IOP Conf. Series: Earth and Environmental Science **1630** (2026) 012031 doi:10.1088/1755-1315/1630/1/012031

Mathematical model of acoustic stimulation of wells to increase rock permeability

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Abstract. The article presents a mathematical model of acoustic stimulation of wells to increase the permeability of productive formations in conditions of uranium deposits exploited by the underground leaching method. The model is based on solving the equations of elastic wave propagation in a saturated porous-fractured medium taking into account the elastic, filtration and viscoelastic characteristics of the ore-bearing rocks. Analytical dependences of the radius of the effective impact of the acoustic field on the frequency-energy parameters of the source (frequency, amplitude, pressure in the well) and the filtration-capacitive properties of the formation are obtained. A parametric analysis of the influence of the acoustic impact spectrum on the dynamics of microcrack opening, destruction of colloidal deposits and mobilization of capillary-bound fluid is carried out. The modeling is consistent with the data of laboratory and pilot studies at operating uranium facilities, which confirms the adequacy of the model. The obtained results allow us to reasonably select optimal acoustic impact modes to intensify filtration with minimal energy costs.

1. Introduction

Acoustic stimulation of wells is a modern technology for increasing the permeability of the bottomhole formation zone by influencing the pore-fluid system with elastic waves of various frequency ranges. This method is used to increase the efficiency of mineral extraction, including in-situ leaching, as well as to intensify the inflow of formation fluids in the oil and gas and uranium mining industries [1–5]. Stimulation of wells using electro-pneumatic-hydro-pulses is effectively utilized in managing the stress-strain state of rock masses [6, 7] and in the extraction of methane from coal deposits [8].

The method is based on the principle of changing the physical and mechanical properties of the rock and the structure of the pore space under the influence of acoustic vibrations. Acoustic waves, propagating from a source (often installed in a well) into the formation, cause:

- elastic deformations of the rock skeleton;
- oscillatory movements of the liquid in the pores;
- changes in capillary forces;
- destruction of cementing bridges between grains;

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• opening of microcracks;
• cavitation phenomena in the liquid [9,10].

These processes lead to an increase in the effective permeability of the formation, which allows for the intensification of filtration and leaching processes. There are also known examples of using acoustic effects to monitor the process of destruction of porous materials, such as coal [11].

The physical model of the formation is considered as a three-phase porous medium consisting of a solid skeleton, liquid and gas phases interacting with each other under external dynamic impact. The fundamental works on the theory of poroelasticity, which laid the foundation for the analytical description of such systems, are presented in the works of M. A. Biot [1], L. N. Ryabushko [2], V. M. Zhirkevich [10], as well as in the fundamental monographs of G. A. Maxwell [14], V. V. Dobrynin [15] and others.

Thus, the relevance of the study is determined by the need for a scientifically grounded selection of acoustic stimulation parameters to optimize the technological processes of uranium in-situ leaching and other mineral recovery methods. The aim of this work is to develop a mathematical model of acoustic stimulation of wells that determines the dependencies of the effective radius of acoustic field influence on the spectral and energy characteristics of the source, as well as on the filtration and storage properties of the reservoir.

2. Methods

One of the promising methods for increasing the permeability of the well bottomhole zone is acoustic impact, in which elastic waves are excited in the formation, which contribute to the change in the structure of the pore space and the removal of clogging particles. This leads to a decrease in hydrodynamic resistance and an increase in the filtration properties of the formation [16-18].

The mechanism of the influence of acoustic waves on the permeability of a porous medium is determined by a number of physical effects: vibration compaction, cavitation in the pore fluid, weakening of adhesive bonds between particles, and loosening of clogging deposits [19, 21]. For a quantitative description of this process, a mathematical model is proposed that establishes the dependence of permeability variation on the acoustic effect of fluid pressure.

The permeability of the formation in the acoustic impact zone changes according to the empirical law:

$$k(p) = k_0\left(1 + \alpha p^n\right) \tag{1}$$

where k_0 – initial permeability of the formation, m²; α, n – empirical coefficients determined by laboratory or experimental field studies, p – acoustic pressure in the porous medium, Pa.

This dependence takes into account the influence of acoustic waves on the destruction of weak cementing bridges and mineral inclusions between quartz grains in sandstones, the formation and opening of microcracks, as well as the reduction of capillary forces.

The problem statement is supplemented by boundary and initial conditions:
– on the borehole walls, the acoustic pressure is set in the form of a harmonic function:

$$p(t) = p_0 \sin(\omega t) \tag{2}$$

– at the remote boundaries of the formation (conditionally infinite) – the condition of wave absorption:

$$p \to p_0, u \to 0 \text{ when } r \to \infty$$

– initial conditions:

$$u = 0, \frac{\partial u}{\partial t} = 0, p = p_0 \text{ at time } t = 0 \text{ s.}$$

A homogeneous isotropic porous medium is considered, the permeability of which changes in time under the action of acoustic pressure. The initial permeability of the formation is designated as k_0, and the current permeability in time and radius is $k(r,t)$.

