Effects of permeability barriers and pore fluids on S-wave attenuation

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Summary

We (Quintal et al., 2012) study seismic attenuation caused by wave-induced fluid flow. Stress relaxation experiments are numerically simulated by solving Biot's equations for consolidation of poroelastic media with finite-elements. The experiments yield time-dependent stress-strain relations, from which frequency-dependent attenuation is determined. Our model consists of periodically distributed circular heterogeneities with much lower porosity and permeability than the background medium. This model can represent a hydrocarbon reservoir, where the porous background is either fully saturated with oil or gas, and the low porosity regions are saturated with water.

Three different saturation scenarios are considered: oil-saturated (80% oil, 20% water), gas-saturated (80% gas, 20% water), and fully water-saturated. A consistent tendency is observed in the relative behavior of the S-wave attenuation among the different saturation scenarios. First, in the gas-saturated media the S-wave attenuation is very low and much lower than in the other two saturation scenarios. Second, at low frequencies the S-wave attenuation is significantly higher in the oil-saturated media than in the fully water-saturated media. The P-wave attenuation exhibits a more variable relative behavior among the different saturation scenarios.

Based on the mechanism of wave-induced fluid flow and on our numerical results we suggest that S-wave attenuation is a better indicator of fluid content in a reservoir than P-wave attenuation.

We also studied the influence of impermeable barriers in the medium. No effect is expected for P-wave attenuation. However, the impermeable barriers cause a significant increase in S-wave attenuation. This suggests that S-wave attenuation could be an indicator of permeability changes.

(I) Methodology

1) Finite-element method using an unstructured mesh (Fig. 1) to solve Biot's equations for consolidation (Biot, 1941).

2) Simulations of two quasi-static relaxation tests (Fig. 2) of a medium containing a heterogeneity (Fig. 1).

3) These simulations yield time-dependent bulk stress rate-bulk strain rate relations for compression and shear.

4) Fourier-transform yields the frequency-dependent and complex bulk stress rate-bulk strain rate relations, which are used to calculate the frequency-dependent P- and S-wave moduli, H and μ, respectively.

5) $$Q_P = \frac{\mathrm{Re}[H(\omega)]}{\mathrm{Im}(H(\omega))} \qquad Q_S = \frac{\mathrm{Re}(\mu(\omega))}{\mathrm{Im}(\mu(\omega))}$$

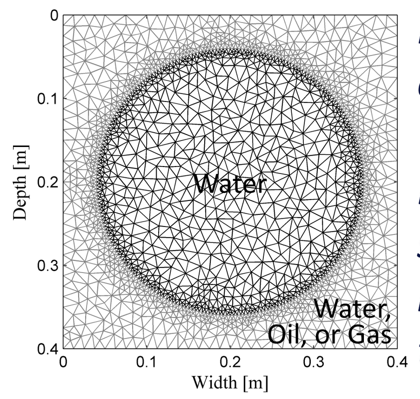

Fig. 1: Finite-element mesh.

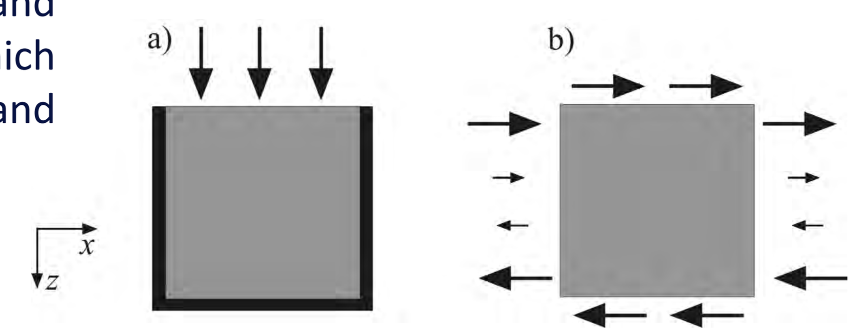

Fig. 2: (a) Compression and (b) shear boundary conditions for quasi-static relaxation tests.

