological result
Disintegration of clogging material	Cyclic stresses weaken weakly cemented deposits	Release of pore channels and the filter surface
Particle mobilization	Reduced adhesion of fine dispersed particles to pore surfaces	Removal of particles during subsequent pumping
Reactivation of microchannels	Periodic variation in pore pressure	Increased connectivity of filtration pathways
Reduction of the skin factor	Decrease in local hydraulic resistance	Increase in injectivity or flow rate
Intensification of mass transfer	Solution pulsation increases contact with the mineral surface	Increase in local leaching efficiency
Local filter cleaning	High-frequency jet-induced pulsations affect the filter surface	Removal of fine deposits in the near-filter zone
Risk of adverse effect	Prolonged stimulation may cause particle re-deposition	Need for cyclic treatment and pumping

The mechanisms presented indicate that hydrodynamic-acoustic stimulation should not be regarded as a destructive impact on the formation, but rather as a local method for restoring filtration conductivity. The main technological effect is associated with filter cleaning, reactivation of existing pore channels, and reduction of hydraulic resistance in the near-filter zone.

3.6. Computational Adaptation to the Sabyrsai, Ketmenchi, and Sugrally Deposits

To assess the applicability of the proposed technological scheme, computational adaptation was carried out for three objects: the Sabyrsai, Ketmenchi, and Sugrally deposits. These deposits were selected as examples of different geotechnological conditions for uranium in-situ leaching. Ketmenchi was considered the most suitable object for the initial computational assessment because parameters of its filter interval and pilot cell are available [32]. For Sabyrsai, the method was considered in relation to repeated development conditions, where reactivation of residual filtration conductivity is particularly relevant [33]. For Sugrally, the key factor is the increased carbonate background and the risk of secondary precipitation, which requires a more cautious selection of the stimulation regime [34].

For the Ketmenchi object, sectional treatment of the 162–170 m filter interval is considered the most rational approach. This scheme involves sequential stimulation of the lower, middle, and upper parts of the filter using the low-frequency range of 10–50 Hz, technological pauses, and subsequent pumping. For Sabyrsai, the priority is the recovery of residual conductivity in repeated development zones. For Sugrally, gentle low-frequency stimulation with mandatory chemical control of the solution is preferable.

Table 6
Recommended acoustic treatment regimes for the three objects

Object	Main problem	Recommended regime	Monitored parameters
Sabyrsai	Decrease in residual filtration conductivity during repeated development	Low-frequency stimulation at 10–50 Hz; pulse-cyclic treatment; local filter cleaning if required	Injectivity, flow rate, turbidity, pH, Eh, U, Fe
Ketmenchi	Clogging of the filter and near-filter zone in pilot cells	Sectional treatment of the 162–170 m filter interval; 10–30 min per section; pumping after each cycle	Q_0 , Q_1 , pressure, pH, Eh, U, suspended solids, skin factor
Sugrally	Carbonate and mixed clogging	Gentle low-frequency stimulation with chemical control	Ca^{2+} , Mg^{2+} , HCO_3^- , SO_4^{2-} , pH, Eh, turbidity

The adaptation results show that a unified technological scheme can be applied to different types of uranium objects; however, the stimulation regime must be adjusted according to lithology, clogging type, solution chemistry, and well operation history. The most universal option is the low-frequency pulse-cyclic regime, whereas the high-frequency component should be considered an auxiliary mechanism for local filter cleaning.

3.7. Calculation Results and Graphical Verification of the Model

To demonstrate the applicability of the proposed calculation scheme, preliminary modeling of acoustic pressure propagation in the near-filter zone was performed. The calculation was carried out using conditional design parameters consistent with the geometry of the Ketmenchi filter interval. It should be emphasized that the presented values are model-based and are intended for selecting a pilot-scale validation regime rather than replacing actual field measurements.

The following baseline parameters were adopted: well radius $r_w=0.08$ m, acoustic pressure amplitude at the filter wall $p_0 = 0.8$ MPa, clogging-material mobilization threshold $p_{\text{mob}}=0.08$ MPa, and geometric spreading exponent $n = 1.2$. To evaluate the influence of energy losses, attenuation coefficients of $\alpha = 0.4, 0.8$, and 1.2 m^{-1} were considered.

3.7.1. Radial Attenuation of Acoustic Pressure

The calculation of the radial acoustic pressure distribution shows that the main decrease in amplitude occurs in the near-wellbore region. At the specified pressure amplitude at the filter wall, $p_0 = 0.8$ MPa, the pressure decreases sharply within the first 0.3–0.5 m from the well axis, after which the attenuation

becomes more gradual. The horizontal line in Fig. 5 corresponds to the clogging-material mobilization threshold $p_{mob}=0.08$ MPa.

As the attenuation coefficient α increases, the radius of the zone in which the acoustic pressure remains above the mobilization threshold decreases. For $\alpha = 0.4\text{ m}^{-1}$, the calculated effective stimulation zone is the largest, whereas for $\alpha = 1.2\text{ m}^{-1}$, it becomes smaller. This behavior is associated with stronger absorption and scattering of acoustic energy in a water-saturated porous medium.

The obtained relationship confirms the local character of the proposed technology: hydrodynamic-acoustic treatment is primarily oriented toward the filter and near-filter zone rather than toward deep destruction of the productive horizon. From a technological standpoint, this is advantageous for uranium in-situ leaching, because it enables stimulation of the clogged zone while preserving the hydrodynamic isolation of the operational block.

3.7.2. Dependence of the Effective Stimulation Radius on Frequency

To evaluate the effect of frequency on the effective stimulation radius, a computational relationship linking the acoustic-pressure attenuation coefficient to oscillation frequency was used. Within the model, the attenuation coefficient increased with increasing frequency, reflecting stronger absorption and scattering of high-frequency oscillations in a water-saturated porous medium. The calculation was performed for the 10–1500 Hz range, covering both the low-frequency region of deformation–filtration stimulation and the high-frequency region of local filter cleaning.