The change in permeability is described by a first-order differential equation:

$$\frac{dk}{dt} = \alpha \cdot \left(p_a(t)\right)^n \cdot \left(k_{\max} - k(t)\right) \tag{3}$$

where $k(t)$ – current permeability of the formation at time t, m²; k_0 – initial permeability of the formation at t=0, m²; k_{max} – maximum (limit) permeability achievable under acoustic stimulation, m²; $p_a(t)$ – amplitude of acoustic pressure as a function of time, Pa; α – empirical coefficient of acoustic stimulation intensity, $s^{-1}\cdot Pa^{-n}$; n – empirical exponent, dimensionless; t – time, s.

The pressure of the acoustic wave in the formation varies with the radius r from the well and time t as follows [16]:

$$p_a(r,t) = p_0 \cdot e^{-\beta r} \cdot \sin(\omega t) \tag{4}$$

where p_0 – is the amplitude of the acoustic wave pressure at the well wall, Pa; β – is the attenuation coefficient of acoustic waves in the formation, m^{-1}; r – radial distance from the well axis, m; ω – is the circular frequency of the acoustic impact, rad/s.

For numerical calculation of the integral change in permeability during the exposure time T, the following is used:

$$\Delta k(r,t) = \int_0^T \alpha \cdot \left(p_a(t)\right)^n \cdot \left(k_{\max} - k(t)\right) \tag{5}$$

In a stationary setting with prolonged exposure, the formula takes the form:

$$k(r) = k_{\max}\left(1 - e^{-\gamma p_o^n e^{-\beta n r} T}\right) \tag{6}$$

where $\gamma = \alpha(k_{max} - k_0)$ – generalized parameter characterizing the intensity of permeability growth under acoustic stimulation, with units $s^{-1}\cdot Pa^{-n}\cdot m^2$.

The constructed model allows to estimate the radial distribution of permeability change from the well depending on the parameters of acoustic impact. The obtained dependencies can be used to design well treatment modes using methods of acoustic impact in order to increase productivity.

Acoustic waves in a saturated formation of uranium deposits are described as the coupled propagation of elastic waves in the solid matrix of the formation and pressures in the pore fluid. Depending on the frequency of impact and permeability of the medium, longitudinal waves of the first and second kind, shear waves, and slow Biot waves can propagate in the formation [12].

To describe the dynamic state of a porous formation under acoustic impact, a system of equations is used:

- the equation of motion of the solid matrix (solid phase) of the formation;
- the equation of motion of the pore fluid (based on Darcy’s law or a modified Biot law);
- the fluid state equation;
- the equation relating the deformations of the solid matrix to changes in fluid pressure.

With regard to the problem of acoustic stimulation, the following physical effects can be distinguished:

- Oscillatory deformations of the solid matrix of the formation lead to changes in the pore space volume, which cause pressure drops in the fluid.
- Acoustic waves periodically modulate the fluid pressure, causing a local increase in pressure within micropores and microcracks.
- The dynamic action of acoustic waves contributes to the rupture of weak bonds between grains and the opening of microcracks in the pores.
- A decrease in capillary forces due to vibration leads to an increase in fluid mobility.
- The destruction of weak bridges between grains contributes to an increase in effective permeability.

These phenomena are quantitatively described through the dynamics of poroelastic systems presented in the works [16-20].

Main assumptions of the problem are:

• The rock is considered as a linearly elastic, homogeneous and isotropic porous medium.
• Porosity and permeability are initially known but can change under the action of acoustic waves.
• The liquid in the pores is incompressible or slightly compressible.
• The process of propagation of acoustic waves is considered linear.
• Thermal influence is negligible.

The physical and mathematical model is based on the laws of conservation of mass, momentum, equation of state and constitutive relations for an elastic porous medium.

Acoustic stimulation of wells induces wave processes in the near-wellbore zone, during which the solid matrix of the formation undergoes periodic elastic deformations. This is one of the key mechanisms leading to a change in the structure of the pore space, the opening of microcracks and an increase in the permeability of the formation.

In the first approximation, the rock is considered as a linearly elastic, isotropic, and porous medium, with the behavior of its solid matrix under the effect of acoustic waves described by the laws of linear elasticity.

The elastic deformations of the solid matrix are determined by the relationship between stresses and strains. For an isotropic medium, this is expressed by the generalized Hooke’s law:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \lambda\delta_{ij}\varepsilon_{kk} \tag{7}$$

where σ_{ij} – is the stress tensor, Pa; ε_{ij} – is the strain tensor; G – is the shear modulus, Pa; λ – is the first Lame coefficient, Pa; δ_{ij} is the Kronecker symbol.

