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Microscale Modeling of Heavy Oil Rocks

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SUMMARY

Due to decline in conventional oil and gas reservoirs, heavy oil has recently become an important resource. In consequence of this demand, it is necessary to have a rock physical model considering the viscoelastic behavior of heavy oils. Such effective properties are modeled on microscale using numerical simulations. Heavy oil rock sample is represented by the realistic digital 3D model. To obtain the effective velocities of such a digital sample, we use the viscoelastic rotated staggered grid FD algorithm. Numerical experiments are performed for transmission and reflection. Synthetic data obtained from numerical simulations are compared with recently developed model of generalized Gassmann equations for porous media with a viscoleastic solid material filling the pore space. The results show a very good agreement and confirm the applicability of the new rock physics model proposed for the modeling of heavy oil rocks.

Introduction

Seismic properties of heavy oil rocks are strongly temperature dependent. At the low temperatures heavy oil behaves as a quasi-solid. The heavy oil rock shows in this case viscoelastic behavior (Batzle and Hoffmann, 2006). Whereas, at high temperatures it behaves as a Newtonian fluid and it can be modeled by Biot's theory of poroelasticity (Biot, 1962). In this paper we numerically model these two regimes, a poroelastic and a viscoelastic one, which characterize the behavior of heavy oil rocks. The numerical simulations provide data for the theoretical analysis and for the development of the new modeling strategy based on recently developed generalized Gassmann's equations for porous rocks filled with a solid material (Ciz and Shapiro, 2008). The new model interconnects these two regimes and its viscoelastic extension is in good agreement with numerically simulated data. Our results show that heavy oil causes significant deviation in reflection coefficients at high viscosities, and/or low temperatures, when compared to the equivalent elastic reflection coefficients obtained by using classical Gassmann's fluid substitution (Gassmann, 1951). Numerical simulation of the elastic wave propagation on the microscale is an emerging tool in the analysis of many rock physics problems. We apply the viscoelastic extension of the displacement-stress rotated staggered grid finite-difference (VRSG FD) technique of Saenger et al. (2005) to simulate the reflection and transmission in 3D realistic digital samples of heavy-oil rocks. This method is based on the elastodynamic wave equation and hence accounts for all types of waves which occur on the microscale. The viscoelastic behavior of the fluid is described in the modeling algorithm as a specific generalized Maxwell body (GMB), which in a wide range of viscosities and frequencies is equivalent to a Newtonian fluid. This numerical technique allows us to simulate and analyze phenomena occurring during the seismic wave propagation in the fluid saturated poroelastic media. Thus, we model both the poroelastic and viscoelastic phenomena of the wave propagation in heavy oil rocks. Figure 1 on the left shows the shear modulus of saturating fluid in dependence of viscosity fully filling the pore space of the 3D porous medium shown in Figure 1 on the right.

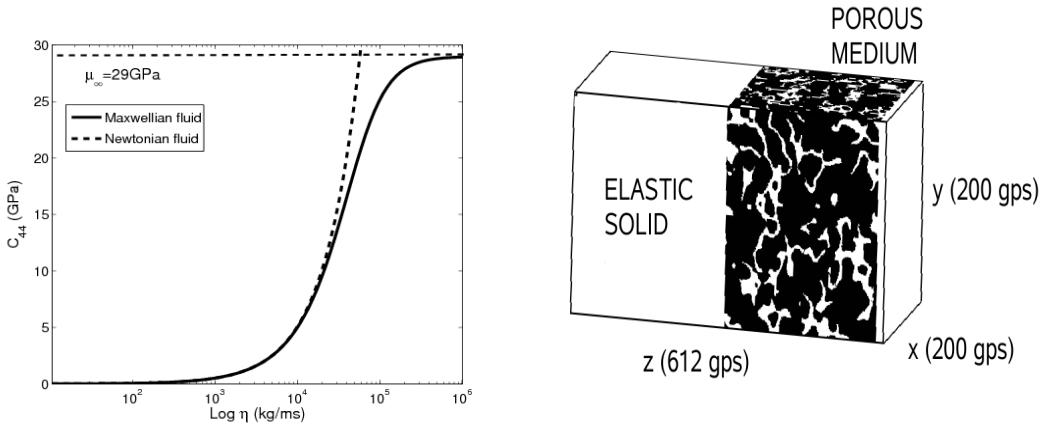


Figure 1. Newtonian and Maxwellian fluid models (left) and the numerical setup with elastic solid and porous medium blocks on the right.

