MODELS FOR SEISMIC WAVE PROPAGATION IN PERIODICALLY LAYERED POROUS MEDIA

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Summary. Several models are discussed for seismic wave propagation in periodically layered poroelastic media where layers represent mesoscopic-scale heterogeneities that are larger than the pore and grain sizes but smaller than the wavelength. The layers behave according to Biot’s theory. Wave propagation normal to the layering is considered and the models are validated with the solution obtained with the use of Floquet’s theory. The first model introduces frequency-dependent effective P-wave modulus and is viscoelastic. The second model introduces frequency-dependent effective Biot coefficients and the third model is governed by an equation with higher-order derivatives and real-valued coefficients. A special case is studied where the viscoelastic effective model significantly underestimates seismic attenuation.

Key words. Seismic attenuation, wave propagation, effective medium, mesoscopic heterogeneities, poroelasticity, periodic layering, permeability, sandy sediments.

INTRODUCTION

Seismic waves in porous media exhibit significant attenuation in the presence of mesoscopic heterogeneities (larger than the pore and grain sizes but smaller than the wavelength). It is believed that the wave-induced fluid flow between inhomogeneities is the main cause of wave attenuation in the seismic frequency band (Müller et al. 2010). The inhomogeneities can occur both in fluid and in frame properties. In many practical situations it is computationally inefficient to model wave propagation in highly heterogeneous materials by solving the equations of poroelasticity with spatially varying coefficients. Effective models are used instead to save the computational time. First, homogenization is applied to an initially heterogeneous medium to derive the effective parameters. Next, these parameters are used as an input to the equations of motion of the effective homogeneous medium.

One of the examples of this approach is a homogenization of media with periodically distributed heterogeneities. The model of White et al. 1975 for periodically layered porous media received a lot of attention in literature because it demonstrated the significance of seismic attenuation due to the presence of inhomogeneities, especially in fluid content. In this model, a low-frequency approximation of an effective compressional (P) wave modulus was derived by applying an oscillatory compressional test to the representative element that consists of half of the periodic cell and has undrained boundaries. A similar approach was used in other analytical derivations (Norris 1993, Johnson 2001) and in numerical studies (Quintal et al. 2012, Rubino et al. 2009) where the P-wave modulus is derived by employing no-flow boundary conditions (the fluid is not allowed to flow into or out of the sample). This kind of modelling is quite popular, because in many practical situations it gives accurate results with the reduction of computational costs. The above-mentioned effective media that capture the mesoscopic attenuation mechanism are in fact viscoelastic media. As a result of employing the no-flow boundary condition, only one frequency-dependent elastic modulus is obtained. Consequently, there is only one degree of freedom in the effective medium, which is the displacement of the frame; the effective medium thus allows for the existence of only one P-wave mode, the slow Biot wave (Biot 1956) is not explicitly present in the effective medium.

The consequence of the reduction of the poroelastic medium to the viscoelastic one is the possible loss of Biot’s global flow attenuation mechanism in the effective medium. Two alternative models have been proposed by the authors that include this mechanism in addition to capturing the mesoscopic-flow attenuation (Kudarova et al. 2013a, b). In this work we focus on the possible application of the proposed models.
COMPARISON OF THE MODELS

Biot’s global flow attenuation mechanism is often not the dominant attenuation mechanism at seismic frequencies in media with mesoscopic heterogeneities, though it is not always negligible since it depends on parameters such as permeability and porosity. It has been shown by the authors (Kudarova et al. 2013b) that the viscoelastic model is not capable to describe dispersion and attenuation properly for saturated porous media with relatively high permeability (1–100D) and porosity and a weak frame, even at very low frequencies. Such media have significantly lower Biot’s critical frequency than most stiff rocks; it can even be in the seismic range. Biot’s macroscopic-scale attenuation mechanism is therefore not negligible at seismic frequencies, whereas for most stiff rocks it is. The reduced-phase (viscoelastic) effective model often underestimates attenuation in such media and, as a result, significantly overestimates the magnitude of the point-source response. This is the case for high permeable sandstones, unconsolidated and weakly consolidated sands and sandy sediments.