The elastic moduli are expressed through Young's modulus E and Poisson's ratio v:

$$G = \frac{E}{2(1+v)}, \lambda = \frac{Ev}{(1+v)(1-2v)} \tag{8}$$

The mechanism of deformations under the action of acoustic waves when acoustic waves pass through the formation, periodic elastic deformations occur:

- longitudinal deformations – compressive-tensile movements of particles along the direction of wave propagation;
- transverse deformations – movements of particles perpendicular to the direction of the wave;
- volumetric deformations – changes in the volume of pore space.

Oscillatory deformations of the solid matrix cause changes in pore volume, leading to variations in fluid pressure, the opening of microcracks, weakening of cementing bridges between grains, and loosening of weakly bound sections of the rock. These processes accelerate filtration and increase permeability, especially in the near-wellbore zone.

The behavior of a porous medium saturated with fluid under the effect of acoustic waves is described by a system of equations that account for the coupled motion of the solid matrix and the pore fluid. Such models most accurately reflect the physics of processes during acoustic stimulation of wells.

A porous medium is considered a two-phase system comprising an elastic solid matrix (rock matrix) and a liquid phase (pore fluid). The coupled motion of the solid matrix and fluid is described within the framework of the theory of elasticity of saturated porous media. The classical approach was proposed by M. A. Biot [1].

The dynamics of the solid matrix, taking into account the pore fluid, is described by the Biot equation:

$$\rho\frac{\partial^2 u_i}{\partial t^2} = \frac{\partial\sigma_{ij}}{\partial x_j} - \alpha\frac{\partial p}{\partial x_i} \tag{9}$$

where u_i– are the components of the skeleton displacement vector, m; p – is the fluid pressure in the pores, Pa; α – is the Biot coefficient (depending on the porosity and elastic properties of the rock), ρ – is the average density of the porous material, kg/m^3.

For filtration fluid (based on modified Darcy's law):

$$m\frac{\partial^2\omega_i}{\partial t^2}+b\left(\frac{\partial\omega_i}{\partial t}-\frac{\partial u_i}{\partial t}\right)=-\alpha\frac{\partial p}{\partial x_i} \tag{10}$$

where ω_i – components of the liquid displacement vector, m; m – liquid density, kg/m^3; b – filtration resistance coefficient (depending on permeability and viscosity), kg/(m^3·s).

Relationship between stresses and strains (Hooke's law for a porous medium)

$$\sigma_{ij}=2G\varepsilon_{ij}+\lambda\delta_{ij}\varepsilon_{kk}-\alpha p\delta_{ij} \tag{11}$$

where ε_{ij} – is the strain tensor of the solid skeleton; G, λ –are the Lame moduli, Pa; α – is the Biot coefficient.

The relationship between pressure and deformation is determined from the equation of volume balance of liquid and skeleton:

$$\frac{\partial p}{\partial t}+M\frac{\partial}{\partial}(\Delta\cdot u)=0 \tag{12}$$

where M – is the compressibility modulus of the saturated medium, Pa.

After combining the equations of motion of the solid matrix and the fluid, along with the relationships between stresses and strains, wave equations are derived that describe the propagation of elastic oscillations in a porous medium. According to Biot's theory [1], two types of longitudinal waves can propagate in such a system:

• Longitudinal wave of the first kind (wave of the solid matrix);

• Longitudinal wave of the second kind (wave of the fluid relative to the solid matrix).

These waves differ significantly in phase velocity, degree of attenuation and mechanism of energy transfer.

The system of Biot equations, in the absence of tangential deformations and with linear small oscillations:

Simplified form of the wave equation:

$$\rho\frac{\partial^2 u}{\partial t^2}+b\frac{\partial u}{\partial t}\left(\frac{\partial u}{\partial t}-\frac{\partial\omega}{\partial t}\right)=\left(K+\frac{4}{3}G\right)\Delta^2 u+\alpha\Delta p \tag{13}$$

$$m\frac{\partial^2\omega}{\partial t^2}-b\left(\frac{\partial u}{\partial t}-\frac{\partial\omega}{\partial t}\right)=-\Delta p \tag{14}$$

$$p=-M\left(\Delta\cdot u+\frac{1}{n}\Delta\cdot(\omega-u)\right) \tag{15}$$

where K – is the bulk modulus of the solid matrix, Pa; n – is the porosity; other parameters are as before.

Wave equations of two types. After eliminating the pressure p and relative displacements, a system of two independent wave equations is obtained for the divergences of the displacements of the solid matrix and the fluid:

For a longitudinal wave of the first kind (solid matrix wave):

$$\frac{\partial^2 U}{\partial \mathrm{t}^2}=c_1^2\Delta^2 U-\gamma(U-W) \tag{16}$$

For a longitudinal wave of the second kind (fluid):

$$\frac{\partial^2 W}{\partial \mathrm{t}^2}=c_1^2\Delta^2 W+\gamma(U-W) \tag{17}$$

where $U=\Delta \cdot u$ – divergence of solid matrix displacement; $W=\Delta \cdot w$ – divergence of fluid displacement; c_1, c_2 – phase velocities of two types of longitudinal waves, m/s; γ – parameter of mutual phase resistance, kg/(m³·s).

