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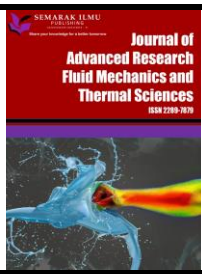

Pore Pressure Diffusion Waves Transmission in Oil Reservoir

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ABSTRACT

Recent studies on seismic wave excitation have revealed that mesoscopic wave-induced fluid flow (WIFF) is a process that attenuates the compressional (P) waves in reservoir rocks at seismic frequency bands. Fluid flow and Biot's slow diffusion (pressure) waves are produced when the P-waves create fluid-pressure gradients at mesoscopic-scale heterogeneities. Pore pressure continuity can be sustained by converting seismic energy into diffusion waves that diffuse away from the interfaces or boundaries. Biot's diffusion waves fail to comply with a square-law approach because of their slow propagation velocity and higher attenuation. It is currently uncertain how to characterize reservoir fluids in mature oil reservoirs during seismic wave-based enhanced oil recovery (EOR). A simplified 1D two-layer reservoir model was investigated in this study. The findings demonstrate that diffusion wave propagation in oil reservoirs is frequency-dependent and affected by rock permeability and fluid viscosity. At a formation layer interface, it was discovered that diffusion waves obeyed the accumulation-depletion relationship rather than the reflection-refraction approach. Therefore, pore pressure diffusion waves can characterize reservoir fluid during seismic EOR and monitor the CO_2 front in depleted reservoirs during storage for CCUS projects. It can also detect shale gas transport in low permeability layers and identify the propagation of fractures during gas/oil recovery.

1. Introduction

The diverse heterogeneities of reservoir rocks can generate wave-induced fluid flows (WIFF) at various scales, resulting in wave amplitude attenuation and phase velocity dispersion. The reservoir rock exhibits multifaceted heterogeneity due to spatial changes in fluid saturation, lithology, permeability, porosity, etc., which generate pore fluid pressure gradients and produce heterogeneous fluid flows at the reservoir rocks' macro-, meso-, and micro-scales [1]. The wave attenuation and velocity dispersion characteristics are advantageous for gathering and collecting subsurface data for various research and practical applications, including energy exploration and production, groundwater management, and monitoring of CO_2 geological storages

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[1,2]. A porous medium may respond dynamically in a time-dependent manner to represent the influence of solid and fluid interaction via rock matrix displacement and fluid flow [3]. The poroelasticity model provides a method for investigating the complex relationship between rock matrix displacement and pore fluid flow [4,5]. It was developed based on the assumption that fluid would flow in an isotropic homogenous medium [4]. As a result, it fails to reflect the detrimental impact of formation heterogeneity. Nevertheless, many real-world problems with subsurface flow rely on estimations at large spatial scales, where various natural heterogeneities are considered. Therefore, including the impact of formation rock heterogeneity in the poroelasticity model becomes necessary. The physics of multiphase fluid flow in porous media coupled with elastic wave transmission is gaining popularity [6]. It is useful in numerous technical applications, including seismic wave imaging and acoustic wave excitation, to improve hydrocarbon recovery from underground oil reservoirs and NAPL (nonaqueous phase liquid) polluted sites [6-9].

Using theoretical formulations, Biot was the first to express poroelasticity in a homogeneous, isotropic, and elastic porous media with a single compressible viscous fluid. The Biot formulations establish the presence of two separate forms of compressional (P) wave propagation in a porous media saturated with fluid [1,3,10-13]. The Biot fast P-wave is the first compressional wave in the porous media when the displacements of the solid rock matrix and pore fluid are in phase. The Biot slow P-wave is a second compressional wave that exits in the porous media when the solid rock matrix vibrates out of phase with the pore fluid [10,14]. The viscous pore fluid dissipative flow relative to the elastic solid matrix causes both P-waves to be attenuated in the porous media [10,11,13]. It is necessary to carry out a normal coordinate conversion that separates P-wave types to generate closed-form analytical formulations of the Biot model equations that involve a range of initial and boundary conditions [10]. The diffusion equation for pore pressure was formulated using the foundations of Rice and Cleary [15], Rudnicki [16], and dynamic poroelasticity [13]. Chandler and Johnson [17] showed that when inertial terms are ignored, it is possible to decouple the Biot mathematical equations in the time domain using two real-valued normal coordinates that agree with a Laplace equation for the Biot fast P-wave and a diffusion equation for the Biot slow P-wave, respectively. The presence of inertial terms in the theoretical formulation does not prevent decoupling into Chandler-Johnson normal coordinates in the time domain. However, it necessitates the application of a constraint model that links the coefficients of elasticity moduli to the inertial terms in the Biot formulations [18]. Moreover, the Fourier transform can decouple Biot mathematical formulations for P-waves into the frequency domain without limitations [19,20]. The products of the decoupled equations are a dissipative wave equation for the Biot slow P-wave and a propagating wave equation for the Biot fast P-wave [10]. The induced pore pressure is predicted to obey a low-frequency wave or diffusion equation, which implies that diffusion waves are the waves that transmit the pore-pressure signal [3].

