Attenuation and dispersion of seismic waves in thin layered porous rocks saturated by two-phase fluids

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Seismic Waves in Hydrocarbon Reservoir Formations. I

- The conversion of fast to slow diffusion P-waves in fluid-saturated porous media induces attenuation and dispersion of waves at seismic frequencies.
- This effect, known as wave induced fluid flow (WIFF), occurs at mesoscopic scales, which are much smaller than the predominant wavelengths but much larger than the average pore diameter.
- M. Biot (1956,1962), presented a theory to describe the propagation of waves in a poroelastic medium saturated by a single-phase fluid.
- Biot's theory predicts the existence of two compressional waves (one fast and one slow) and one shear (fast) wave.

Seismic Waves in Hydrocarbon Reservoir Formations. II

- In hydrocarbon reservoirs the pore space is saturated by multiphase fluids, characterized by capillary forces and effective permeabilities, which depend of saturation.
- We use an extension of Biot's theory to model waves propagation in porous rocks saturated by two-phase fluids (Santos et al., JASA, 1990, Ravazzoli et al., JASA, 2003).
- The theory includes capillary forces and interferences between the two fluid phases as they flow
- The generalization of the Biot classic model is achieved via two main steps:

Seismic Waves in Hydrocarbon Reservoir Formations. III

- The capillary relation betweeen the two fluid pressures is included in the complementary virtual work principle via a Lagrange multiplier.
- The dissipation function in the Lagrange formulation of the equation of motion is defined in terms of the two-phase Darcy's law.
- The theory predicts the existence of three compressional waves, (one fast and two slow) and one shear (fast) wave.
- Capillary forces are responsible for the existence of one additional slow wave, while relative permeability functions model energy losses due to interferences between the two fluids as they flow, modifying the WIFF mechanism.

Seismic Waves in Hydrocarbon Reservoir Formations. IV

- To analyze the WIFF mechanism in porous rocks saturated by two-phase fluids we apply compressibility tests defined as boundary value problems (BVP's) to representative samples of the material.
- The solution of the (BVP's) is achieved using a Finite Element (FE) procedure.
- The experiments simulate the seismic response of a three periodic sequence of thin poroelastic layers saturated by two-phase fluids.
- Cases analyzed: different two-phase fluids on each layer and patchy saturation.
- Results: residual and wetting fluid saturation play an important role to determine the P-wave velocities and dissipation factors.

The generalized Biot model for two-phase fluid saturation. I

In a poroelastic medium saturated by a two-phase fluid there exist wetting and non-wetting fluid phases and a solid phase denoted with the subscripts “w", “n" and “s".

S_w, S_n, S_{rw}, S_{rn}: wetting and non-wetting saturation and residual saturations of the wetting and non-wetting phases.

Assumptions:

$S_w + S_n = 1$, $\quad S_{rw} > 0$ (as $S_w \to S_{rw}$ capillary pressure approaches ∞) .

$[0, S_{rw}]$ has immobile wetting fluid.

$[0, S_{rn}]$ has immobile non-wetting fluid

funicular regime of flow, i.e., both fluids simultaneously flow along continuous paths:

$$S_{rw} < S_w < 1 - S_{rn}, \quad S_{rn} < S_n < 1 - S_{rw}.$$

The generalized Biot model for two-phase fluid saturation. II

$\mathbf{u}^s$, $\tilde{\mathbf{u}}^n$, $\tilde{\mathbf{u}}^w$: averaged displacement vectors of the solid, non-wetting and wetting phases. ϕ: matrix total porosity.

$\mathbf{u}^\theta = \phi(\tilde{\mathbf{u}}^\theta - \mathbf{u}^s)$, $\xi^\theta = -\nabla \cdot \mathbf{u}^\theta$, $\theta = n, w$, $\quad \mathbf{u} = (\mathbf{u}^s, \mathbf{u}^n, \mathbf{u}^w)$,

$\tau(\mathbf{u}), \mathcal{T}_n(\mathbf{u}), \mathcal{T}_w(\mathbf{u})$: stress tensor of the bulk material and generalized forces of the two fluid phases of pressures P_n, P_w.