Table 7
Calculation of the effective stimulation radius as a function of frequency

Frequency, Hz	Attenuation coefficient α , m^{-1}	Effective stimulation radius, m
10	0.385	0.480
20	0.420	0.476
30	0.455	0.470
50	0.525	0.462
100	0.700	0.443
200	1.050	0.409
500	2.100	0.344
1000	3.850	0.284
1500	5.600	0.248

The results summarized in Table 7 and Fig. 6 demonstrate a consistent decrease in the effective stimulation radius with increasing frequency. In the 10–50 Hz range, the calculated radius is approximately 0.46–0.48 m, which corresponds to the scale of the near-filter zone and confirms the suitability of low-frequency stimulation for restoring filtration conductivity. At frequencies above 500 Hz, the radius decreases to 0.25–0.34 m, indicating the predominantly local character of the high-frequency component. Therefore, the low-frequency range should be considered the primary regime for near-filter zone recovery, whereas the high-frequency component should be used as an auxiliary mechanism for cleaning the filter surface and adjacent pore channels.

3.7.3. Predicted Permeability Change

The recovery of filtration properties was predicted using the relationship previously given in Eq. (8). In the calculation scenario, the following parameters were adopted: the maximum achievable relative permeability increase $A = 1.5$ and the empirical coefficient of medium sensitivity to acoustic stimulation $m = 0.8$. The acoustic activation criterion P_a was treated as an integral indicator of the energetic adequacy of stimulation.

As shown in Fig. 7, the dependence exhibits a pronounced saturation behavior. At low values of P_a , the relative permeability increases most intensively, indicating that an increase in the energetic adequacy of stimulation leads to rapid recovery of filtration properties. However, with further increase in P_a , the curve gradually approaches a plateau, and the relative permeability asymptotically tends to a value of about 2.5.

This behavior is of major technological importance. It indicates that once a certain level of acoustic activation has been reached, further increases in stimulation power or treatment duration do not provide a proportional increase in permeability. Therefore, excessive intensification of stimulation may be energetically inefficient and may simultaneously increase the risk of secondary migration of fine particles, their re-deposition in the pore space, and recurrent clogging of the near-filter zone.

Thus, the calculated relationship confirms the need to select an optimal, rather than a maximum possible, regime of hydrodynamic-acoustic stimulation. In practical terms, this means that the treatment regime should be selected to achieve sufficient permeability recovery with minimal energy input and acceptable technological risk.

3.7.4. Model Comparison of Injectivity Before and After Treatment

To illustrate the expected technological effect of the proposed method, a model-based comparison of well injectivity before and after hydrodynamic-acoustic treatment was performed. The values presented in Table 8 and Fig. 8 represent a calculation scenario and should be replaced with actual field data during pilot-scale validation.

Table 8
Model comparison of well injectivity before and after acoustic treatment

Well	Before treatment, m ³ /h	After treatment, m ³ /h	Relative increase, times
S-1	0.70	1.15	1.65
S-2	0.82	1.32	1.61
K-1	0.65	1.22	1.88
K-2	0.78	1.45	1.86
Su-1	0.60	0.98	0.63

The model scenario indicates that hydrodynamic-acoustic treatment may increase well injectivity by approximately 1.6–1.9 times. The greatest relative improvement is observed for the model Ketmenchi wells, where the increase reaches 1.86–1.88 times, which is consistent with the assumed applicability of sectional filter treatment for this object. For the Sabyrsai and Sugrally scenarios, the predicted increase is slightly lower, approximately 1.6 times, reflecting the need to adjust the treatment regime according to the geological and geochemical conditions of each deposit.

Under actual field conditions, these values must be verified using hydrodynamic testing, solution-chemistry monitoring, and post-treatment stability assessment after 1, 7, and 30 days. Therefore, the results shown in Table 8 and Fig. 8 should be interpreted as a model-based forecast of the expected technological effect rather than as confirmed field performance.

3.7.5. Summary of Calculation Results

The calculation results confirm that low-frequency stimulation in the 10–50 Hz range is the most rational primary regime for near-filter zone recovery. The high-frequency range above 500 Hz may serve an auxiliary function associated with local filter cleaning. For the Ketmenchi object, where the 162–170 m filter interval is known, sectional treatment of the lower, middle, and upper parts of the filter is recommended, followed by pumping and monitoring of turbidity, pH, Eh, uranium concentration, and hydrodynamic parameters.

4. Discussion

4.1. Practical Significance of the Proposed Technological Scheme

The obtained results indicate that hydrodynamic-acoustic stimulation can be considered a gentle physical method for restoring the permeability of the near-filter zone of technological wells used in uranium in-situ leaching. The principal difference between the proposed technology and high-energy stimulation methods is that its target function is not the creation of new extended fractures, but the

restoration of existing pore conductivity, removal of clogging material, and reduction of local hydraulic resistance.

From an engineering standpoint, the hydrodynamic acoustic emitter based on a self-rotating valve has three important properties: broadband spectral response, controllability of the operating regime, and adaptability to downhole conditions. The broadband response makes it possible to combine low-frequency deformation–filtration stimulation with local high-frequency filter cleaning. Regime controllability is achieved by changing the pressure and direction of the working-fluid supply. Adaptability to well conditions is associated with the possibility of positioning the emitter directly within the filter interval and performing sectional treatment.

The most important result is confirmation of the local character of the stimulation effect. The calculated effective action radius in the 10–50 Hz range is approximately 0.46–0.48 m, which corresponds to the scale of the near-filter zone. Therefore, the method should not be regarded as a technology for deep formation destruction, but rather as a means of restoring the filter, adjacent pore channels, and the zone of increased hydraulic resistance.

4.2. Comparison with Oil and Gas, Coal, and Laboratory Studies

In uranium ISL wells, physical declogging has already been experimentally confirmed as an effective way to restore injectivity when the energy input is controlled [8]. In the oil and gas industry, ultrasonic and acoustic stimulation has been applied to improve fluid mobility, reduce oil viscosity, enhance oil recovery, and restore well productivity [9–13]. In coal seams, acoustic stimulation has been used to increase permeability, activate natural fractures, and enhance gas drainage [14–18]. Laboratory studies of porous media also show that acoustic stimulation can enhance flow, mobilize trapped particles, and modify mass-transfer conditions [19–22].