Diffusion wave models have been applied to represent a variety of transmission phenomena in poroelastic media, including wave-induced motion of solutes in homogeneous and mixed porous media with hybrid heterogeneity or interfaces/boundaries where wave field discontinuities continue to exist [21-24]. The diffusion wave field is also characterized as a hydraulic head in the groundwater hydrology field. It is often driven by tidal forces in surface water bodies, earth tides, or seasonal effects. Low-frequency diffusion waves can travel through aquifers, whereas high-frequency waves are significantly damped according to the governing equation. It is quite interesting to study nonlinear diffusion waves because these phenomena frequently occur in groundwaters near beaches, riverbanks, etc., while possessing distinctive features [25,26]. Mandelis focused his formulations on areas critical to modern physics, such as materials science, photonics, and other fields. Dialysis membranes, electrolytes, metals, and the study of periodic atomic and molecular diffusion mechanisms in polymers using pressure oscillations in a vacuum chamber were among the initial applications of diffusion waves for mass transport using modulated input sources [24,27]. Mandelis [28,29] developed the present theory of diffusion wave transmission in porous media [30,31]. The essential property of diffusion waves is that their transmission obeys Fick's Law of Diffusion, which impacts the waveform at boundaries/interfaces [29]. The model of diffusion waves was developed by coupling the standard diffusion equation to an oscillating force function [30]. Parabolic formulations can mathematically express pressure diffusion wave distribution in porous media [29]. These waves are called pressure diffusion or thermal waves due to the heat conductance and diffusion mechanisms regulated by parabolic equations [30]. A Fourier transform was used to develop a pseudo-wave Helmholtz model. The diffusion length governs the spatial correlation of the phase lags in diffusion waves. Dynamic diffusion phenomena can be spatially controlled using diffusion waves. Studies showed that any local disturbance at physically infinite field transmission velocity causes abrupt perturbations over complete wave domains due to the dissipative properties of diffusion waves.

The transmission of low- and high-frequency waves in porous media saturated with pore fluid continues to be of great interest in scientific research. Biot developed the concept of poroelasticity and projected the occurrence of slow P-waves of the diffusive kind that are significantly attenuated at low-frequency bands. Nevertheless, Biot's theory could not accurately estimate the reported enormous attenuation of low-frequency waves [32]. Biot's poroelasticity models failed to account for squirt flow since it occurs at the microscopic scale [33]. Pore pressure buildup and depletion were linked to wave transmission in saturated poroelastic media. Norris developed a model of pressure diffusion waves within saturated porous media to describe the pore pressure relaxation (relaxed and unrelaxed) limitations of WIFF [34]. In addition to establishing the framework for a pressure diffusion process that can be used in the low-frequency band of pressure fluctuations, Norris paid attention to the initial investigations by Silin *et al.,* [35]. Pressure diffusion wave mechanisms have recently been discovered in several significant geophysical and geological processes, such as ground deformation due to the injection of CO_2 into saline aquifers, hydraulic fracturing conducted during shale gas exploration, micro-seismicity swarms caused by subsurface fluid injections, sedimentary rock fracture development, viscous fingering triggered by pore pressure shifts in reservoirs during CO_2 capture and sequestration processes, and other geophysical inversion and interpretation [30,31,36-47]. Diffusion waves have recently been developed to represent some characteristics of thermal waves and dispersed laser beams transmitting in a diffuse photon-density porous media [30]. In recent years, effective heat transmission has become a challenge for numerous mechanical industry sectors, chemical processing facilities, microelectronic chips, etc. [48].

Pore pressure diffusion waves have higher frequency-dependent attenuation and slow propagation velocities in porous media. The oil recovery industry continues to lack an in-depth understanding of the role that strongly attenuated and slow-speed diffusion waves play in characterizing reservoir fluid during seismic wave-based enhanced oil recovery (EOR). Another issue in the energy industry concerns how diffusion waves detect and visualize CO_2 plume displacement at the interface between different formation layers during the geo-sequestration process. More research is needed to validate the performance of complex diffusion wave mechanisms in oil reservoirs during seismic EOR. This study investigates the complex behavior and process of pressure diffusion wave propagation at the interface of a two-layer oil reservoir model. The significance of EOR strategies to boost oil production from mature oil reservoirs has grown because of the ongoing demand for hydrocarbon-based energy sources and the challenges (financial and technological) associated with exploring and developing new oilfields [49-52]. Seismic wave transmission approaches can be used to monitor and visualize CO_2 plume displacement in subsurface geological storages, such as depleted offshore oil reservoirs and deep saline aquifers, etc. [53]. The pressure diffusion wave governing equation in a two-layer reservoir was solved using the Fourier and Laplace transforms. A diffusion wave model was implemented in MATLAB 2023a to characterize reservoir fluids during seismic wave stimulation.

2. Methodology

2.1 Pore Pressure Diffusion Waves Physics in the Oil Reservoir

Due to the seismic excitation, the pore fluids in a heterogeneous oil reservoir can be characterized efficiently using a simplified two-layer reservoir model (Figure 1). It is possible to expand the traditional fluid flow model in reservoir engineering to a coupled fluid flow and geomechanical formulation to create a diffusion wave model. This work emphasizes understanding logical relationships and interpretations of the diffusion wave behavior in oil reservoirs due to the application of seismic stress fields. The diffusion expression of pore pressure wave transmission in saturated porous media can be derived when the excitation forces are neglected, and there is no delay during the energy conversion process [30,31,34]. We focus on transmitting pressure diffusion waves in a 1D, two-layer reservoir model for simplification and generalization. This study adopted the geomechanical formulation of Chen *et al.,* [53] to model pressure diffusion wave processes in the poroelastic media. The dynamic Biot approach is used to simulate the propagation of slow P-waves across the layers in the reservoir. Since the slow P-wave involves the movement of coupled fluid and solid phases, its speed and attenuation are influenced by the geometry of the pore spaces, which also affects fluid transport characteristics such as formation permeability [54]. At interfaces, the manner of conversion from fast P-wave to slow P-waves should be a major source of significant wave attenuation as the slow P-wave travels through pore space. The mechanical response of a porous media is influenced by the presence of a flowing viscous fluid in the pore spaces. Simultaneously, the viscous fluid within the pores changes how the internal physical state of the matrix skeleton behaves [55]. During seismic excitation, more energy can be directed toward the slow waves through pore-flowing coupling. The propagation of slow P-waves cannot be applied for deeper target formations based on estimations of penetration depth, which is significantly less than a meter [56,57]. However, it was predicted that seismic waves could penetrate regions with low permeability and highly heterogeneous reservoir formations that conventional oil recovery techniques could not easily access [52,53,58,59].