Theoretical model

We consider a porous rock with an uniformly distributed porosity Φ whose pores are filled with a viscoelastic solid infill. The viscoelastic infill solid body is characterized by the effective bulk and shear moduli K_{if} and μ_{if} related to the average displacement. The infill solid body composes of the elastic grain material described by the elastic bulk and shear moduli K_{ifgr} and μ_{ifgr} , and a density ρ_{ifgr}. The drained solid frame formed from grains and pore spaces are characterized by bulk and shear moduli and density K, μ, ρ, respectively. The grains of the solid frame are characterized by the bulk and shear moduli K_{gr}, μ_{gr} and density ρ_{gr}. According to Ciz and Shapiro (2008) the generalized Gassmann's equations for the isotropic viscoelastic solid infill of the pore space and for the isotropic inhomogeneous material building up the

rock frame yields the "solid-saturated" bulk and shear moduli:

$$K_{sat}=K+\alpha^2 M \quad 1/M=\varphi/K_{if}+(\alpha-\varphi)/K_{gr} \quad \alpha=1-K/K_{gr}\ , \tag{1}$$

$$\mu_{sat}=\mu+\beta^2 N \quad 1/N=\varphi/\mu_{if}+(\beta-\varphi)/\mu_{gr} \quad \beta=1-\mu/\mu_{gr}\ , \tag{2}$$

$$\mu_{if}(\omega)=\mu_\infty/\left((-i\mu_\infty/\omega\eta)+1\right)\ , \qquad K_{if}(\omega)=K_f+5\mu_\infty/\left[3\left((-i\mu_\infty/\omega\eta)+1\right)\right] \tag{3}$$

$$V_p=\sqrt{(K_{sat}+4\mu_{sat}/3)/\rho}\ , \qquad V_s=\sqrt{\mu_{sat}/\rho}\ , \tag{4}$$

$$R_{P,S}=\frac{\rho_b V_{P,S}-\rho_a V_{P,S}}{\rho_b V_{P,S}+\rho_a V_{P,S}}\ , \tag{5}$$

where K_{sat}, μ_{sat} are viscoleastic solid saturated bulk and shear moduli, V_p, V_s are P- and S-wave velocities, $R_{P,S}$ are P- and S-wave reflection coefficients, η is viscosity and μ_∞ is the real shear modulus of the infill medium.

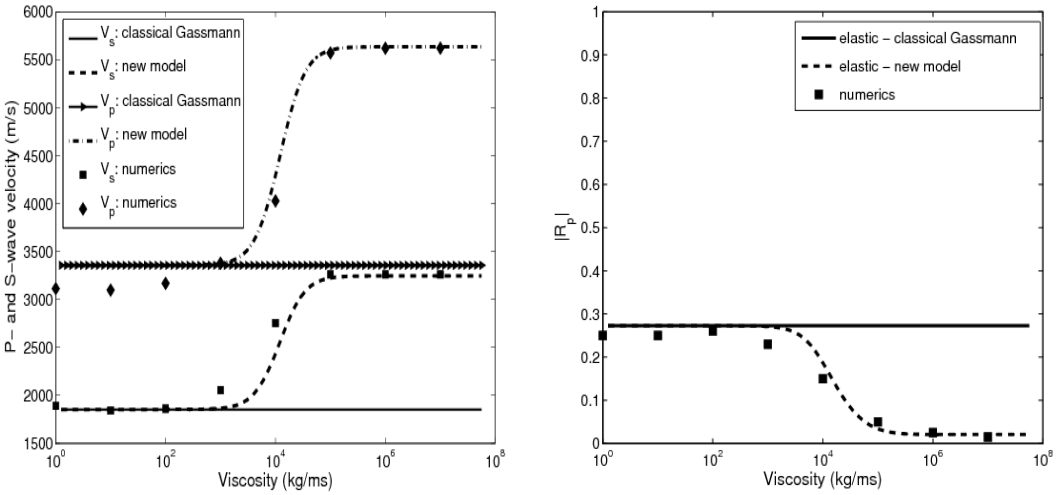


Figure 2. P- and S-wave velocities in dependence of the fluid viscosity for the low-contrast in elastic moduli of frame and infill grains (left) and the P-wave reflection (right) is compared with the classical and generalized Gassmann equations and numerical simulations.