For uranium-bearing formations, these results should be regarded as a physically justified analogy rather than direct evidence of industrial efficiency. The main specific feature of uranium in-situ leaching is that the technological effect must be achieved with minimal risk of filter damage, sand production, and disturbance of the hydrodynamic isolation of the operational block. Therefore, transferring acoustic methods to uranium deposits requires separate adaptation of the operating regime, monitoring of solution chemistry, and verification using field data.

In this respect, the proposed scheme differs from acoustic stimulation in oil-bearing and coal-bearing formations. Its main efficiency criterion is not the creation of new fractures or expansion of the drainage volume, but the recovery of filtration conductivity in the local near-filter zone. This makes the method potentially compatible with the technological requirements of uranium in-situ leaching.

4.3. Study Limitations and Directions for Further Verification

The present study is technological, methodological, and computational in nature. The presented plots, tables, and calculation dependencies reflect the expected patterns of hydrodynamic-acoustic stimulation but do not replace actual field testing. The main limitation is the absence of direct experimental verification of the proposed treatment regime in technological wells of uranium deposits.

To transform the proposed scheme into a fully validated experimental technology, data are required on flow rate or injectivity before and after treatment, injection pressure, acoustic-emitter parameters, treatment duration, turbidity, solution chemistry, and stability of the treatment effect over time. The Ketmenchi object is the most suitable for initial computational and field-scale verification, since parameters of its filter interval and pilot cell are available.

At the next stage, it is necessary to conduct laboratory modeling of clogging in water-saturated porous-medium samples, determine the clogging-material mobilization threshold, refine the attenuation coefficient for different frequencies, and perform pilot-scale treatment of one or several technological wells with monitoring of the effect after 1, 7, and 30 days.

The validation logic can be guided by previous uranium ISL field studies, where physical stimulation efficiency was evaluated using pre- and post-treatment injectivity, filter integrity, and time-dependent monitoring of the treatment effect [8]. For hydrodynamic-acoustic stimulation, the same validation framework should be supplemented by acoustic parameters, including frequency, pressure amplitude, treatment duration, and cyclicity.

5. Conclusions

1. A technological scheme for hydrodynamic-acoustic stimulation of the near-filter zone of uranium in-situ leaching wells was developed. The proposed scheme integrates well-condition diagnostics, selection of the stimulation regime, calculation of emitter parameters, sectional treatment of the filter interval, post-treatment pumping, and subsequent hydrodynamic control.
2. It was established that the hydrodynamic acoustic emitter with a self-rotating valve generates two functionally different regions of acoustic activity: a low-frequency region of 10–50 Hz, associated with deformation–filtration effects in the near-filter zone, and a high-frequency region above 500 Hz, caused by jet-induced turbulent flow and local filter cleaning.
3. The physicomathematical justification of the method was based on Biot’s poroelasticity theory, Darcy’s law, a radial acoustic pressure attenuation model, and a safe-stimulation criterion. It was shown that, under uranium in-situ leaching conditions, acoustic stimulation should be aimed not at creating new large fractures, but at restoring existing pore conductivity, reducing the skin factor, and removing clogging formations.
4. Computational adaptation of the technology to the Sabyrsai, Ketmenchi, and Sugrally deposits showed that Ketmenchi is the most suitable object for initial verification, as filter-interval, porosity, pore-volume, and pilot-cell parameters are available for this object. Sabyrsai should be considered as an object for repeated development and residual filtration-conductivity recovery, whereas Sugrally

represents an object for adapting the method to carbonate-bearing and complex mining-geological conditions.

5. 5. Model calculations showed that, under low-frequency stimulation at 10–50 Hz, the effective stimulation radius is approximately 0.46–0.48 m, whereas at frequencies above 500 Hz it decreases to 0.25–0.34 m. This confirms that the main regime for near-filter zone recovery should be low-frequency pulse-cyclic stimulation, while the high-frequency component may be used as an auxiliary mechanism for local filter cleaning.
6. 6. Further verification of the proposed technology requires pilot-scale testing with registration of flow rate or injectivity before and after treatment, injection pressure, acoustic-emitter parameters, turbidity, solution chemistry, and treatment-effect stability after 1, 7, and 30 days. The obtained results provide a scientific and methodological basis for developing a technological protocol for hydrodynamic-acoustic treatment of uranium in-situ leaching wells.

Declarations

Availability of data and materials

The datasets used and/or analyzed during the current study, including calculated parameters of acoustic pressure attenuation, effective stimulation radius, frequency-dependent response, injectivity recovery, and model-based permeability improvement, are available from the corresponding author upon reasonable request. Field-related data for the uranium in-situ leaching wells considered in the study were analyzed in an aggregated form and may be provided subject to institutional and industrial data access restrictions.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Maksud Mekhmonov developed the research concept and methodology, designed the technological scheme for hydrodynamic-acoustic stimulation of the near-filter zone, performed the analytical calculations, interpreted the results, and prepared the original draft of the manuscript.

Shukhrat Tadjiev contributed to the experimental investigation of the hydrodynamic-acoustic emitter, analysis of its technical and vibroacoustic parameters, preparation of graphical and calculation

materials, and editing of the manuscript.

Mansurjon Israilov contributed to the geotechnological interpretation of uranium-bearing formation conditions, evaluated the applicability of the proposed stimulation method, and critically revised the manuscript for important intellectual content.

Farkhod Kurbanov contributed to the analysis of industrial operating conditions of uranium in-situ leaching wells, interpretation of field-related parameters, assessment of the practical applicability of the proposed technology, and validation of the technological recommendations.

All authors read and approved the final manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT, developed by OpenAI, solely for language editing, translation assistance, and improvement of readability. The authors subsequently reviewed and revised the entire manuscript and take full responsibility for its scientific content, accuracy, originality, and integrity.