Capillary pressure relation:

$P_{ca}(S_n) = P_n - P_w > 0, \quad P'_{ca}(S_n) > 0.$

Constitutive equations:

$$\begin{aligned}
\tau_{ij}(\mathbf{u}) &= 2\mu\, \varepsilon_{ij}(\mathbf{u}^s) + \delta_{ij}(\lambda_u \nabla \cdot \mathbf{u}^s - F_1\, \xi^n - F_2\, \xi^w), \\
\mathcal{T}_n(\mathbf{u}) &= (S_n + \beta) P_n - \beta P_w = -F_1\, \nabla \cdot \mathbf{u}^s + N_1\, \xi^n + N_3\, \xi^w, \\
\mathcal{T}_w(\mathbf{u}) &= S_w\, P_w = -F_2\, \nabla \cdot \mathbf{u}^s + N_3\, \xi^n + N_2\, \xi^w.
\end{aligned}$$

ε_{ij}: solid strain tensor $\quad \beta = P_{ca}(S_n)/P'_{ca}(S_n)$,

The generalized Biot model for two-phase fluid saturation. III

The coefficients in the constitutive equations can be determined in terms of the properties of the individual phases and the capillary pressure function.

Diffusion equations for a poroelastic medium saturated by a two-phase fluid:

$$
\begin{aligned}
&\nabla \cdot \tau(\mathbf{u}) = 0,\\
&i\omega\, d_n\, \mathbf{u}^n - i\omega\, d_{nw}\, \mathbf{u}^w + \nabla \mathcal{T}_n(\mathbf{u}) = 0,\\
&i\omega\, d_w\, \mathbf{u}^w - i\omega\, d_{nw}\, \mathbf{u}^n + \nabla \mathcal{T}_w(\mathbf{u}) = 0.\\
&d_l(S_l) = (S_l)^2 \frac{\eta_l}{\kappa K_{rl}(S_l)}, \quad l = n, w,\\
&d_{nw}(S_n, S_w) = \epsilon \left(d_n(S_n) d_w(S_w) \right),
\end{aligned}
$$

η_n, η_w: fluid viscosities

κ, $K_{rn}(S_n), K_{rw}(S_w)$: absolute permeability and the relative permeability functions.

Harmonic experiment to determine the effective P-wave modulus. I

$\Omega = (0, L)^2$: a square in the (x, z)-plane containing a three periodic sequence of fine poroelastic layers saturated by a two-phase fluid.

$\widetilde{\mathbf{u}}^s$: macroscopic solid displacement vector in Ω

$\mathcal{T}(\widetilde{\mathbf{u}}^s)$ $\mathcal{E}(\widetilde{\mathbf{u}}^s)$: macroscopic stress and strain tensors in Ω.

Constitutive equations of an effective viscoelastic medium long-wave equivalent to the fluid-saturated layered poroelastic medium Ω:

$$\mathcal{T}_{jk}(\widetilde{\mathbf{u}}^s) = \overline{\lambda}\nabla \cdot \widetilde{\mathbf{u}}^s \delta_{jk} + 2\overline{\mu}\mathcal{E}_{jk}(\widetilde{\mathbf{u}}^s). \qquad (1)$$

$\overline{M}_u = \overline{\lambda} + 2\overline{\mu}$: effective P-wave modulus

Harmonic experiment to determine the effective P-wave modulus. II

$\Gamma^L, \Gamma^R, \Gamma^B$ and Γ^T : left, right, bottom and top boundaries of Ω, $\Gamma = \Gamma^L \cup \Gamma^B \cup \Gamma^R \cup \Gamma^T$.

$\{\nu, \ \chi\}$ the unit outer normal and a unit tangent oriented counterclockwise on Γ

To determine $\overline{M}_u = \overline{\lambda} + 2\overline{\mu}$ we solve the following Boundary Value Problem (BVP):

$$
\begin{aligned}
&\tau(\mathbf{u})\nu \cdot \nu = -\Delta P, \quad (x,z) \in \Gamma^T, \\
&\tau(\mathbf{u})\nu \cdot \chi = 0, \quad (x,z) \in \Gamma, \\
&\mathbf{u}^s \cdot \nu = 0, \quad (x,z) \in \Gamma^L \cup \Gamma^R \cup \Gamma^B, \\
&\mathbf{u}^n \cdot \nu = 0, \quad \mathbf{u}^w \cdot \nu = 0, \quad (x,z) \in \Gamma.
\end{aligned}
$$