(II) Accuracy

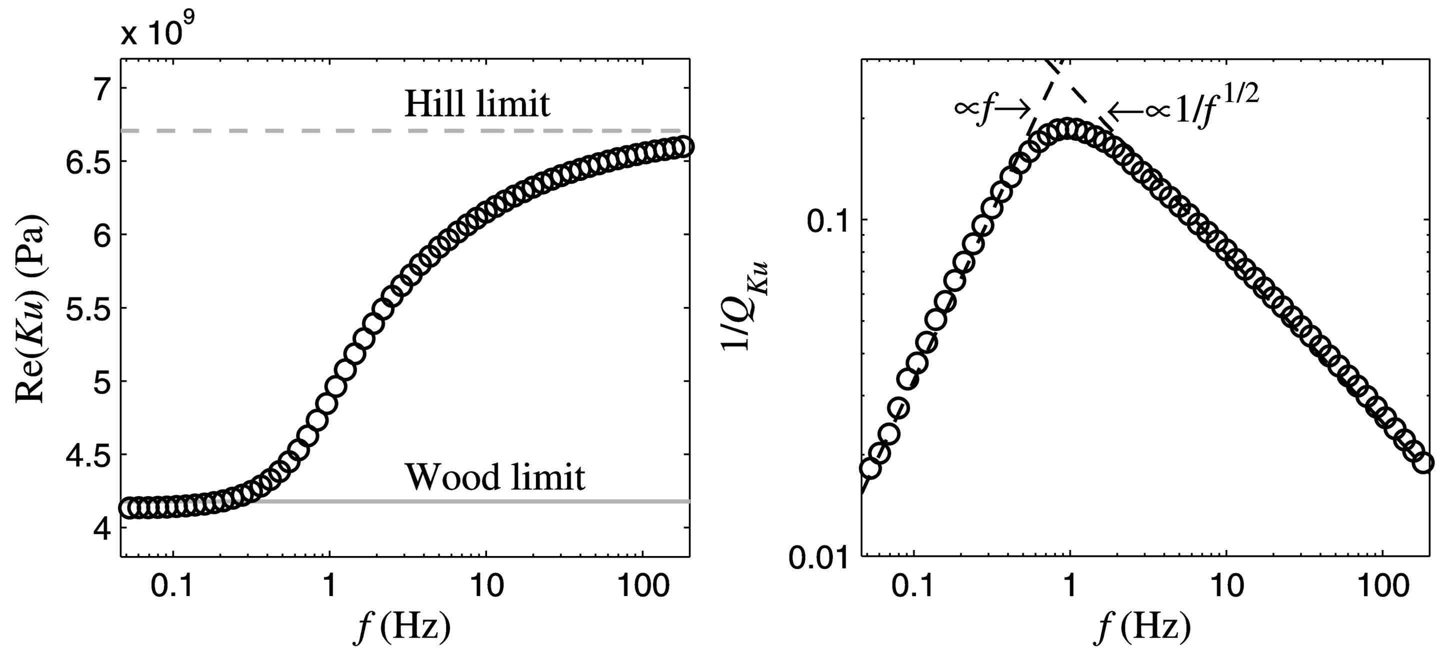

Fig. 3: Real part of the undrained bulk modulus, K_u (left), and the inverse of quality factor, $1/Q_{Ku}$, for pure undrained compression of a partially gas- and water-saturated rock. The theoretical limits (dashed) are accurately matched.

In Quintal et al. (2011) it was shown that the applied numerical algorithm is highly accurate over a frequency range of several orders of magnitude. The shown numerical results (Fig. 3) correspond to a gas-saturated background with a water-saturated heterogeneity. The performed test is a pure compression from all sides.

(III) Simulation examples

Fig. 4 shows the pore-fluid pressure field, P, and the fluid velocity in x- and z-direction, V_x and V_z, respectively, all normalized by their maximum value. S is the applied strain (i.e. arrows in Fig. 2). All models comprise the frame properties of Case A (Fig. 5; Table 2) and the background is saturated by oil (Table 1).