Wave properties: The longitudinal wave of the first kind (solid matrix wave) propagates faster, with lower attenuation, as the elastic framework of the rock carries the main energy. The longitudinal wave of the second kind (fluid wave) is much slower and strongly attenuates at a distance of several pore sizes, causing relative motion between the fluid and the solid matrix – an important effect for crack opening and permeability changes.

In a saturated porous medium, both types of waves are subject to dispersion and viscous attenuation. Their phase velocities and attenuation coefficients depend on: the frequency of acoustic oscillations, permeability, viscosity of the liquid, elasticity moduli.

This makes it possible to select effective frequencies of acoustic stimulation, minimizing the attenuation of the solid matrix wave and enhancing oscillatory fluid filtration.

Thus, in a porous medium, under the action of acoustic waves, two types of longitudinal vibrations with different physical mechanisms and effects on the permeability of the formation are propagated. The mathematical description of these processes through the Biot equations allows modeling and optimizing the parameters of acoustic stimulation of wells. They allow an adequate description of the dynamics of processes leading to a change in the permeability of the bottomhole zone, as well as optimizing the parameters of acoustic impact.

Acoustic impact on fluid-saturated porous media causes a complex of elastic and filtration processes, accompanied by deformations of the solid skeleton. These deformations lead to a number of physical effects that significantly affect the filtration-capacitive properties of rocks.

The main effects of deformation of the solid matrix of a porous medium include: changes in the pore space volume; depressurization and opening of microcracks; destruction of cementing bridges between grains; reduction of capillary forces and increase in fluid mobility; stress redistribution in the rock; possible occurrence of cavitation phenomena. A schematic representation of the deformation effects is shown in figure 1.

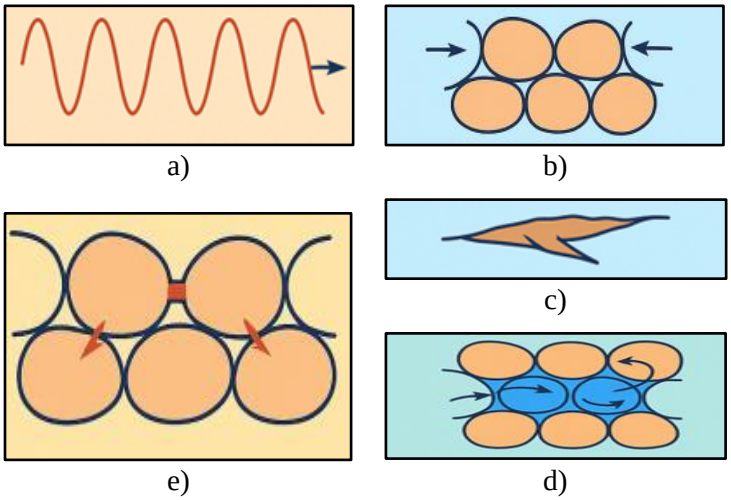


Figure 1 – Schematic representation of deformation effects in a porous medium under the influence of acoustic waves: a – propagation of a longitudinal wave; b – elastic deformation of the solid matrix; c – opening of microcracks; d – fluid movement in the pore space; e – loosening of cementing bridges.

Under the influence of cyclic deformations, the pore volume changes, which leads to periodic compression and expansion of the pores, causing local pressure drops in the liquid. This effect is accompanied by the movement of liquid within the pore space and initiates filtration flows [1, 2].

Oscillatory loads lead to the accumulation of elastic and residual deformations, especially in fractured and heterogeneous rocks. This contributes to the opening of existing cracks, as well as the formation of new microcracks, which leads to an increase in effective permeability [3].

Acoustic waves provoke high-frequency deformations of contacts between mineral grains. In this case, weak cementing bonds are weakened and destroyed, which increases the mobility of the grain

framework and opens up new paths for fluid filtration [4, 5].

Cyclic deformations and vibrations reduce capillary forces due to dynamic changes in the curvature of the meniscus and oscillations of phase boundaries. This is especially pronounced in fine-pored structures with capillary connectivity between pores [9].

Wave action causes a temporary redistribution of stresses, leading to a local decrease in the effective stress in the bottomhole zone, which facilitates fluid movement and initiates filtration [10,11].

At a sufficiently high amplitude of the acoustic wave pressure in the pore fluid, the formation and collapse of cavitation bubbles may occur. This effect is accompanied by high-speed microjets and local pressure surges that destroy the pore framework and clean the pore channels [12].

The effects of deformations in porous media under the action of acoustic waves have been repeatedly confirmed by laboratory and field studies. In the works of Akhmetov S.I. and Gulyaev R.N., permeability in fractured reservoirs increased by 1.5–3 times after acoustic treatment [13]. In the experiments of Dobrynin V.V., a decrease in capillary pressure and an increase in the filtration capacity of sand samples under the action of acoustic waves with a frequency of 15–25 kHz were recorded [3].