Harmonic experiment to determine the effective P-wave modulus. III

The solution of the BVP satisfies:

$$\epsilon_{11}(\mathbf{u}^s) = \epsilon_{13}(\mathbf{u}^s) = \nabla \cdot \mathbf{u}^n = \nabla \cdot \mathbf{u}^w = 0.$$

Thus, $\mathcal{E}_{11}(\widetilde{\mathbf{u}}^s) = \mathcal{E}_{13}(\widetilde{\mathbf{u}}^s) = 0$ and the macroscopic constitutive relation (equation (1)) reduces to

$$\mathcal{T}_{33} = \overline{M_u} \mathcal{E}_{33}. \qquad (2)$$

$\overline{M_u}$ can be determined from equation (2) by computing $\mathcal{T}_{33}$ and $\mathcal{E}_{33}$ as averages over Ω:

$$\mathcal{T}_{33} = \frac{1}{\Omega} \int_{\Omega} \tau_{33} d\Omega, \qquad \mathcal{E}_{33} = \frac{1}{\Omega} \int_{\Omega} \epsilon_{33} d\Omega.$$

P-wave phase velocity and Quality factors

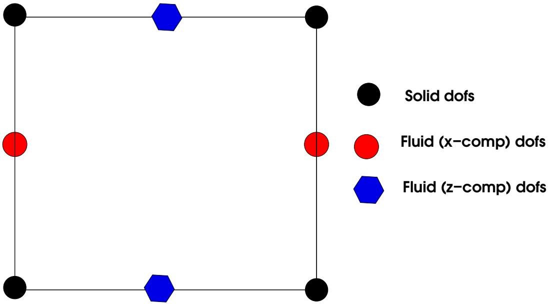
The P-wave phase velocity $V_p(\omega)$ and quality factor $Q(\omega)$ of the three periodic layered medium are obtained from the equations

$$V_p(\omega) = \left[\mathrm{Re}\left(\frac{1}{V_c(\omega)}\right)\right]^{-1}, \quad \frac{1}{Q(\omega)} = \frac{\mathrm{Im}(V_c(\omega)^2)}{\mathrm{Re}(V_c(\omega)^2)} \quad ,$$

$$V_c(\omega) = \sqrt{\frac{\overline{M_u(\omega)}}{\overline{\rho_b}}},$$

$\overline{\rho_b}$: bulk density, computed in terms of the grain density, ρ_s, and the non-wetting and wetting phases densities, ρ_n and ρ_w,

Solution of the BVP's using the FE method. Local DOF.



The approximate solution of the time-harmonic BVP is computed using the FE procedure in Santos et al., CMAME, 2009, where uniqueness and apriori error estimates are presented.. The figure displays the local degrees of freedom (DOFs) associated with each component of the solid displacement and the wetting and non-wetting fluid displacement vectors.

Numerical Experiments. I

We consider a square sample and six periods, each consisting of three 20 cm layers saturated by a two-phase fluid.

The sample is discretized using a 90×90 uniform mesh.

Relative permeability and Capillary Pressure functions (Douglas et al., Comp. Geos., 1997, Ravazzoli et al, JASA, 2003):

$$K_{rn}(S_n) = (1 - (1 - S_n)/(1 - S_{rn}))^2 \,,$$
$$K_{rw}(S_n) = ([1 - S_n - S_{rw}]\,/\,(1 - S_{rw}))^2 \,,$$
$$P_{ca}(S_n) = A\left(1/(S_n + S_{rw} - 1)^2 - S_{rn}^2/[S_n(1 - S_{rn} - S_{rw})]^2\right)$$

$A = 30$ kPa: Capillary pressure amplitude.

Numerical Experiments. II

Material properties of the sandstone and the saturant fluids.