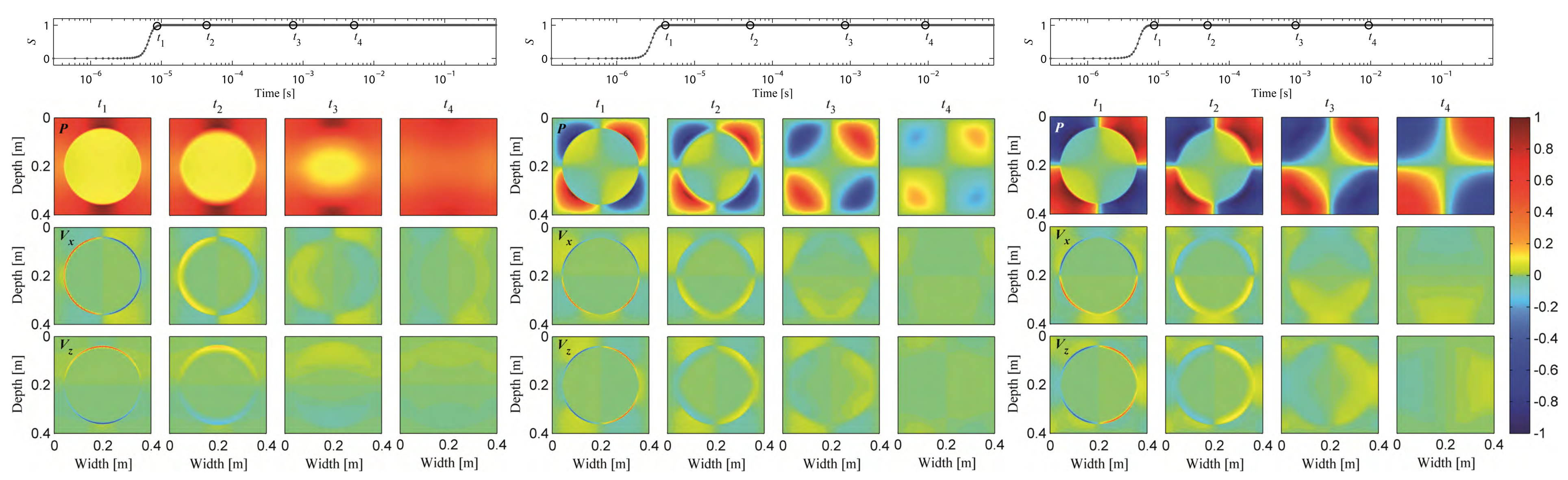

Fig. 4a) Compression test (Fig. 2a). The result is the same for the different boundary conditions.

Fig. 4b) Simple-shear test (Fig. 2b) with permeable boundaries around the unit cell.

Fig 4c) Simple-shear test (Fig. 2b) with impermeable boundaries around the unit cell.