Results of the detailed study show that for high permeable materials with a weak frame it depends on a number of parameters whether the viscoelastic effective model can be applied. It is better to use the fully poroelastic solution for unconsolidated sands, in case of high gas saturations, large values of the quality factor and propagation distance, and at relatively high frequencies. For weakly consolidated sands and sandstones, inaccuracy of the viscoelastic model can be not visible on the response when attenuation and propagating distance is small and at low frequencies. However, in other situations it can be extremely large and result in overestimation of the amplitude of the propagating wave by a factor two to five.

Our effective poroelastic models are in agreement with the exact analytical solution obtained with the use of Floquet’s theory, also for high permeable materials. The first model (Kudarova et al. 2013a) is obtained by asymptotic expansions with multiple spatial scales. It results in a homogenized Biot’s equations of motion with extra higher-order terms. The important property of the model is real-valued and frequency-independent coefficients determined analytically exclusively by the physical parameters of the layers. It serves as an alternative to the existing models with frequency-dependent effective elastic properties. The other advantage of the model is possible extension to multidimensional problems. The second model uses homogenized Biot’s equations with frequency-dependent coefficients. As in White’s model, they were derived by applying an oscillatory compressional test to the representative element that consists of a periodic cell. But the boundary conditions were chosen differently: the continuity of pressure at the outer edges of the cell replaced the no-flow condition. Thus, the fluid flow is allowed on the macroscopic scale and the effective medium contains both solid and fluid phases. Comparison of the predictions of the models with the predictions of the exact solution shows that the frequency dependence of the effective coefficients in the second model makes it applicable to a wider frequency range.

APPLICATION TO SEISMIC RESERVOIR MONITORING

Given the results of the study on application of different models to sandy sediments, it is interesting to see if the choice of model affects the results of the reservoir monitoring. A schematic representation of the offshore CO2 storage site is depicted in Fig. 1. A layer of marine sediments is located at the bottom of the fluid half-space. Marine sediments are modelled with the effective homogenized models as a partially saturated medium: it consists of many thin alternating layers saturated with water and gas. The remaining layers are modelled as homogeneous porous media with Biot’s equations: typical rock, CO2 and water-saturated sandstone trapped by mudstone layers, and a rock half-space below. A source is located at the bottom of the fluid half-space and the receiver is located below the storage layer, as indicated in the Figure 1. Ricker wavelet is chosen as a source. We use the exact solution (the sediment layers are solved with Floquet’s theory) to obtain the “observed” data at the receiver location (solid particle displacement). Then the marine
sediments layer is modelled with the effective media for the solution of the inversion problem, to obtained the modelled data. The cost function to minimize is the $L_2$-norm of the difference between the modelled and “observed” data at the receiver location. We invert for the parameters of the CO$_2$-saturated layer: the thickness and fluid density. The equations are solved in the frequency domain. The total thickness of the layers is approximately 1 km.

![Diagram of offshore CO$_2$ storage site](image1)

**Fig. 1.** Schematic representation of the offshore CO$_2$ storage site

![Amplitude spectrum and sensitivity plots](image2)

**Fig. 2.** Amplitude spectrum (left panel), sensitivity of the cost function to the thickness of the CO$_2$ layer (middle panel) and to the fluid density (right panel). Black line – poroelastic model, red line – viscoelastic model. Gas saturation 10%

![Amplitude spectrum and sensitivity plots](image3)

**Fig. 3.** The same as in Fig. 2 (the right panel is split in two plots). Gas saturation 0.1%

The unconsolidated sediment with frame properties from Williams (2001) is chosen for an example. The sensitivity study is presented in Fig. 2 and 3. Fig. 2 shows that although the amplitude prediction by the model that uses viscoelastic effective medium for marine sediments is not correct, the parameters of the layer can be predicted with the same accuracy as with the poroelastic effective
medium. However, with different gas saturation in the sediments, the predictions by the poroelastic model are more accurate, as shown in Fig. 3.

CONCLUSIONS

The effective viscoelastic model of White which consists of a homogeneous porous frame saturated by gas and fluid layers that are organized in a periodic way, has been the starting point of many studies in the research on wave attenuation in partially saturated media. We validated the model with the exact solution and discovered the situations when it underestimates attenuation due to its failure to capture the global flow attenuation mechanism. In seismic frequency range, it applies to some sandstones and sandy sediments. We showed that the application of the alternative poroelastic model to the partially saturated marine sediments can significantly increase accuracy of the predictions.

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