The combined effect of the listed effects leads to an increase in the effective permeability of the bottomhole formation zone, which is the technological task of acoustic stimulation.

The effects of deformations in porous media under the action of acoustic waves include mechanical, filtration, and capillary processes leading to structural changes in the solid matrix and an increase in its permeability. Taking these effects into account is mandatory when constructing mathematical models and designing acoustic stimulation technologies.

3. Results and discussion

For the numerical analysis of the proposed mathematical model, the finite difference method (FDM) or the finite element method (FEM) is used, which allows solving problems of interaction between an elastic porous medium and a liquid under external acoustic influence.

The calculation area is taken as a ring area with radius R_{max} and thickness H, the borehole axis is aligned with the symmetry axis. The calculation grid is constructed with a uniform step by radius and time.

The calculation scheme includes:

- discretization of the equations of rock motion and fluid filtration;
- calculation of changes in permeability at each time step;
- accounting for acoustic pressure as a boundary condition;
- adaptive time step for stability according to the Courant criterion.

As an example, let's consider a layer with the following parameters (table 1).

Table 1. Reservoir parameters.

Parameters	Values	Parameters	Values
Rock density, ρ_s	2600 kg/m³	Initial permeability, k_0	1×10^{-15} m²
Young’s modulus, E	18 GPa	Acoustic impact coefficient, α	0.02 MPa^{-n}
Poisson’s ratio, ν	0.25	Exponent, n	1.5
Fluid density, ρ_f	1000 kg/m³	Acoustic wave pressure, p_a	3.0 MPa
Fluid viscosity, μ	1.2 mPa·s	Frequency, $\omega/2\pi$	20 kHz

The results of calculating the change in permeability over time are shown in table 2.

Table 2. Calculating results.

Time, ms	0	5	10	20	50
Permeability, m²	1.00×10^{-15}	1.52×10^{-15}	2.10×10^{-15}	3.08×10^{-15}	4.85×10^{-15}

The simulated dependence of the change in permeability on the time of acoustic exposure is shown in figure 2.

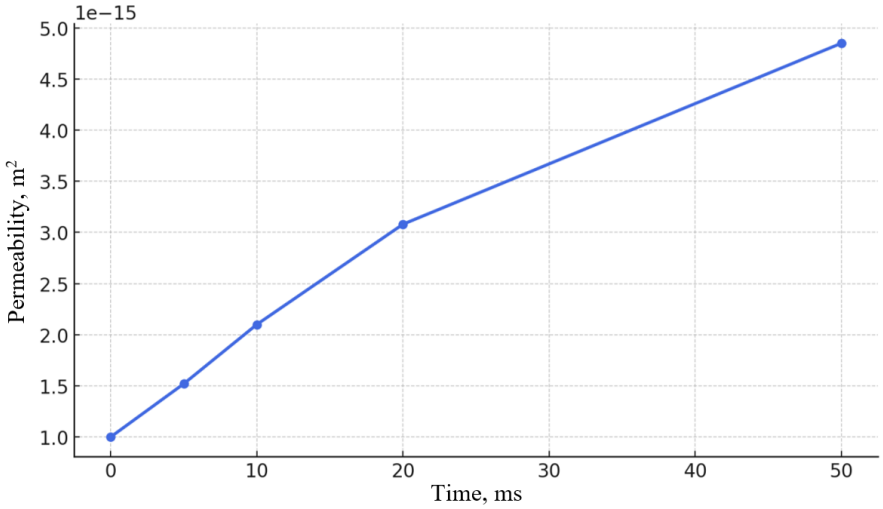


Figure 2. Graph of change in permeability over time under acoustic impact.

Acoustic impact on the bottomhole formation zone leads to a change in permeability due to deformation of the porous skeleton and opening of microcracks. However, the intensity of the acoustic wave pressure decreases with distance from the source, which limits the zone of effective influence.

The effective influence radius Reff is defined as the distance from the well within which the amplitude of the acoustic wave pressure is sufficient to produce a specified change in permeability.

In a simplified model of spherically symmetric attenuation of the amplitude of the acoustic pressure in a porous medium is based on the works [22, 23]. Propagation of acoustic waves within the framework of the biophysical theory of acoustics in saturated porous media in a porous medium, the pressure amplitude decreases according to the law:

$$p(r) = p_0 \frac{R_0}{r} \exp(-\alpha(r - R_0)) \tag{18}$$

where p_0 – is the pressure amplitude at the borehole wall, Pa; R_0 – is the borehole radius, m; α – is the attenuation coefficient of acoustic waves in the medium, m^{-1}; r – is the distance from the borehole axis, m.