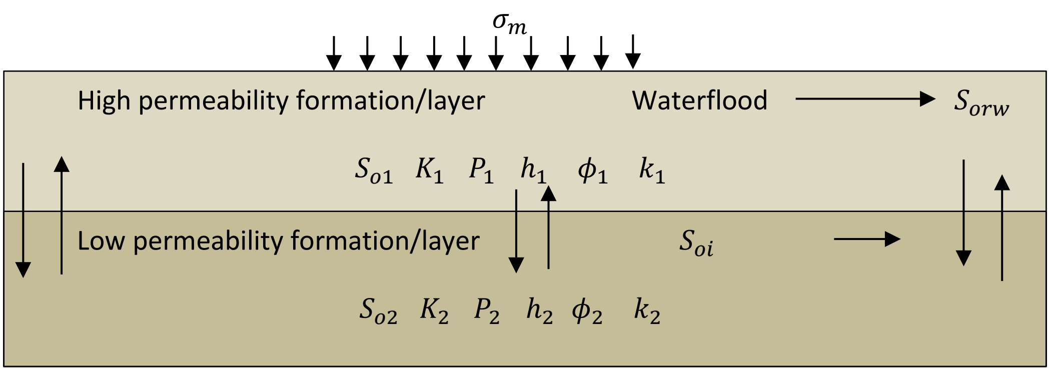

Fig. 1. Illustrates the two-layer oil reservoir model stimulated by the mean normal seismic stress (σ_m) [51]

$$\nabla.\left(\frac{\kappa}{\mu}\nabla p\right)+\frac{\kappa}{\mu}c(\nabla p)^2=\left[\phi c_t+c_b-(1+\phi)c_s+(c_b-c_s)\frac{d\sigma_m}{dp}\right]\frac{dp}{dt}, \tag{1}$$

The coupled geomechanical formulation (Eq. (1)) satisfies the decoupled diffusion equation conditions when the pore viscous fluid is slightly compressible and the mean (average) normal seismic stress (σ_m) remains constant [60]. Therefore, the generated parabolic equation governs the pressure diffusion wave propagation in porous media can be expressed as [30,31]

$$c_t \phi \frac{\partial P(x,t)}{\partial t} = \nabla . \left(\frac{\kappa}{\mu} \nabla P \right), \tag{2}$$

where $P(Pa)$ is the pore pressure, $\mu(Pa.s)$ is the pore fluid viscosity, $c_t(Pa^{-1})$ is the total compressibility coefficient of both pore fluid and the rock matrix, $\phi(\%)$ is the rock porosity, and $\kappa(m^2)$ is the rock permeability, $c_b(Pa^{-1})$ is the jacketed bulk compressibility, $c_s(Pa^{-1})$ is the unjacketed bulk compressibility, and $c(Pa^{-1})$ is the fluid compressibility.

The compressibility of the rock matrix can be expressed in Eq. (2) as a change in porosity caused by variations in fluid pressure. Porosity can only be measured using an elementary volume significantly larger than the volume of a single pore or grain. Darcy's description of velocity necessitates an elementary surface with linear dimensions substantially bigger than a single pore or grain. This allows the elastic and hydraulic components of Eq. (2) to be stated in the same dimensional size, in contrast to the traditional Biot's model [35]. Eq. (2) can be simplified to Eq. (3), if the pressure only varies on one coordinate, as is the case when variations in pressure are caused by a source of stimulation inside a fracture or at the upper (top) portion of an oil reservoir [35,60,61].

$$c_t \phi \frac{\partial P(x,t)}{\partial t} = \frac{\kappa}{\mu} \frac{\partial^2 P}{\partial x^2}, \tag{3}$$

The solution of Eq. (3) can be obtained by applying a Fourier transform.

$$P(x,t) = P_o \exp(iKx - i\omega t - \alpha x), \tag{4}$$

A plane harmonic wave with frequency (Hz) can be expressed by Eq. (4). where α is the attenuation factor in the x-direction, and K is the real component of the wave number. By inserting Eq. (4) into Eq. (3), we can derive the attenuation factor and diffusion wavenumber in Eq. (5) [30]

$$\alpha = K = \sqrt{\omega \phi \mu c_t / 2\kappa}, \tag{5}$$

The mathematical expression for the wavelength (λ) and phase velocity (V_{ph}) in terms of frequency (ω) can be described in Eq. (6)

$$V_{ph} = \frac{\omega}{K} = \sqrt{2\kappa\omega / \phi c_t \mu}, \qquad \lambda = \frac{2\pi}{K} = 2\pi \sqrt{2\kappa / \phi c_t \mu \omega}, \tag{6}$$

2.2 Analytical Solution of Pore Pressure Diffusion Waves in the Oil Reservoir

In a 1D semi-infinitely two-layer oil reservoir, the transmission of pore pressure diffusion waves is evaluated in this section. Under initial and boundary conditions, the parabolic Eq. (2) governs the pressure diffusion wave behavior.

$$t = 0, x > 0,\ P = 0 \quad t > 0, x = 0, P(0,t) = P_o \qquad t > 0, x = \infty, P(\infty, t) = 0, \tag{7}$$

Applying the fundamental concept of the inverse Laplace transform to Eq. (3) and integrating by partition in the range $(0, \infty)$ to produce pore pressure distribution solutions which can be expressed in terms of the complementary error function $(erfc)$ in Eq. (8).

$$P = P_o erfc\left(\frac{x}{2\sqrt{Dt}}\right), \tag{8}$$

The complementary error function and the error function are related in the following form:

$$P = P_o\left[1 - erfc\left(\frac{x}{2\sqrt{Dt}}\right)\right], \tag{9}$$

where D is the diffusion coefficient, which can be mathematically expressed by Eq. (10)

$$D = \frac{\kappa}{\phi c_t \mu}, \tag{10}$$

The diffusion wave frequency (ω) and the penetration depth (L_ω), which are inversely related, can be expressed in Eq. (11).