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Figures

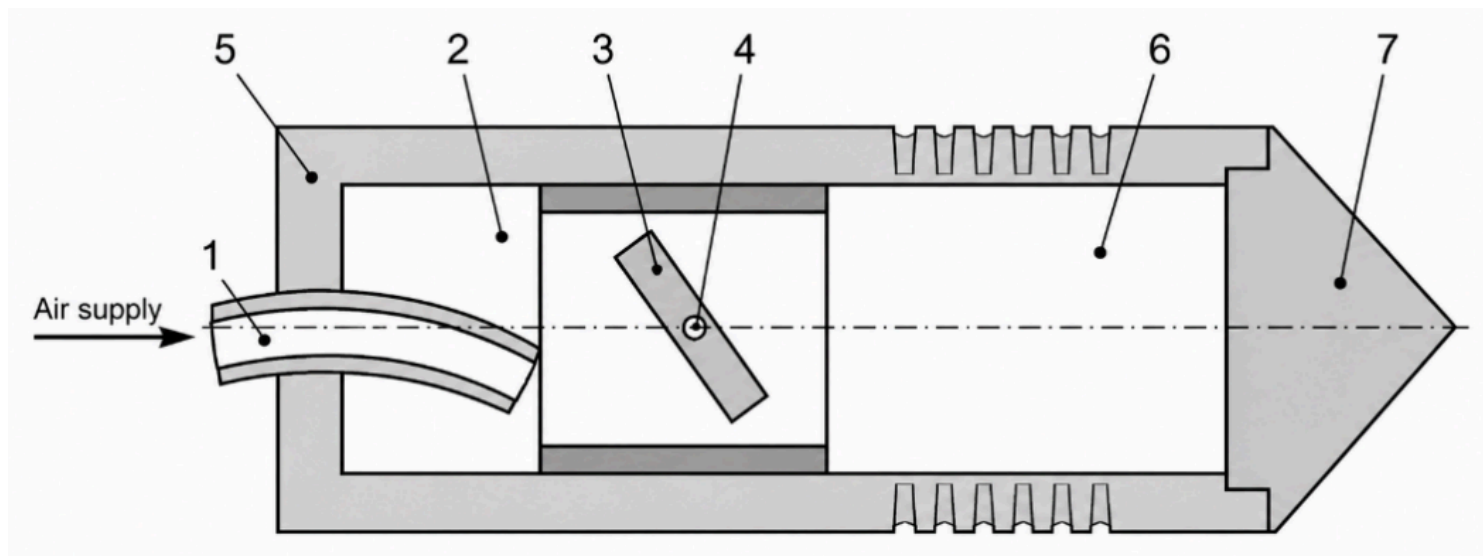


Figure 1

Schematic design of the hydrodynamic acoustic emitter: 1–air inlet channel; 2–working chamber; 3–self-rotating valve; 4–rotation axis; 5–housing; 6–outlet channel; 7–nozzle.

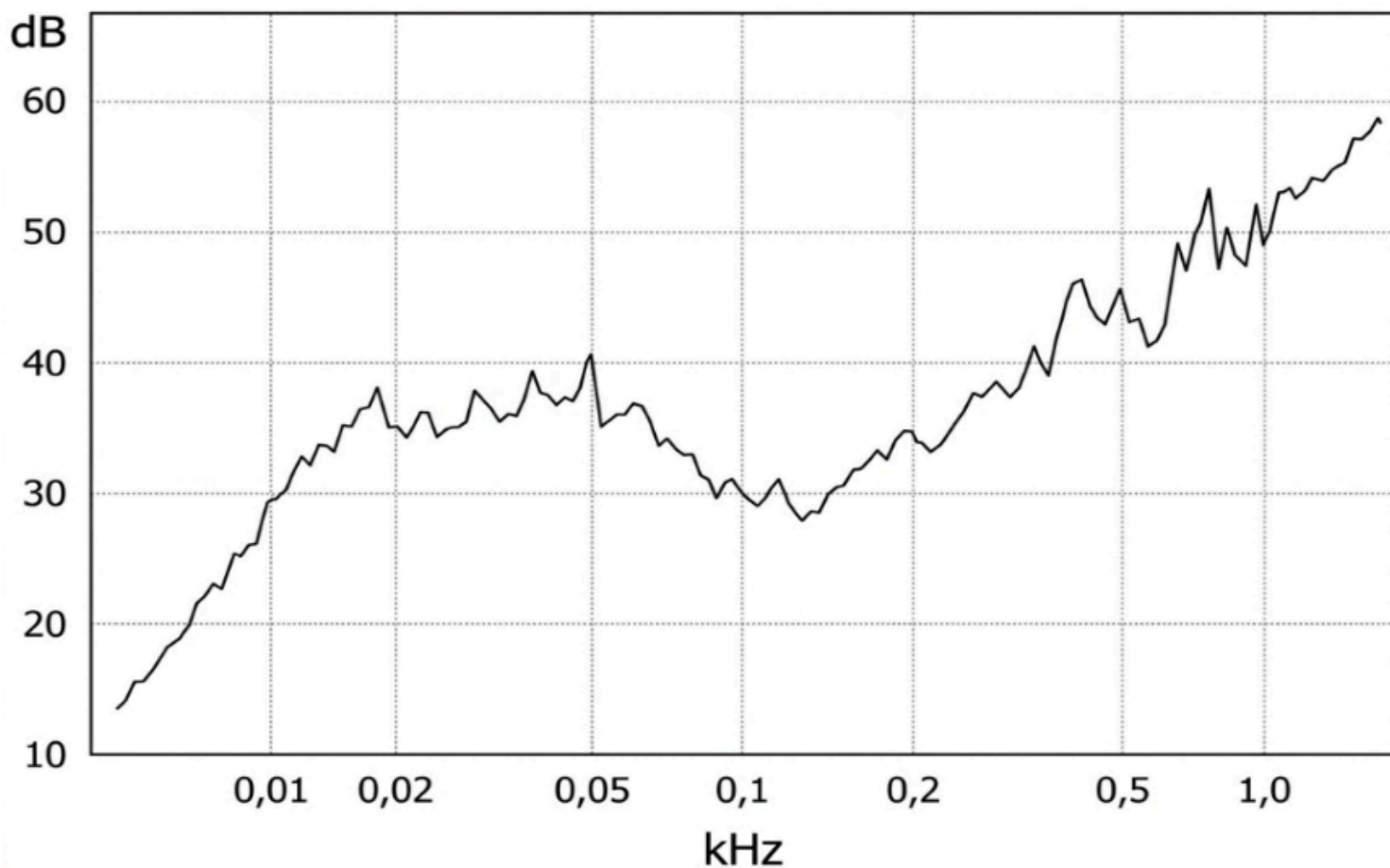


Figure 2

Amplitude–frequency response of the hydrodynamic acoustic emitter with a self-rotating valve.