Let us assume that the effective impact is realized up to the distance at which the pressure does not fall below the critical p_{cr}, causing a change in permeability:

$$R_{eff} = R_0 + \frac{1}{\alpha} \ln\left(\frac{p_0 R_0}{p_{cr} R_{eff}}\right) \tag{19}$$

Transforming the equation:

$$R_{eff} = \frac{R_0}{1 - \frac{\alpha R_0}{\ln(p_0 / p_{cr})}} \tag{20}$$

For cases when $\alpha R_0 << \ln(p_0 / p_{cr})$, we can adopt the approximation:

$$R_{eff} \approx \frac{\ln(p_0 / p_{cr})}{\alpha} \tag{21}$$

Dependence on environmental parameters and impact.

- With an increase in the amplitude of the acoustic pressure p_0, the radius of effective action increases logarithmically.
- With an increase in the attenuation coefficient α, the zone of action narrows.

- The critical pressure p_{cr} depends on the mechanical properties of the collector and the presence of cracks.

Figure 3 shows the change in the dependence of the radius of action on the pressure amplitude at a fixed attenuation coefficient α = 2.5 m^{-1} for the conditions of uranium deposits (sandstones with a permeability of 0.2–1.0 mD and a porosity of 25–35%).

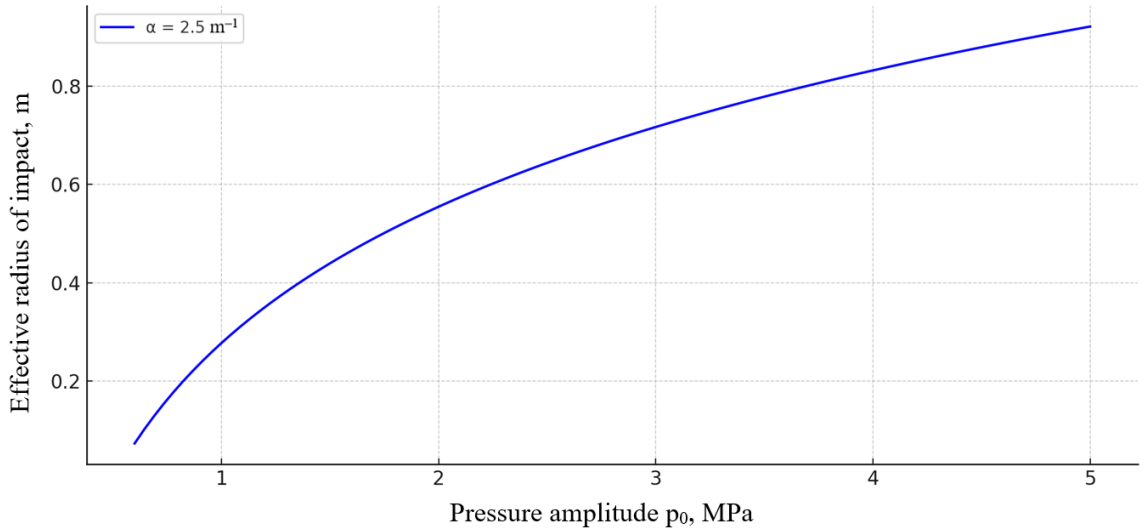


Figure 3. Dependence of the radius of influence on the amplitude of acoustic wave pressure at α= 2.5 m^{-1}.

Studies have shown that as the amplitude of the acoustic wave pressure increases, the positive effect on the expansion of the effective influence zone grows in a logarithmic manner.

Figure 4 shows how the effective impact radius decreases with increasing attenuation coefficient. In uranium deposits, the value is usually in the range of 1.5–3.5 m^{-1}.

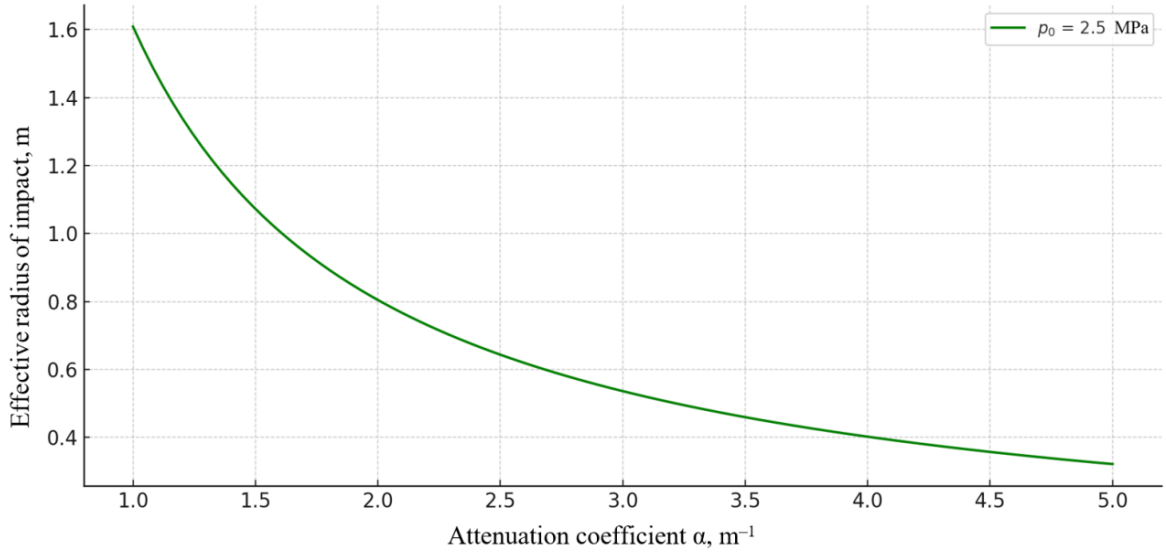


Figure 4. Dependence of the effective impact radius on the attenuation coefficient at p_0=2.5 MPa.