$$L_\omega = \sqrt{\frac{2D}{\omega}}, \tag{11}$$

The pressure gradient in the x-direction can be approximated using Eq. (12) [30]

$$\frac{\partial P}{\partial x} = P_o\left[-\frac{1}{\sqrt{\pi}\sqrt{Dt}} e^{-\frac{x^2}{4Dt}}\right], \tag{12}$$

In the case of layer formations, the summation of diffusion wave solutions also represents superposition solutions. A solution for a finite layer between two semi-infinite formations can be obtained by adding two-step functions [62]. The two-step functions (moved left/right by $\Delta x/2$) for a superposed solution at the interface can be expressed in Eq. (13).

$$P_{int} = \frac{P_o}{2}\left[erf\left(\frac{x+\Delta x/2}{2\sqrt{D_l t}}\right) - erf\left(\frac{x-\Delta x/2}{2\sqrt{D_h t}}\right)\right], \tag{13}$$

where D_l and D_h are diffusivity coefficients of the low and high permeability semi-infinite layers, P_{int} (Pa) is the pore pressure at the interface between layers and P_o (Pa) is the initial pore pressure. The boundary conditions can be expressed in Eq. (14).

$$P(-\infty, t) = 0;\ P(\infty, t) = 0; P(x \leq -\Delta x/2, 0) = 0;\ P(-\Delta x/2 < x < \Delta x/2) = 1;\ P(x \geq \Delta x/2, 0) = 0, \tag{14}$$

3. Results

3.1 Diffusion Wave Propagation in the Oil Reservoir

Analyses are conducted on how reservoir rock and fluid properties affect the propagation of diffusion waves in oil reservoirs. The mobility of fluid in the pore spaces can be characterized by reservoir rock permeability and fluid viscosity. Fluid mobility can be improved by increasing permeability or decreasing viscosity [62]. In addition, we evaluate the spatial-temporal motion of pressure diffusion waves in oil reservoirs at the interface between two layers. Table 1 shows the reservoir rock and fluid properties.

3.1.1 The effect of fluid viscosity on wave propagation

Studying four cases with a permeability of 200md allows us to investigate how viscosity affects diffusion wave attenuation, phase velocity, wavelength, and penetration depth. Oil and water are the fluids under consideration for investigation of fully saturated conditions in the reservoir. Figure 2 illustrates the phase velocity graphs as a function of diffusion wave frequencies for different viscosities. The water phase velocity curve at 1cp viscosity was slightly higher than the oil phase velocity curve at the same viscosity value. As fluid viscosity increases, the phase velocity peak moves towards a higher wave propagation frequency in the reservoir. The velocity of the waves decreases with the increased viscosity. What impact does viscosity have on diffusion rate? The viscosity value controls the rate of diffusion. High-viscosity fluids have large intermolecular collisions or friction between the molecules, which restricts the motion of diffusion waves and results in a low rate of diffusion. However, if the pore fluid is less viscous, the rate of diffusion will naturally increase. The pore pressure waves can travel and propagate more easily because the intermolecular distance between the molecules is greater.

Table 1
Reservoir Rock and fluid properties

Properties	Symbol	Value	Unit
Porosity	ϕ	23	%
Rock permeability	κ	1.97×10^{-13}	m^2
Rock compressibility	C_t	3.0×10^{-10}	Pa^{-1}
Oil compressibility	C_o	7.1×10^{-10}	Pa^{-1}
Water compressibility	C_w	4.2×10^{-10}	Pa^{-1}
Oil viscosity	μ_o	5.0×10^{-3}	Pa. s
Water viscosity	μ_w	1.0×10^{-3}	Pa. s
Oil density	ρ_o	880	Kg/m^3
Water density	ρ_w	1010	Kg/m^3
Low permeability layer height	h_L	5	m
Height permeability layer height	h_H	5	m
Length of the porous media	L	1	m
Average normal seismic stress	σ_m	10	N/m^2
Excitation frequency	f	3	Hz

The diffusion coefficient and viscosity are interrelated variables governing fluid transport phenomena. According to Eq. (10), the diffusion coefficient (D) is inversely proportional to the viscosity (μ).

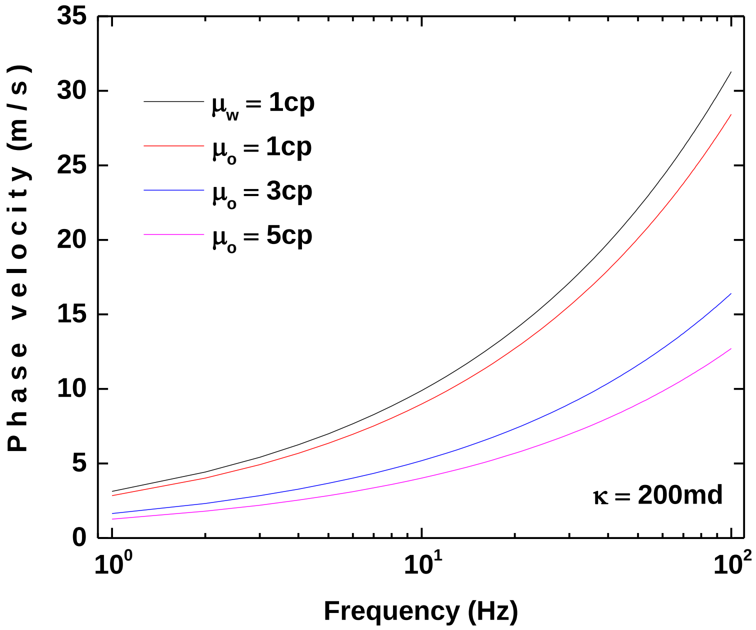

Fig. 2. Illustrates the phase velocity as a function of diffusion wave frequency at different fluid viscosity

Figure 3 depicts the frequency-dependent attenuation factor for diffusion waves at different viscosity values. When viscosity rises, the peak location of wave attenuation shifts towards a high-frequency range. Depending on the frequency value, attenuation changes with viscosity and can either increase or decrease, but the greatest loss increases as viscosity rises. The attenuation trends showed that the diffusion wave attenuation factors in the reservoir increased when fluid viscosity increased. At 1cp, the wave attenuation in oil is slightly higher than in water. As a result of the energy losses caused by energy and momentum exchange between pore fluid motion and rock matrix, diffusion waves exhibit significant attenuation.