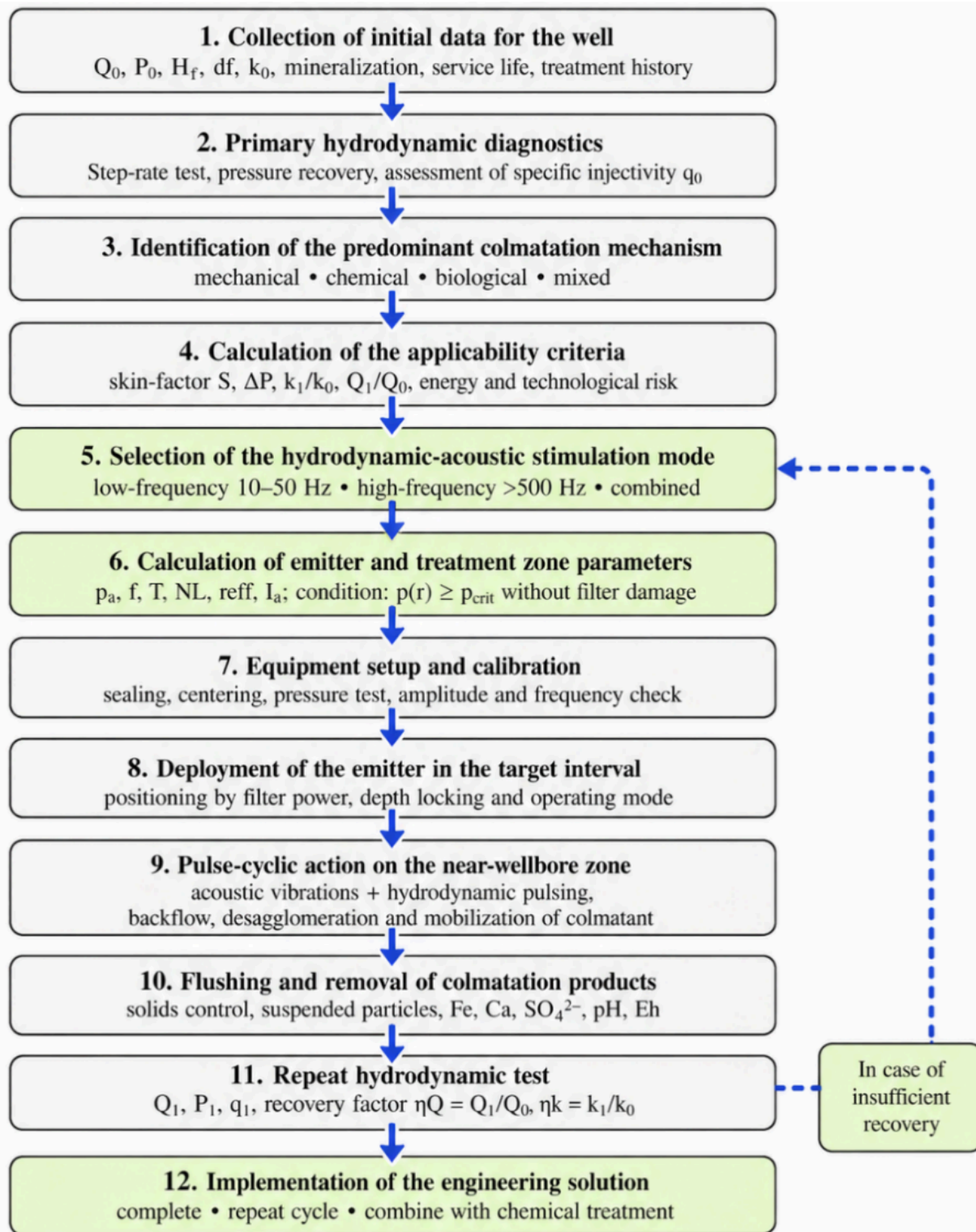


Figure 3

Algorithm for the technological selection and implementation of hydrodynamic-acoustic stimulation of the near-filter zone of a uranium in-situ leaching well.