Research has established how the effective impact radius decreases exponentially with increasing attenuation coefficient. The stronger the energy dissipation in the rock, the smaller the effective impact zone. An increase in the attenuation coefficient associated with an increase in frequency or a change in lithology significantly limits the impact radius.

Dependence of the radius on the frequency of acoustic waves.

Since in saturated porous media the attenuation coefficient depends on the frequency, it can be approximately described by the expression:

$$\alpha(f) = k\sqrt{f} \tag{22}$$

where k – is an empirical coefficient (in the range of 0.2–0.4 for sandstones).

Figure 5 shows the change in the maximum radius of effective impact with acoustic impact on the bottomhole formation zone depending on the frequency of acoustic waves (20–300 Hz) in a porous medium, determined by mathematical calculations.

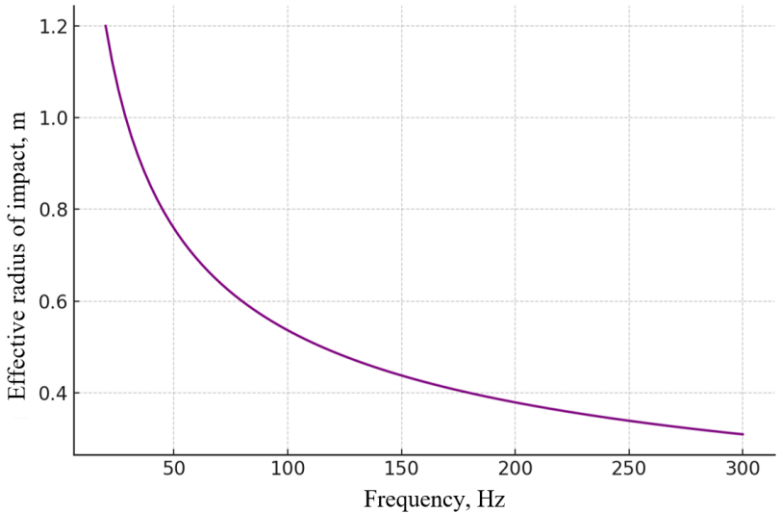


Figure 5. Dependence of the effective impact radius on the frequency of acoustic waves.

Research has shown that with an increase in the frequency of acoustic waves, the radius of effective action decreases, which is associated with an increase in the attenuation coefficient $\alpha \infty \sqrt{f}$ in a saturated porous medium.

Figure 6 shows the dependence of the maximum radius of effective impact with acoustic impact on the bottomhole formation zone on the wellbore radius.

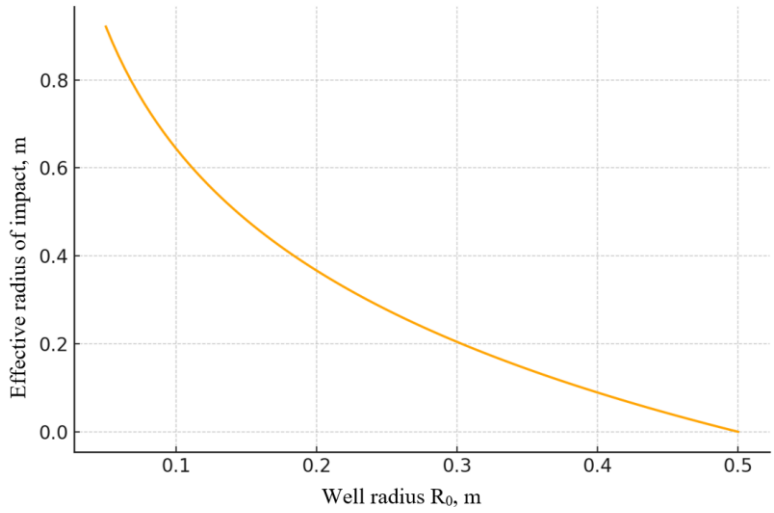


Figure 6. Dependence of the effective impact radius on the frequency of acoustic waves.

Increasing the well radius reduces the initial pressure at the acoustic wave front and decreases the effective radius. The effective radius of acoustic pressure is determined logarithmically from the ratio of the pressure amplitude to the threshold value and is inversely proportional to the attenuation coefficient of the medium. This indicator is used in designing well bottomhole zone stimulation modes.

