Seismic attenuation in fluid-filled fractured porous media – a wave propagation study

Mikhail Novikov[a], Eva Caspari[b], Vadim Lisitsa[a], Beatriz Quintal[b], J. Germán Rubino[c], Klaus Holliger[b]

[a] *Institute of Petroleum Geology and Geophysics, Novosibirsk, Russia;* [b] *University of Lausanne, Lausanne, Switzerland;* [c] *CONICET, Centro Atómico Bariloche – CNEA, San Carlos de Bariloche, Argentina.*
Contact email:lisitsavvbiz@gmail.com

Introduction

Recent studies of seismic attenuation in fluid-saturated fractured porous media illustrate the significance of fluid pressure diffusion phenomena. This physical process occurs between the compliant fracture-filling material and the stiff host rock (FB WIFF) as well as between intersecting fractures (FF WIFF). As shown numerically (Rubino et al. 2013) and theoretically (Guo et al. 2016), wave-induced fluid pressure diffusion causes a local increase in seismic attenuation at characteristic frequencies, which depend on the material properties and the geometrical characteristics of the fracture network. However, these studies are based either on the solution of Biot's quasi-static equations or on effective medium theories, which neglect dynamic effects, such as Biot global flow and scattering. Here, we present a 2D numerical study of wave propagation in fluid-saturated fractured porous media and compare the attenuation estimates with those obtained from a quasi-static upscaling approach and the analytical scattering theory of Rytov et al. (1987). The aim is to investigate the interplay of the aforementioned attenuation mechanisms.

Methods

We consider four simple models of randomly distributed fractures: (a) fractures parallel and (b) perpendicular to the wave propagation direction, (c) 50% of fractures parallel and 50% perpendicular to the wave propagation direction with no fracture intersections, (d) same as (c) but we require each fracture to intersect with at least one other fracture. The fractures are represented as highly compliant and highly permeable heterogeneities, having a rectangular geometry with an aperture and length of 4 and 30mm. For each model, we simulate plane wave propagation using a Ricker wavelet with central frequencies ranging from 500 Hz to 10 kHz. To cover all attenuation mechanisms in this frequency regime, the permeability of the fracture-filling material varies from 10^{-16} to 10^{-8} m^2, whereas the matrix permeability is 10^{-13} m^2. The signals are recorded at two receiver lines, before and after propagation in the fractured layer. A deconvolution procedure is applied to the recorded signals to estimate the frequency-dependent attenuation. Estimates of attenuation due to scattering are based on the single-scattering theory in random media (Rytov et al. 1978). In the numerical upscaling scheme, we apply a compressional oscillatory relaxation test to a square sample of the fractured domain (Rubino et al. 2013). The resulting frequency-dependent attenuation is associated with pressure diffusion phenomena.

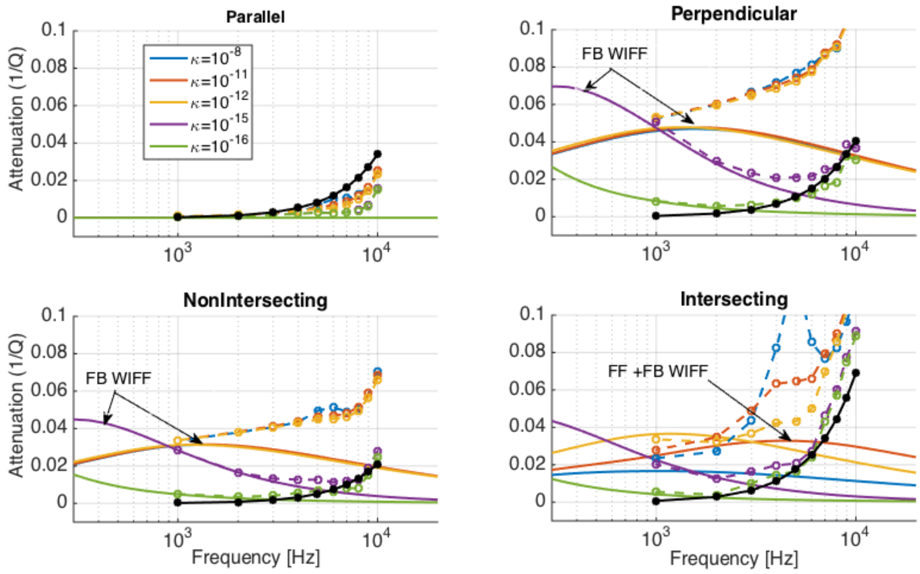

Fig. 1.: Comparison of attenuation estimates from wave propagation experiments (circles) and oscillatory tests (solid lines) for parallel, perpendicular, intersecting, and non-intersecting fractures. The black lines correspond to the estimated scattering attenuation. The legend in the plots represents the fracture material permeability.

Results

Attenuation estimates based on the dynamic and quasi-static simulations as well as the theoretical scattering solution are presented in Fig. 1. At frequencies below 2000 Hz, the attenuation obtained from the oscillatory tests for FB WIFF and wave propagation simulations show a good agreement, which indicates that in this frequency regime diffusion processes are dominating. For higher frequencies, scattering clearly starts to dominate, as indeed predicted by the theoretical estimates. However, in the case of intersecting fractures for permeabilites higher than 10^{-11} m^2, a clear deviation from the predicted scaling of scattering attenuation can be observed, which might be related to FF WIFF and Biot global flow effects.

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