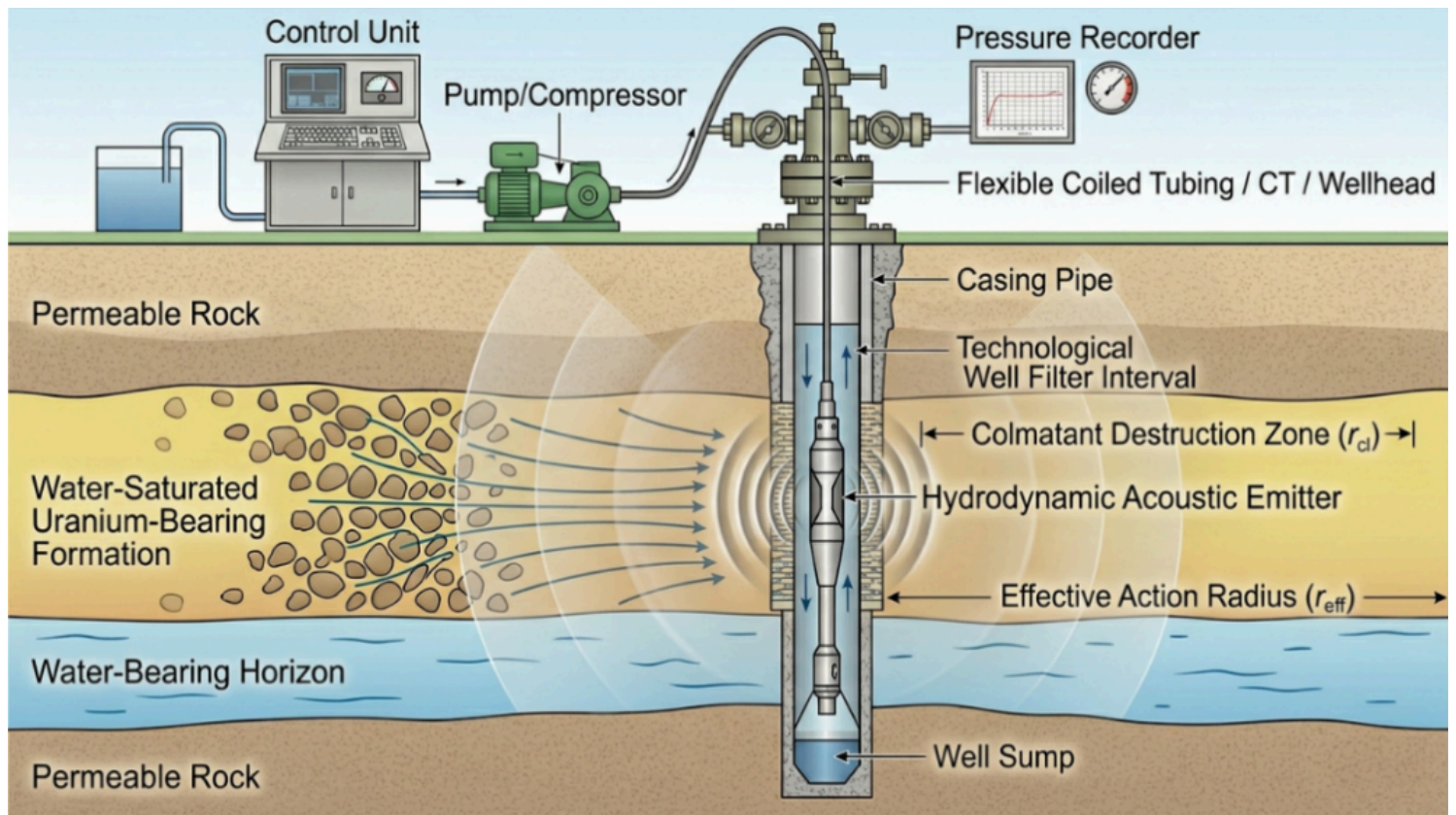


Figure 4

Well configuration of hydrodynamic-acoustic stimulation of the near-filter zone of a technological uranium in-situ leaching well.

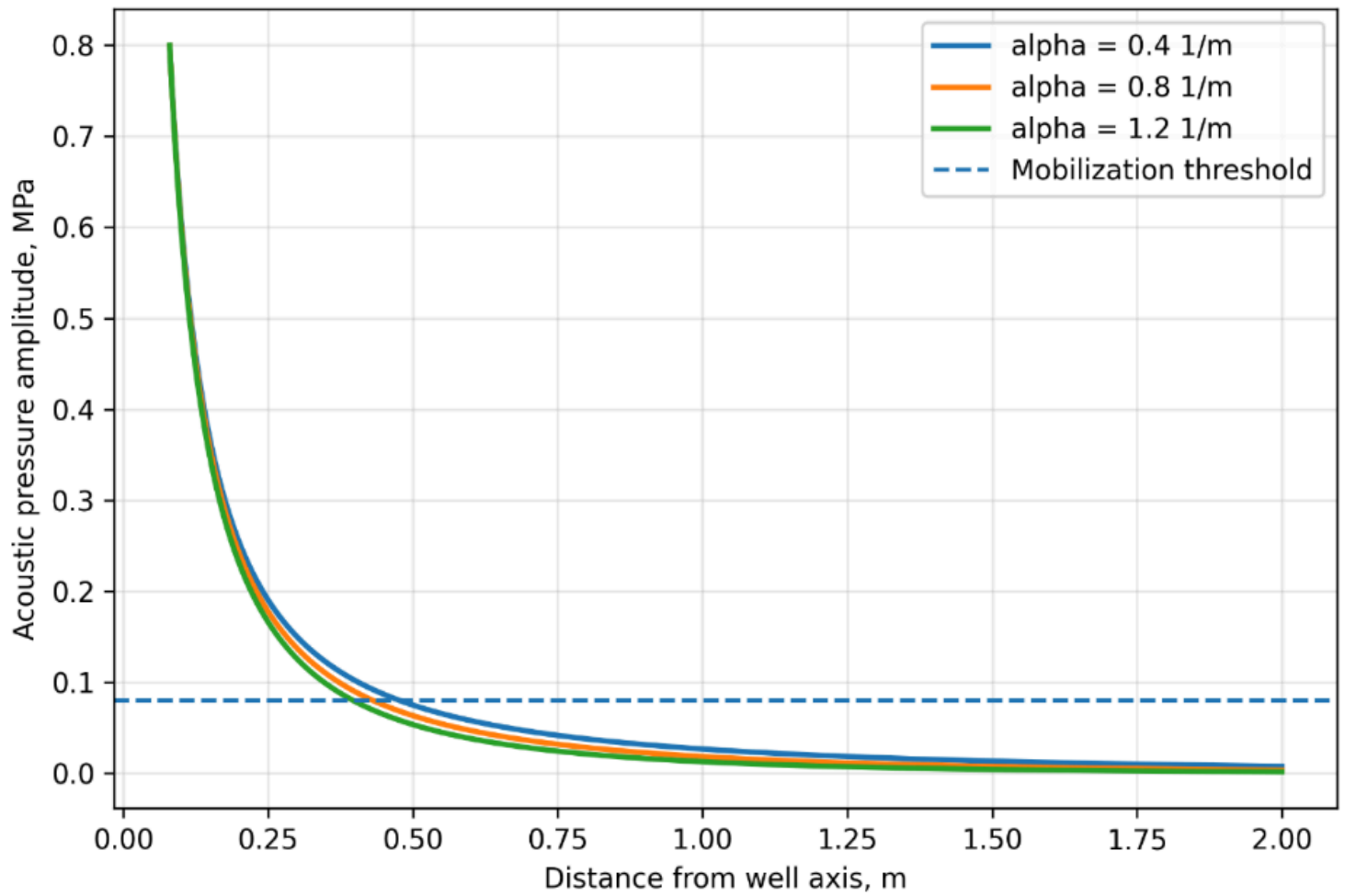


Figure 5

Radial attenuation of acoustic pressure in a water-saturated porous medium at $\alpha=0.4, 0.8$, and 1.2 m^{-1} . The horizontal dashed line corresponds to the clogging-material mobilization threshold $p_{\text{mob}}=0.08 \text{ MPa}$.