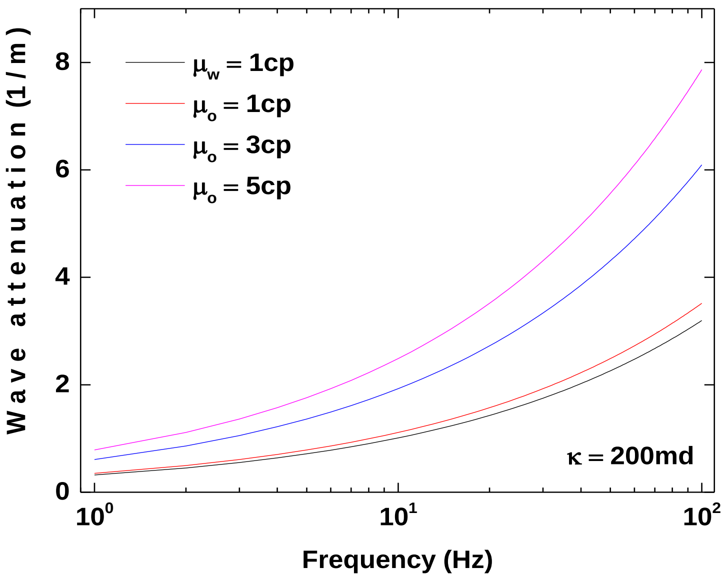

Fig. 3. Illustrates the wave attenuation as a function of diffusion wave frequency at different fluid viscosity

The wavelength and penetration depth are linearly decreasing as a function of propagation frequency, as shown in Figure 4 and Figure 5. The wavelength and penetration depth trends generated via the pressure diffusion approach exhibit identical patterns as viscosity changes. When viscosity increases, the peak location of the wavelength and penetration depth move towards low-frequency bands. Viscosity can affect wavelength and penetration depth depending on the frequency value, but it can also affect their magnitude by increasing viscosity values. Pressure diffusion waves in the water phase have a slightly higher wavelength and deeper penetration length than those in the oil phase at one cp.

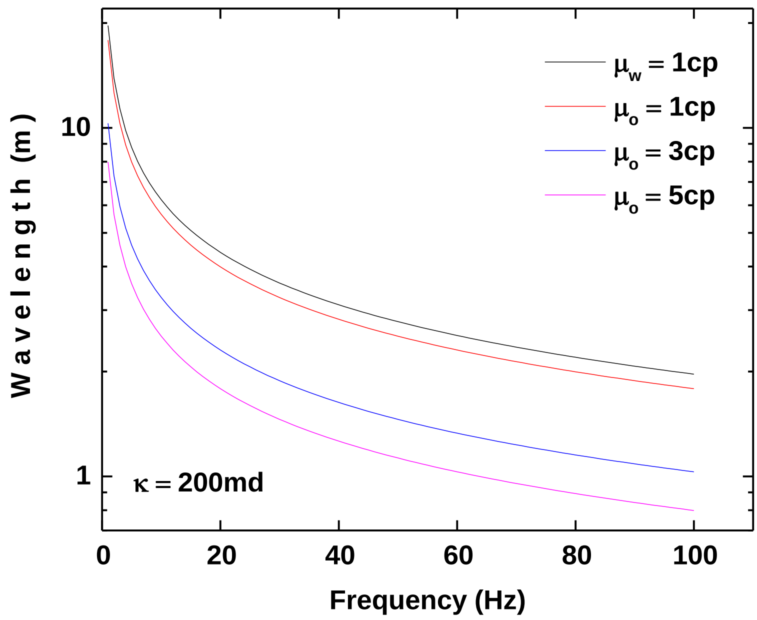

Fig. 4. Illustrates the wavelength as a function of diffusion wave frequency at different fluid viscosity

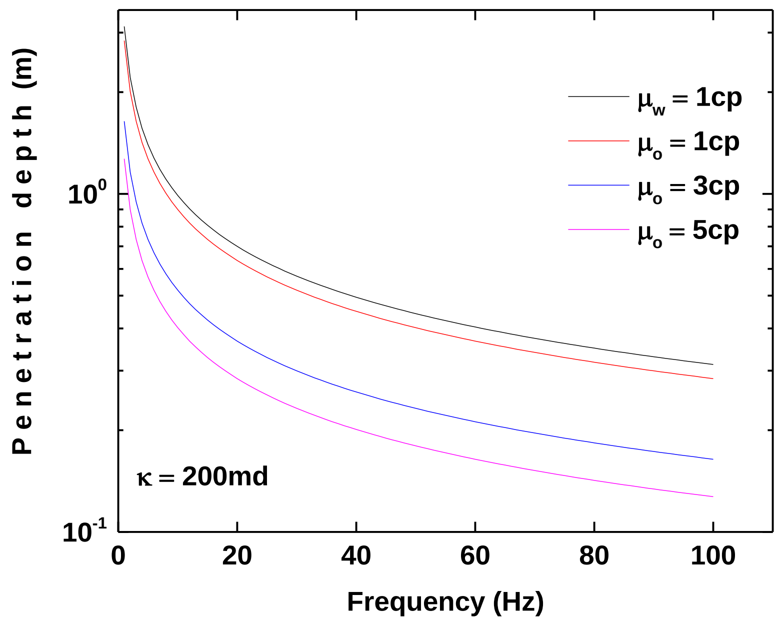

Fig. 5. Illustrates the penetration depth as a function of diffusion wave frequency at different fluid viscosity