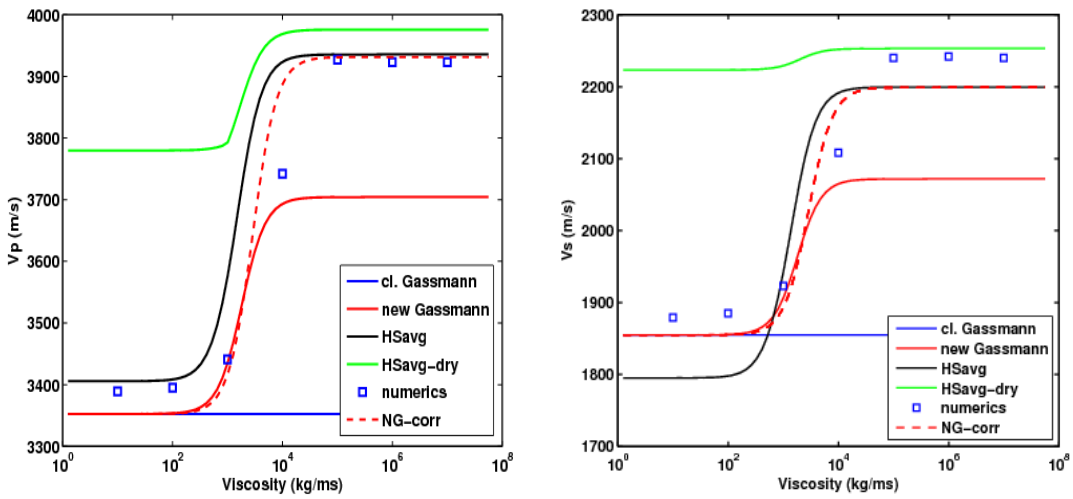
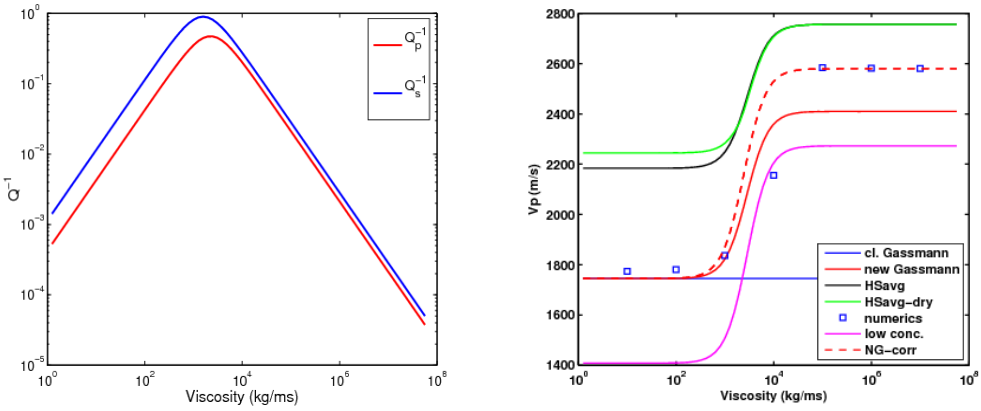


Figure 3. Effective P- and S-wave velocities in dependence of varying viscosity for heavy oil digital rock sample. We compare classical, generalized and generalized corrected Gassmann model with Hashin-Shtrikman (HS) viscoelastic model related to HS upper and lower bounds and HS average.

Figure 4. Viscoelastic attenuation (inverse quality factor for P- and S-waves) on the



left and P-wave velocity on the right in dependence of viscosity. Comparison with other effective medium model shows that the corrected generalized Gassmann equation provides the best fit of the numerical data.