Table 1. Properties of the sandstone

Grain bulk modulus, K_s	33.4 GPa
density, ρ_s	2650 kg/m^3
Dry-matrix bulk modulus, K_m	1.3 GPa
shear modulus, μ	1.4 GPa
porosity, ϕ	0.3
permeability, κ	10^{-12} m^2

Table 2. Properties of the saturant fluids

Brine bulk modulus, K_w	2.2 GPa
density, ρ_w	975 kg/cm^3
viscosity, η_w	0.001 Pa · s
Oil bulk modulus, K_o	2 GPa
density, ρ_o	870 kg/cm^3
viscosity, η_o	0.3 Pa · s
Gas bulk modulus, K_g	0.0044515 GPa
density, ρ_g	42.316 kg/m^3
viscosity, η_g	1.1186 $\times 10^{-5}$ Pa · s

Comparison with single-phase fluid saturation. $S_{rw} = 1$ %

- Case 1:

  Layer 1: gas-brine saturation, 0.12 % gas,

  Layer 2: gas-brine saturation, 98 % gas,

  Layer 3: oil-brine saturation, 98 % oil,

  brine is the wetting phase in the three layers.

- Case 2:

  Layer 1: gas-brine saturation, 0.12 % gas,

  Layer 2: gas-brine saturation, 98 % gas,

  Layer 3: oil-gas saturation, 98 % oil,

  Wetting phase is brine in Layers 1 and 2, oil in Layer 3.

The theory of Cavallini et al. GJI, 2017, for three periodic thin poroelastic layers holds for single-phase fluids. We compare the results with those of effective single-phase fluid saturation using a Reuss average of the fluid bulk modulus and arithmetic averages of densities and viscosities of each fluid phase.

P-wave phase velocity for two-phase and effective single-phase fluid saturation. Case 1

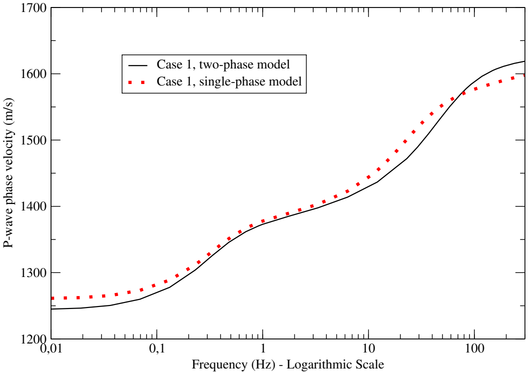


Figure 1. Case 1: brine is the wetting phase in the three layers, Layer 1: gas-brine saturation, 0.12 % gas

, Layer 2: gas-brine saturation, 98 % gas, Layer 3: oil-brine saturation, 98 % oil

P-wave dissipation factor 1000/Q for two-phase and effective single-phase fluid saturation. Case 1

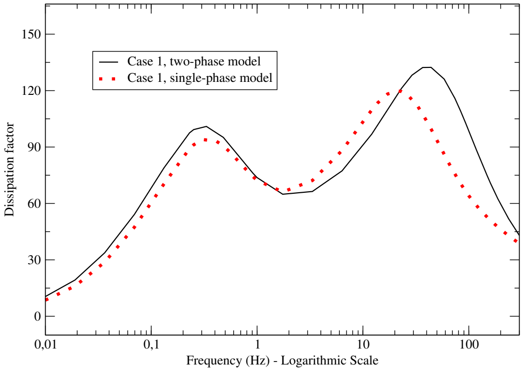


Figure 2. Case 1: brine is the wetting phase in the three layers, Layer 1: gas-brine saturation, 0.12 % gas , Layer 2: gas-brine saturation, 98 % gas, Layer 3: oil-brine saturation, 98 % oil.

P-wave phase velocity for two-phase and effective single-phase fluid saturation. Case 2

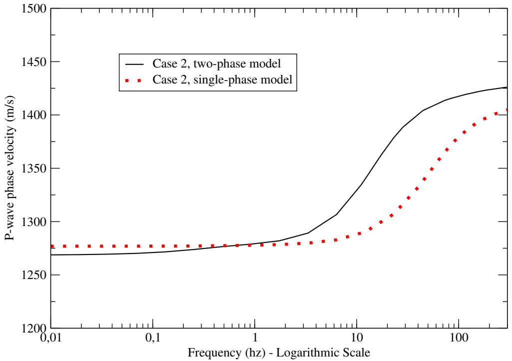


Figure 3. Case 2: Layer 1: gas-brine saturation, brine is wetting, 0.12 % gas, Layer 2: gas-brine saturation, brine is wetting 98 % gas, Layer 3: oil-gas saturation, oil is wetting, 98 % oil.