3.1.2 The effect of rock permeability on wave propagation

Figure 6 and Figure 7 demonstrate the phase velocity and attenuation curves as a function of frequency for different permeabilities. When the reservoir rock permeability decreases, the phase velocity peak of the diffusion waves changes to a higher propagation frequency. Pore pressure diffusion waves are significantly damped, a property shared by attenuated waves of non-diffusive electromagnetic energy and thermal waves in dissipative porous media. The imaginary and real components of the wavenumber are not equal for diffusion waves (Eq. (5)). Until a reasonably high-frequency range is attained, the imaginary portion fails to accumulate sufficient energy to become visible [30]. Therefore, there are no diffusion waves at low-frequency ranges. When a frequency is raised sufficiently, the diffusion wave characteristic emerges, and an apparent phase lag in the spatial coordinate is observed. This observation significantly influences the diffusion wave fields' spatial dispersion. In response to an increase in permeability, the peak location of the diffusion wave attenuation coefficient moves towards a high-frequency range (Figure 7). When rock permeability decreases, wave attenuation shifts towards a lower frequency range (Eq. (5)).

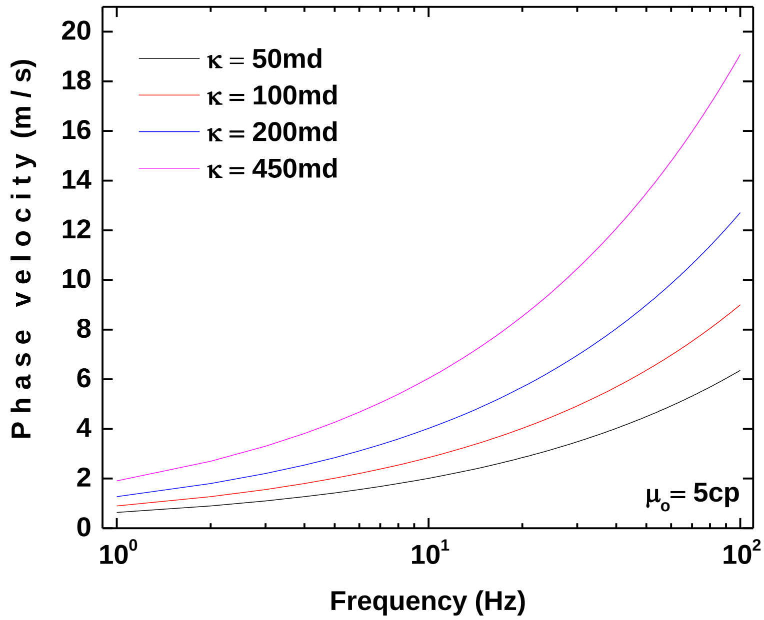

Fig. 6. Illustrate the phase velocity as a function of diffusion wave frequency at different permeability

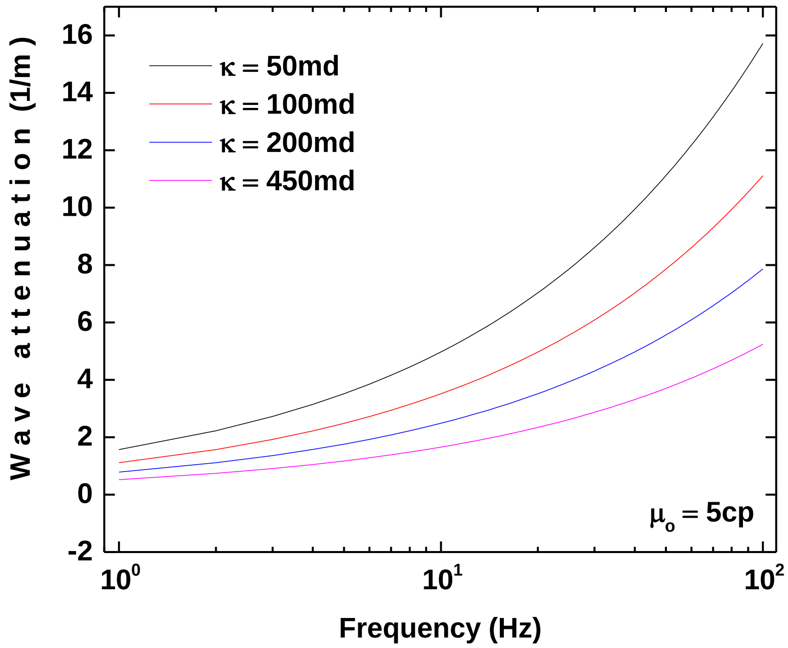

Fig. 7. Illustrates the wave attenuation as a function of diffusion wave frequency at different permeability

Because of energy losses caused by the momentum change between pore fluid flow and rock matrix, diffusion waves exhibit considerable attenuation. The high attenuation of low-frequency seismic waves in oil reservoirs can be explained by pressure diffusion formulation, which fails to be sufficiently estimated by Biot's model of poroelasticity [33]. The diffusion wave phase velocity and attenuation coefficient are linearly increasing as a function of propagation frequency. The results demonstrated that diffusion waves propagate slowly and with considerable frequency-dependent attenuation. Therefore, diffusion waves caused by pore pressure do not propagate in a square-law approach. When reservoir rock permeability declines, the penetration depth and wavelength peaks were observed to be moved towards a low-frequency range. Pressure diffusion waves can image thin fluid-saturated layers in oil reservoirs due to their high penetration depth and wavelength at low frequencies (Figure 8 and Figure 9). Depending on the frequency values, the wavelength and penetration depth decrease as frequency increases due to the increased permeability of the different formation layers.