Results

We perform numerical simulations in 3D digital models represented by Gaussian random fields created by Saenger et al. (2005). In our numerical setup we take a subsample of the GRF5 as shown in Figure 1. Thus, our digital model of the porous rock contains a subsample having 200x200x200 grid points. Our numerical setup contains two elastic blocks and the GRF5. We set the P- and S-wave velocities of the homogeneous block V_p=5100 m/s, V_s=2940 m/s and the density ρ_{gr} = 2540 kg/m^3. The same velocity is set to the grain material of the porous rock. The drained bulk and shear moduli of the digital porous block are obtained according to Saenger et al. (2005): K_{dr}=0.272 K_{gr} and μ_{dr}=0.344 μ_{gr}. In our numerical code the fluid is represented by a generalized Maxwell body (GMB) which can simulate both Newtonian and Maxwellian fluid models. Thus the rheological properties of the heavy oils are in our simulations represented by this GMB model. The modeling parameters are in Figure 2 set to c_{11}=89 GPa and c_{44}=29 GPa representing the case of low-contrast between infill and frame parameters. The parameters representing the heavy oil are set to c_{11}=5.3 GPa, c_{44}= 1.05 GPa and a density ρ_f = 1000 kg/m^3. The viscosity varies in the range from 1 kg/ms to 10^7 kg/ms. For this case we perform two types of simulations representing possible heavy oil rock configurations: 1) The digital heavy oil rock model is presented by the subsample of GRF5 model with porosity 22% and heavy oil filling the pore space. In this case we propagate through the digital sample a plane wave with a dominant frequency f_{dom}=80 kHz. This configuration represents the heavy oil rock in many heavy oil reservoirs as listed by Hinkle and Batzle (2006). The results are shown in Figure 3.; 2) We invert the rock and pore space, i.e. we have rock frame presented by former pore space. The porosity of such sample is 78%. In this case the heavy oil supports the grains. These simulations are performed at the dominant frequency f_{dom}=50 kHz. Figure 4 represents this case. The viscoelastic attenuation in the sense of inverse quality factor yields $1/Q_{p,s}=\mathrm{Im}V_{p,s}^{-2}/\mathrm{Re}V_{p,s}^{-2}$, where the complex velocities are given by equation 4. Our synthetic data are compared with viscoelastic extension and modifications of Hashin-Shtrikman model (Mavko et al., 1998), dilute suspension spherical inclusions model (Christensen, 1969) and the classical and generalized Gassmann's equations.

Modeling strategy

The comparison between numerical simulations and generalized Gassmann's equations initiated the development of the new strategy for the heavy oil rocks modeling. This strategy can be summarized in the following steps:

1. At low viscosities and/or high temperatures the heavy oil rock can be modeled using generalized Gassmann's equations, which are in this range identical with classical Gassmann's equations. This is shown in our numerical simulations for wide range of heavy oil viscosities.

2. At high viscosities (higher than 1000 kg/ms) and/or low temperatures (lower than 50°C), the generalized Gassmann's equations require the correction of the effective infill bulk and shear moduli K_{if} and μ_{if}.
3. To obtain this correction we use another effective medium model which provides correct effective elastic parameters at high viscosities or low temperatures. This is shown in our examples (Figure 3) using the Hashin-Shtrikman average.
4. Another and more correct way of obtaining this correction is the use of a measured data point. We take the measured effective velocity (or in our case also numerically simulated data) and derive the correcting parameter. This is performed in Figure 4.
5. The generalized Gassmann's equations and the obtained corrections build the rock physical model and strategy for modeling heavy oil rocks in wide range of viscosities and/or temperatures.

The proposed approach models the viscoelastic dispersion, i.e. we can model the transition from poroelastic to viscoelastic regime. The strategy summarized in 1 - 5 is demonstrated in our numerical simulations in Figures 3 - 4.

Conclusions

We have performed a number of numerical simulations analyzing the new theory and investigating the capability of this theory for the modeling of heavy oil rocks. These simulations were performed for two possible situations in which the heavy oil either infills the pore space or in the second case when heavy oil supports the grains. In both cases the generalized Gassmann's equations can be applied in the wide range of viscosities and/or temperatures. The main result of this paper is the proposed strategy for the modeling of heavy oil rocks. The results suggest that classical Gassmann's equations are inapplicable when the pore filling material is a solid or material whose shear modulus has a finite component. The new model overcomes these limitations and the developed strategy enables modeling of heavy oil rocks.

Acknowledgement

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