P-wave dissipation factor 1000/Q for two-phase and effective single-phase fluid saturation. Case 2

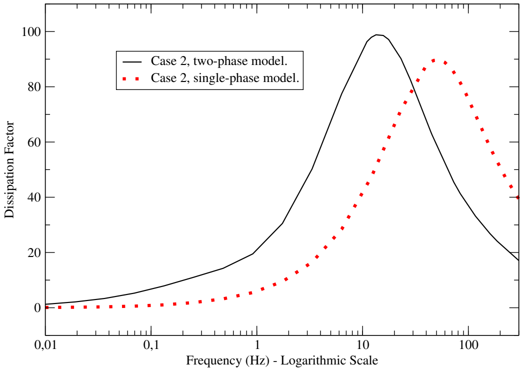


Figure 4. Case 2: Layer 1: gas-brine saturation, brine is wetting, 0.12 % gas, Layer 2: gas-brine saturation, brine is wetting 98 % gas, Layer 3: oil-gas saturation, oil is wetting, 98 % oil. The single attenuation peak for two-phase fluids is higher and shifted to lower frequencies.

Two-phase fluids and patchy saturation. $S_{rw} = 10$ %

- Case 3: Brine is the wetting phase in the three layers.
  Layer 1: gas-brine saturation, 0.12 % gas.
  Layer 2: patchy gas-brine saturation, overall gas saturation is 10 % or 30 %.
  Layer 3: oil-brine saturation, 89 % oil.

- Case 4: Brine is the wetting phase in the three layers.
  Layer 1: gas-brine saturation, 0.12 % gas,
  Layer 2: patchy gas-brine saturation, overall gas saturation is 10 % or 30 %,
  Layer 3: patchy oil-brine saturation, overall oil saturation is 10 % or 30 %

- Case 5:
  Layer 1: gas-brine saturation, 0.12 % gas, brine is the wetting phase.
  Layer 2: patchy gas-oil saturation, oil is the wetting phase.
  Layer 3: patchy brine-oil saturation, oil is the wetting phase.
  Overall gas/brine saturations 10 % and 40 %.

P-wave phase velocity. Case 1 for $S_{rw} = 10$ % and Case 3 of two-phase patchy saturation.

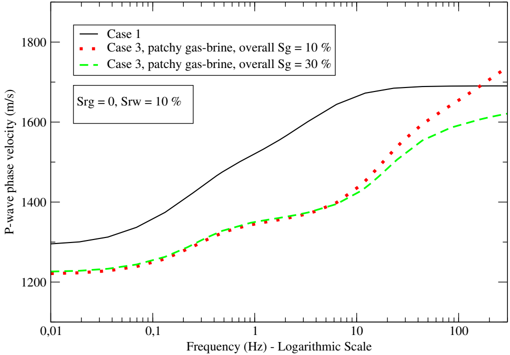


Figure 5. P-wave phase velocity as a function of frequency for the two-phase model for Cases 1 and 3.

Overall patchy gas-brine saturations in Layer 2 are 10 % and 30 %.

P-wave dissipation factor 1000/Q. Case 1 for $S_{rw} = 10$ % and Case 3 of two-phase patchy saturation

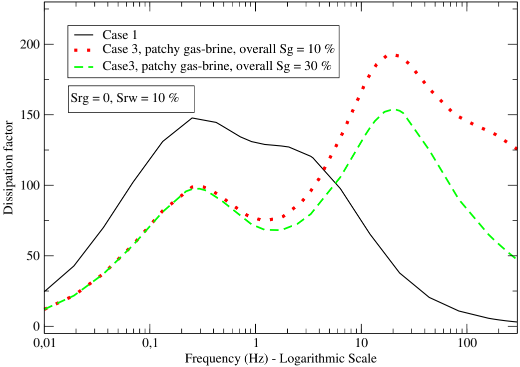


Figure 6. Two attenuation peaks for both overall values of patchy saturation, at lower and higher frequencies associated with the oil and gas, respectively. The peaks for Case 1 for $S_{rw} = 10$ % are close to each other, and located at lower frequencies than for Case 1 for $S_{rw} = 1$ % (Figure 2).