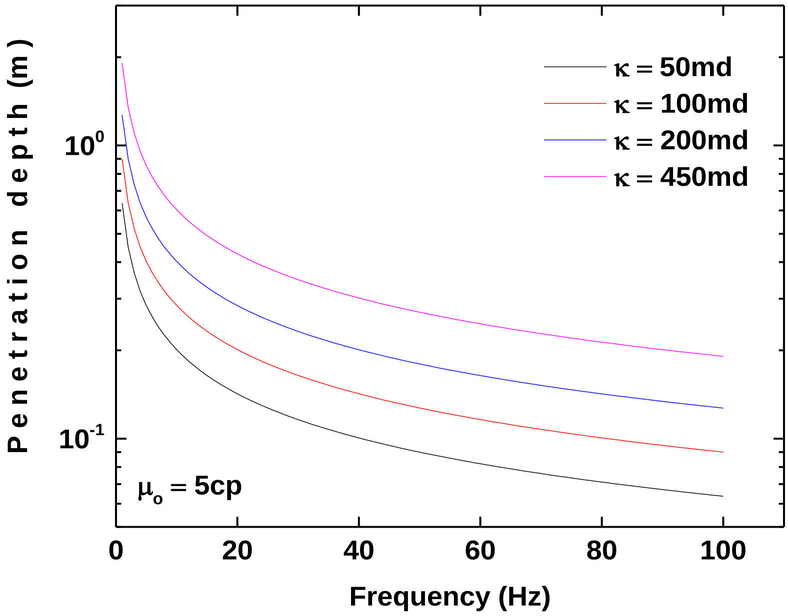

Fig. 8. Illustrates the penetration depth as a function of diffusion wave frequency at different permeability

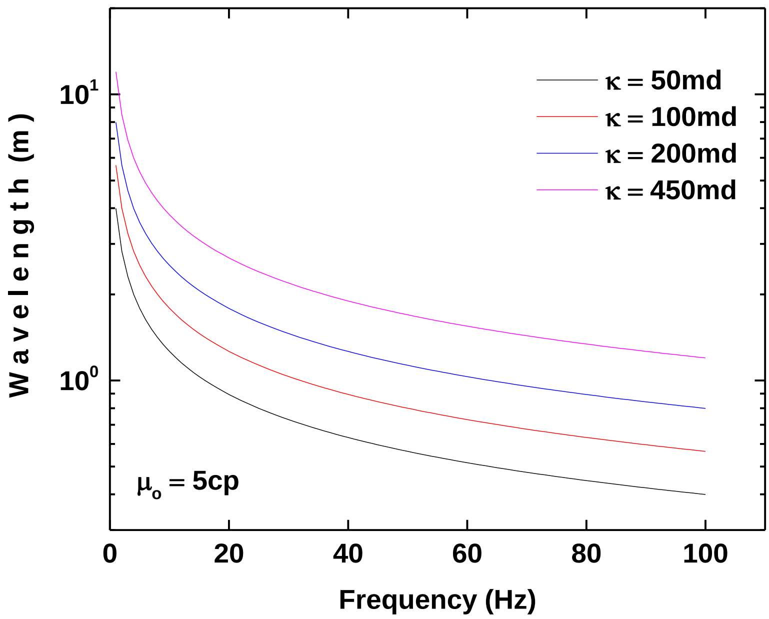

Fig. 9. Illustrates the wavelength as a function of diffusion wave frequency at different permeability

3.1.3 Pore pressure waves transmission analysis

The plots of pore pressure observed as a function of transmission distance for different permeability values are illustrated in Figure 10. The pore pressure peak moves towards a smaller distance when rock permeability increases. In the oil reservoir, pore pressure gradually declines as the transmission distance increases over time. The pore pressure plots as a function of time indicated a phase lag for a 1-meter distance, as shown in Figure 11. Depending on the propagation time, pore pressure rises as formation layer permeability rises.

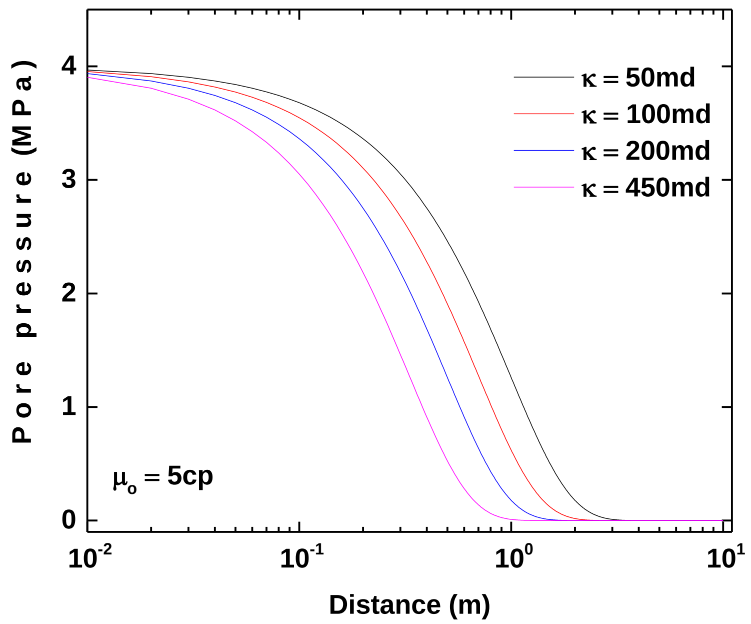

Fig. 10. Illustrates the pore pressure as a function of diffusion wave distance at different permeability