4. Conclusions

The developed mathematical model of acoustic stimulation of wells accounts for the combined influence of elastic deformations, acoustic wave pressure, and fluid filtration on changes in the permeability of the bottomhole zone. It enables the prediction of treatment effectiveness depending on the acoustic field parameters and the physical properties of the rock. The modeling results can be applied to optimize the parameters of acoustic technologies under the conditions of specific deposits.

Numerical modeling has shown that acoustic stimulation is capable of significantly enhancing the permeability of the bottomhole zone over a short timescale. The maximum increase is achieved in the first milliseconds of exposure, after which the process stabilizes. The calculated data are consistent with experimental and field results.

Increasing the pressure amplitude has a positive effect on expanding the effective impact zone. An increase in the attenuation coefficient associated with an increase in frequency or a change in lithology significantly limits the radius of impact. The optimal frequency range for stimulating uranium deposits is within 50–200 Hz.

References

[1] Biot M A 1956 *Theory of propagation of elastic waves in a fluid-saturated porous solid* I Low-frequency range *J Acoust Soc Am* **28** p 179–91
[2] Ryabushko L N 1974 *Wave processes in porous media* (Minsk: Nauka i tekhnika)
[3] Carcione J M, Morency C and Santos J E 2010 Computational poroelasticity – A review Geophysics 75 75A229–75A243 https://doi.org/10.1190/1.3474602
[4] Akhmetov S I 1987 *Acoustic methods for enhancing oil recovery from reservoirs* (M.: Nedra)
[5] Gulyaev R N Gubaidullin AA 2018 Acoustic wave stimulation of oil production *J Petrol Sci Eng* **170** 169–78
[6] Bulat A F 2004 *Rock deformation problems* Int Appl Mech **40** 1311–22 https://doi.org/10.1007/s10778-005-0039-y
[7] Zberovskyi V , Bubnova O and Babii K 2018 *Specifics of hydro-loosening of coal seams with account of rocks displacement parameters* E3S web of conferences 60 00025 DOI: https://doi.org/10.1051/e3sconf/20186000025
[8] Ahaiev R, Prytula D, Kliuiev E, Zhytlonok D, Cabana E, Kabakova L 2020 *The determination of the influence degree of mining-geological and mining-technical factors on the safety of the degassing system* E3S web of conferences **168** 00040 https://doi.org/10.1051/e3sconf/202016800040
[9] Zhang L, Zhao J, Chen Y and Xu J 2021 *Acoustic wave stimulation to enhance permeability of porous rocks: laboratory experiments and numerical simulation* Journal of Petroleum Science and Engineering 205 108913 https://doi.org/10.1016/j.petrol.2021.108913
[10] Zhirkevich V M 1982 *Physics of processes in porous bodies* (M.: Nedra)
[11] Zberovskyi V, Ahaiev R, Vlasenko V and Kyrychenko M 2025 *Acoustic monitoring of the coal-rock massif state in stress-strain zones during hydroimpulsive impact application experience* Acoustical Engineering (London: IntechOpen) chapter 100664 https://doi.org/10.5772/intechopen.100664
[12] Gubaidullin A A and Mustafin H H 2020 *Propagation of acoustic waves in porous rocks: mathematical modeling and field experiments* Appl Acoust **167** 107392
[13] Akhmetov S I and Gulyaev R N 2015 *Acoustic methods for increasing the permeability of fractured reservoirs* Neftegazovoe delo **13** 45–52

[14] Maxwell G 1975 *Mechanical Properties of Rocks* (Academic Press)
[15] Dobrynin V V 1986 *Acoustics of porous media* (M.: Nedra)
[16] Abramov A A 2017 *Acoustic methods of impacting the bottomhole zone of wells* (M.: Nedra)
[17] Panov K A and Pustovalov V N 2019 Increasing the permeability of oil reservoirs with acoustic waves *Geologiya i razrabotka neftyanykh i gazovykh mestorozhdeniy* **6** 35–42
[18] Zberovskyi V V, Krukovskyi O P, Zhulai Yu O and Angelovskyi OA 2024 *Hydrodynamic Cavitation in Solving the Problem of Gas-Dynamic Factor in Coal Mines* (K.: Naukova dumka) p 340
[19] Johnson D L and Plona TJ 1982 *Acoustic wave propagation in porous media* J Acoust Soc Am **72** 556–65
[20] Mikhailov V and Gurevich B 2015 Influence of acoustic waves on permeability of porous media *Geophysics* **80** EN1–EN13
[21] White JE 1983 *Underground Sound: Application of Seismic Waves* (Amsterdam: Elsevier) p 352
[22] Li Y, Gurevich B and Müller T M 2020 *Effects of wave-induced fluid flow on seismic attenuation and dispersion in fractured porous rocks* Geophysical Journal International 221 2121–2135 https://doi.org/10.1093/gji/ggaa124
[23] Pride S R 1994 *Governing equations for wave propagation in fluid-saturated porous media* Phys Rev *B* **50** 15678–96