(IV) Results

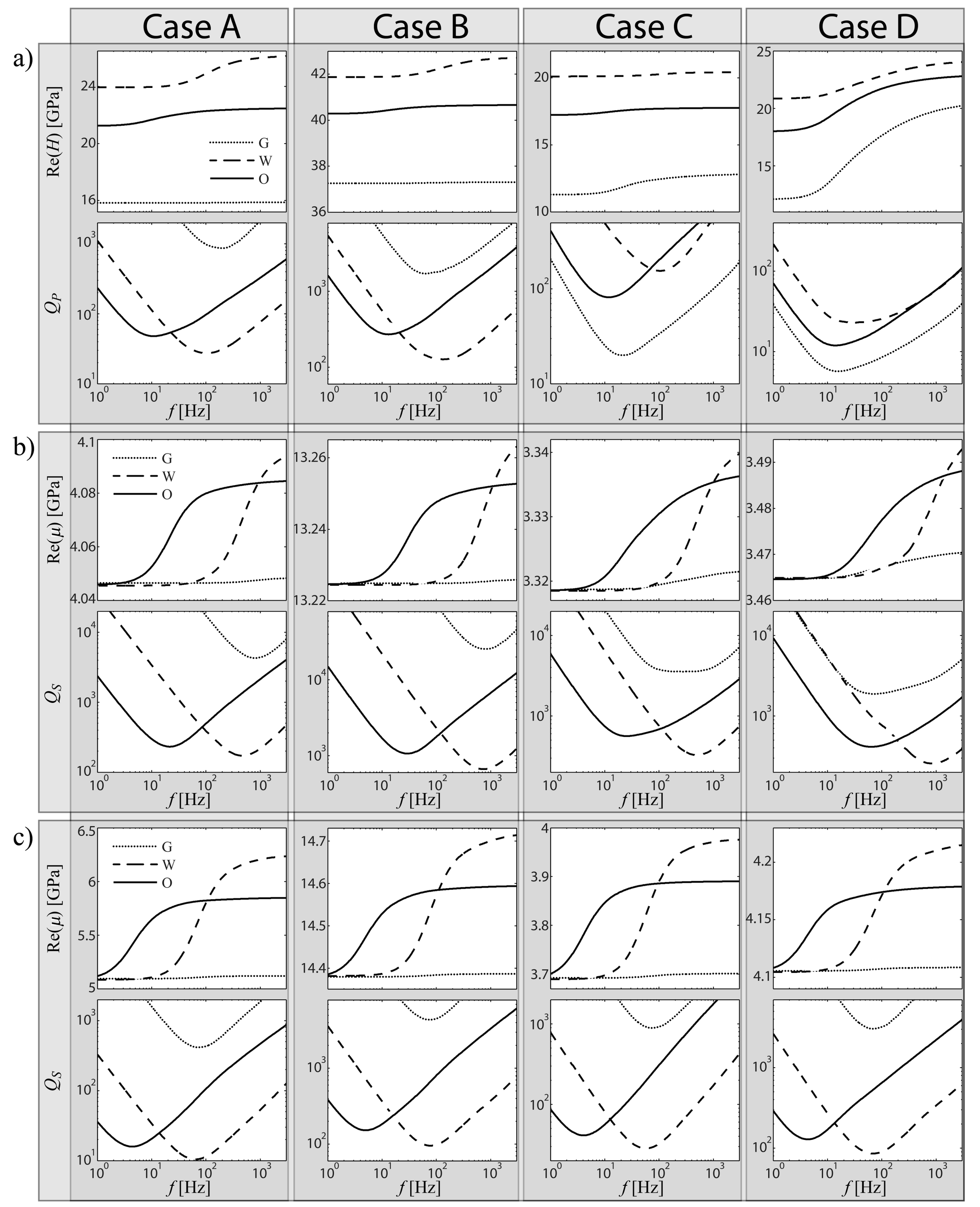

Fig. 5 shows that the relative positions of the three S-wave attenuation curves corresponding to the three different saturation scenarios are almost independent of the rock type. However, the rock type strongly influences the relative positions of the P-wave attenuation curves.

Also, the S-wave attenuation is much stronger in the case of impermeable boundaries around the unit cell, but the P-wave attenuation is not affected.

Fig. 5: Numerical results for the real part of the P- (a) and S-wave modulus (b and c) and the corresponding quality factors, Q_P and Q_S, respectively. a) compression test (Fig. 2a & 4 left); b) and c) simple-shear test with permeable (Fig. 2b & 4 middle) and impermeable boundaries (Fig. 2b & 4 right), respectively.

Parameter	Water	Oil	Gas
ρ_f [kg/m^3]	1010	880	160
η [Pa s]	0.001	0.02	2×10^{-5}
K_f [Gpa]	2.4	1.4	0.04

Table 1: Pore-fluid parameters.

Case	Parameter	Heterogeneity	Background
A-D	ρ_S [kg/m^3]	2700	2700
	K_S [GPa]	40	48
	φ [%]	6	26
	k [mD]	40	1000
A	K_d [GPa]	36	4
	μ_d [GPa]	32	2
B	K_d [GPa]	36	10
	μ_d [GPa]	32	8
C	K_d [GPa]	10	4
	μ_d [GPa]	8	2
D	K_d [GPa]	4	10
	μ_d [GPa]	2	8

Table 2: Solid frame parameters for the four Cases A-D.

Conclusions

Because the relative position of the S-wave attenuation curves hardly depend on the rock type (Fig. 5), but only on the pore-fluid, we suggest that S-wave attenuation may be a reliable pore-fluid indicator, superior to P-wave attributes.

S-wave attenuation is stronlgy affected by permeability barriers, but P-waves are not. Therefore, we suggest that S-wave attributes may be used as an indicator for permeability changes in a reservoir, e.g. during fracturing operations.

References

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