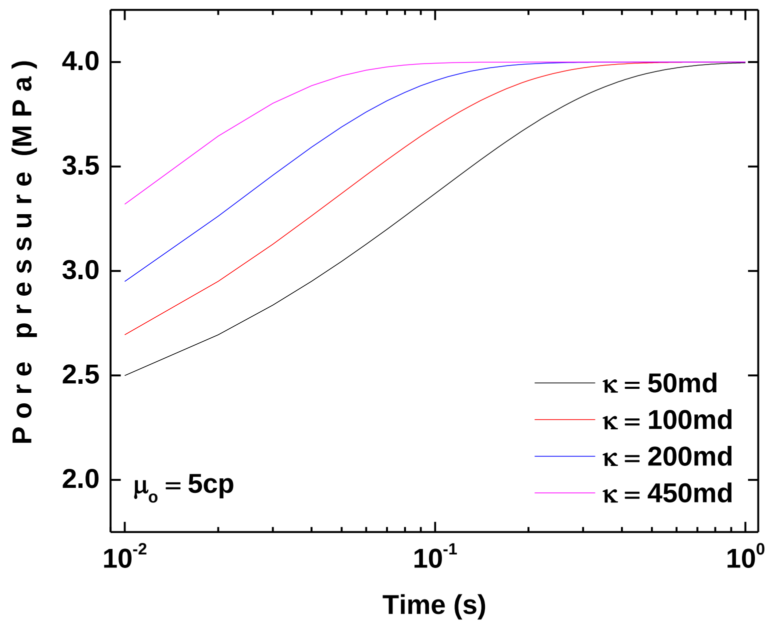

Fig. 11. Illustrates the pore pressure as a function of diffusion wave time at different permeability

According to Eq. (6), diffusion waves have an infinite field transmission velocity with vanishingly small magnitude at locations far from the seismic source [30]. This characteristic causes rapid perturbations across whole pressure domains. During the diffusion of pressure waves, the penetration depth governs only the spatially associated phase delays. In an isotropic medium, pressure diffusion waves lack field directionality. Pressure gradients are illustrated in Figure 12 and are represented by an abrupt change clearly defined numerically and caused by the jumping diffusivity. A linear law, as opposed to a square law, governs the pressure distribution, which appears as spatial diffusion gradients. The behavior of the waves at interfaces is influenced by the linear law that governs the propagation of the diffusion wave field. Pressure diffusion waves don't obey the reflection-refraction law when encountering a boundary or interface between layers in oil reservoirs;

instead, they obey the accumulation-depletion principle. According to Eq. (13), a step function of diffusivity is provided along the diffusion wave traveled distances at the interface. In this situation, a space-dependent diffusivity field accelerates and amplifies the pressure diffusion waves in low permeability layers rather than high permeability layers (Figure 10). As the diffusivity coefficient rises, the pore pressure increases for the specified distance due to the short transmission distance of strongly attenuated diffusion waves. In applications like the monitoring of the CO_2 front in oil reservoirs during EOR and CO_2 storage processes, the observation of shale gas migration in different permeability formations, and the detection of the propagation of fractures during EOR/EGR by CO_2 flooding, diffusion waves performance at an interface or boundary between formation layers are of enormous practical value.

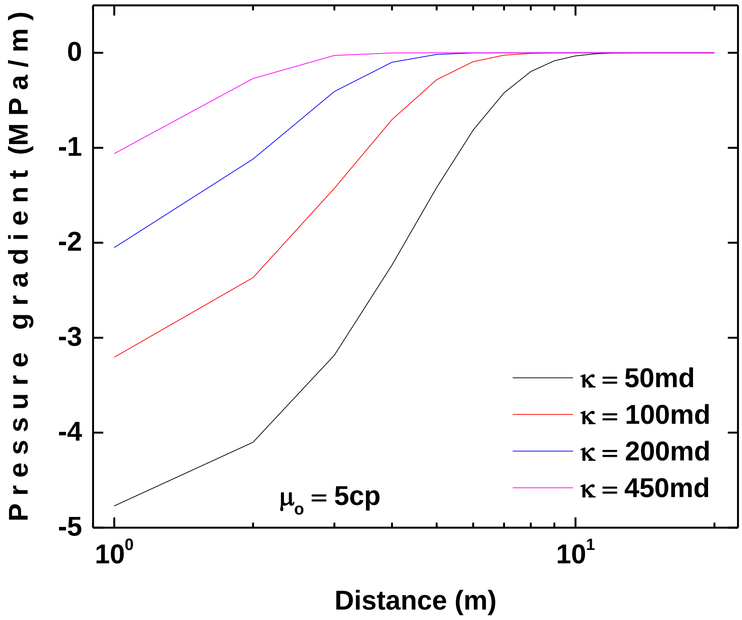

Fig. 12. Illustrates the pressure gradient as a function of diffusion wave propagation distance at different permeability

4. Conclusions

The findings of this study reveal that wave attenuation, phase velocity, penetration depth, and wavelength depend on frequency. Pressure diffusion waves exhibit strong attenuation behaviors at a low-frequency range, which is highly beneficial in real-world applications for detecting thin fluid-saturated layers in oil reservoirs. Moreover, spatial diffusion gradients, which follow a linear law, are found to regulate pressure diffusion. An accumulation-depletion law governs pressure diffusion waves at a solid boundary/interface between reservoir rock poroelastic layers. The findings demonstrate that diffusion waves can potentially characterize reservoir fluid in mature oil reservoirs during seismic EOR due to their response to fluid viscosity and rock permeability changes. Pressure diffusion waves can also be used in heterogeneous oil reservoirs to detect and monitor the CO_2 front during the CO_2-EOR and CO_2 geo-sequestration process for CCUS projects, monitor shale gas movement in low permeability reservoirs, and identify the spread of fractures during EOR/EGR via CO_2 flooding.

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