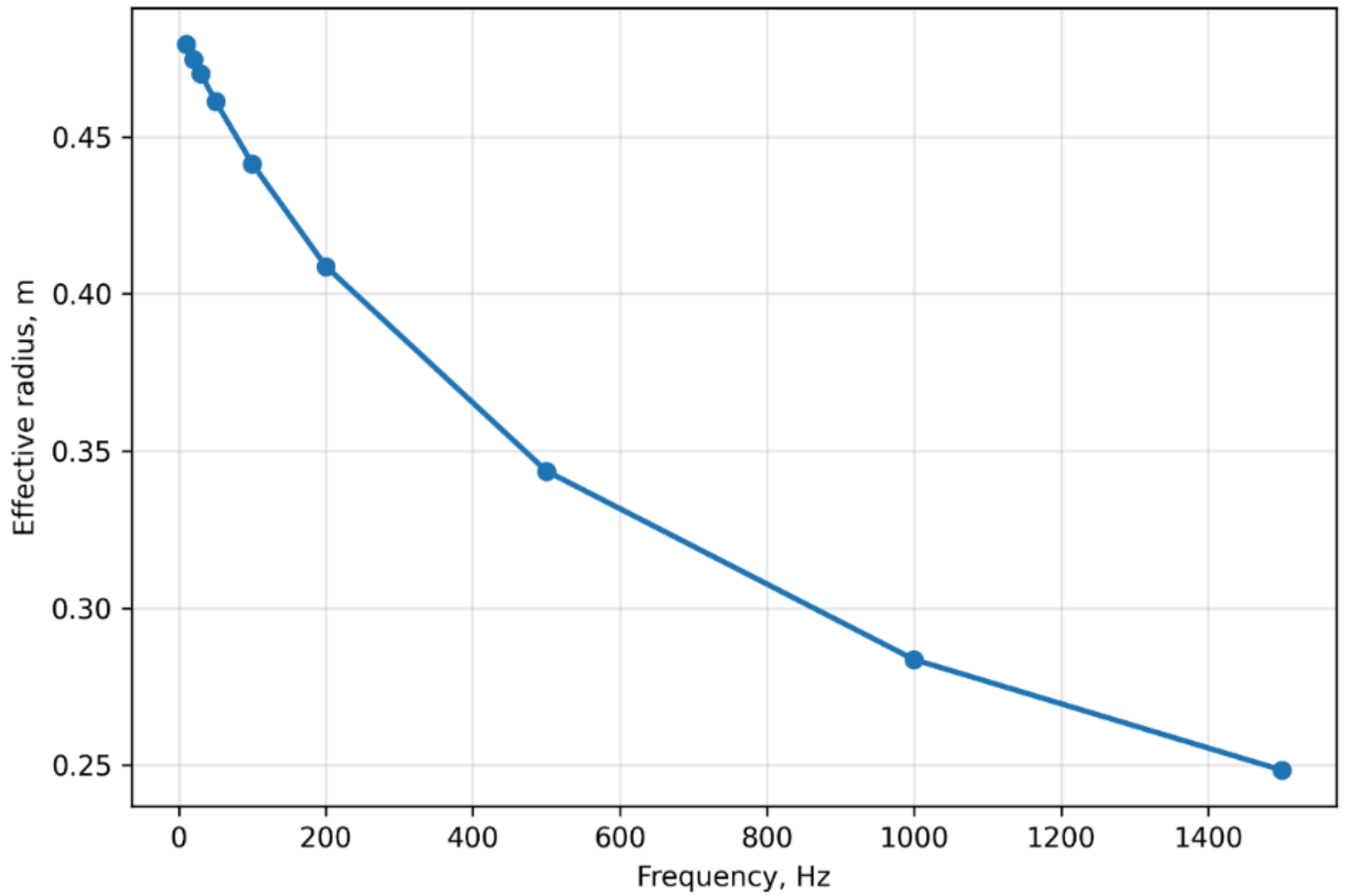


Figure 6

Dependence of the effective stimulation radius on the frequency of acoustic stimulation.