Fluid pressure at 20 Hz for Case 3. Overall gas saturation in Layer 2 are 10 % (left) and 30 % (right).

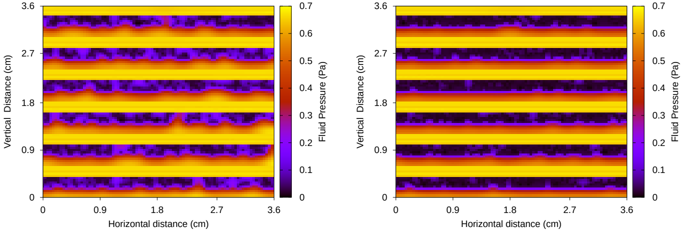


Figure 7. Case 3: Brine is the wetting phase in the three layers. Layer 1: gas-brine saturation, 0.12 % gas. Layer 2: patchy gas-brine saturation, overall gas saturation is 10 % or 30 %. Layer 3: oil-brine saturation, 89 % oil. Gradients of fluid pressure in the Layer 2 region are much more noticeable at overall patchy gas saturation 10 % (left) than at 30 % (right), in agreement with the previous Figure.

P-wave dissipation factor 1000/Q. Case 1 for $S_{rw} = 10$ % and Case 4 of two-phase patchy saturation

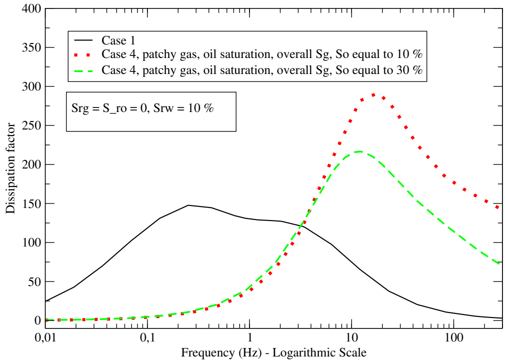


Figure 8. Case 4: Brine is the wetting phase in the three layers. Layer 1: gas-brine saturation, 0.12 % gas, Layer 2: patchy gas-brine saturation, overall gas saturation is 10 % or 30 %, Layer 3: patchy oil-brine saturation, overall oil saturation is 10 % or 30 %. One attenuation peaks is seen for both overall values of patchy saturation, with a second peak of negligible amplitude located at low frequencies.

P-wave dissipation factor 1000/Q. Case 5 of two-phase patchy saturation

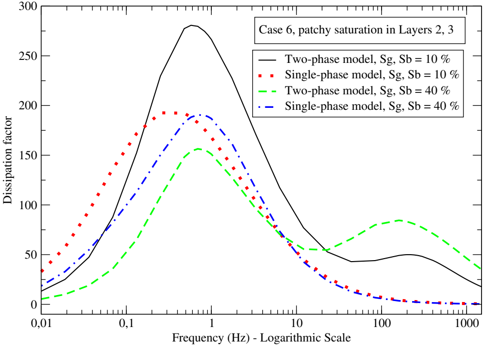


Figure 8. Case 5: Layer 1: gas-brine saturation, 0.12 % gas, brine is the wetting phase. Layer 2: patchy gas-oil saturation, oil is the wetting phase. Layer 3: patchy brine-oil saturation, oil is the wetting phase. Overall gas/brine saturations 10 % and 40 %. Two attenuation peaks are seen for two-phase fluids. The effective single-phase fluids curve exhibits a single peak.

Conclusions

- Capillary forces and the relative flow between the two fluids induce changes in velocity and attenuation of P-waves as compared with effective single-phase fluids.
- Cases 1 and 2 (first 4 Figures) show higher P-wave velocities for two-phase fluids (at high frequencies) and higher attenuation as compared with effective single-phase fluids.
- wettability is important (the role of each fluid as wetting or non-wetting phase). The last Figure (Case 5) shows two attenuation peaks for two-phase fluids and only one for single phase fluids. The second peak is related with the oil wettability of Layers 2 and 3 and is due of flow interactions between the two fluids via the relative permeability functions.

Attenuation and dispersion of seismic waves in thin layered porous rocks saturated by two-phase fluids.

Thanks for your attention !!!!