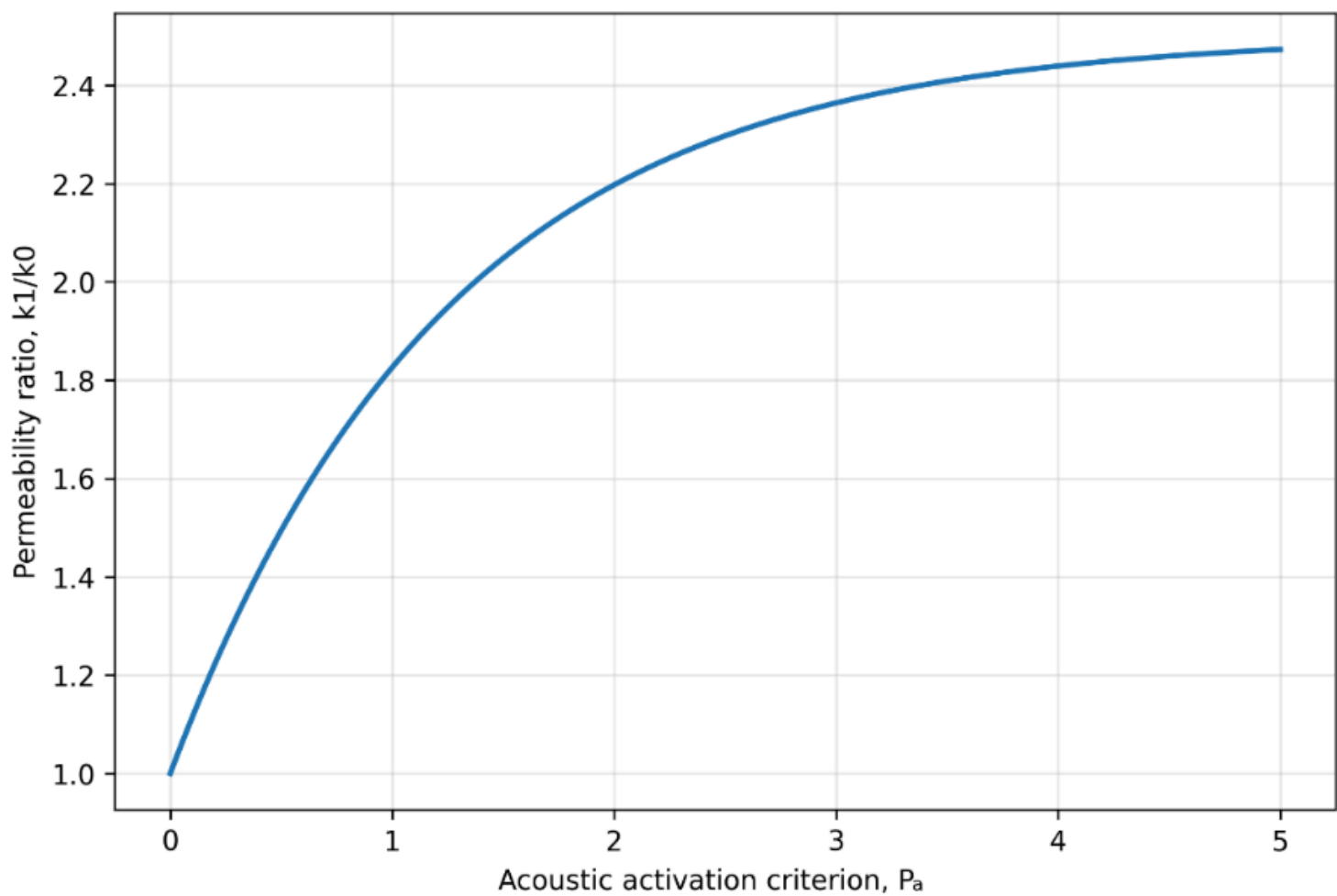


Figure 7

Predicted dependence of the relative permeability ratio k_1/k_0 on the acoustic activation criterion P_a .

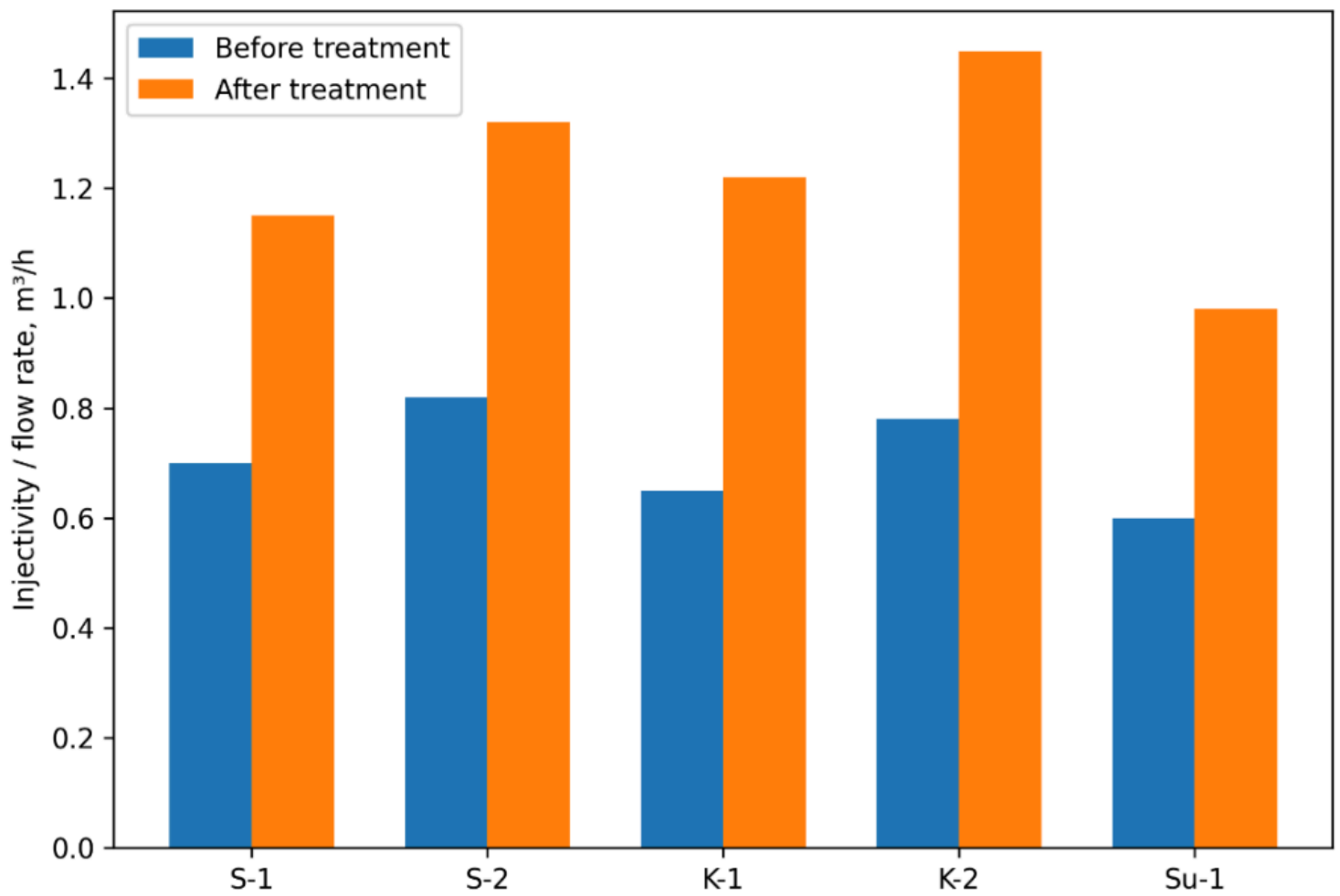


Figure 8

Model comparison of well injectivity before and after hydrodynamic-acoustic treatment.