Effects of fracture aperture distributions on seismic attenuation and P-wave modulus dispersion caused by fluid pressure diffusion

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Introduction

Fractures in rocks occur in a wide range of scales and their identification and characterisation are important for several applications such as oil and gas exploration and extraction, production of geothermal energy, nuclear waste disposal, civil engineering works, among others. Given that seismic waves properties are significantly affected by the presence of fractures, seismic methods are a valuable tool for characterising them. In particular, when a fluid-saturated fractured rock is compressed by a propagating P-wave, a pressure gradient is generated due to the compressibility contrast between the fracture and the embedding background. Consequently, energy dissipation occurs during the corresponding fluid pressure diffusion. This mechanism can be an important cause of seismic wave attenuation and stiffness modulus dispersion. In this work, we numerically quantify the effects that fracture aperture distributions have on seismic wave attenuation and stiffness modulus dispersion in a medium containing parallel fractures.

Methodology

We numerically perform uniaxial oscillatory relaxation tests (Rubino et al., 2009) by solving Biot's (1941) quasi-static equations of poroelasticity in the **u**-p (solid displacement and pressure) formulation with the finite element method (Quintal et al., 2011). The considered numerical model has a cubic shape and contains a horizontal fracture in its center, which is characterized by high porosity and a highly compliant solid frame, and is embedded in a homogenous background of lower porosity and much less compliant solid frame. Such a model corresponds to the representative elementary volume of a medium containing a periodic distribution of parallel fractures. The effective P-wave modulus normal to the fractures is obtained by applying a vertical homogeneous harmonic displacement on top of the 3D numerical model while restricting normal displacements on its sides.

Results and discussion

Fractures (Figure 1a) with variable aperture promoting contact areas were generated using a stratified percolation algorithm (Nolte and Pyrak-Nolte, 1991). The correlation length represents an approximation to the average size of the contact areas. For comparing the seismic response of our fracture models of realistic complex geometries with that of simple fracture models given by an analytical solution (White, 1975), we numerically calculate the equivalent dry bulk and shear moduli for each realistic fracture. Then, using these equivalent properties, as well as the equivalent fracture porosity and mean aperture, as input in White's analytical solution, we quantify the seismic behaviour of the equivalent simple fracture model having a constant aperture.

Our results (Figure 1b) show that a higher contact area density as well as a lower correlation length produce a stiffer fracture and therefore negligible seismic attenuation is exhibited for fracture C. Fracture

B, on the other hand, having the lowest density and the highest correlation length of contact areas, is the most compliant and exhibits the highest attenuation. It is also interesting that fractures A and D show a similar seismic response despite their very different geometries. This illustrates that increasing the correlation length of contact areas compensates for an increase in contact area density. Furthermore, there is excellent agreement between the numerical results for fractures with aperture distributions and those for fractures with a constant aperture and equivalent physical properties.

(a) *(b)*

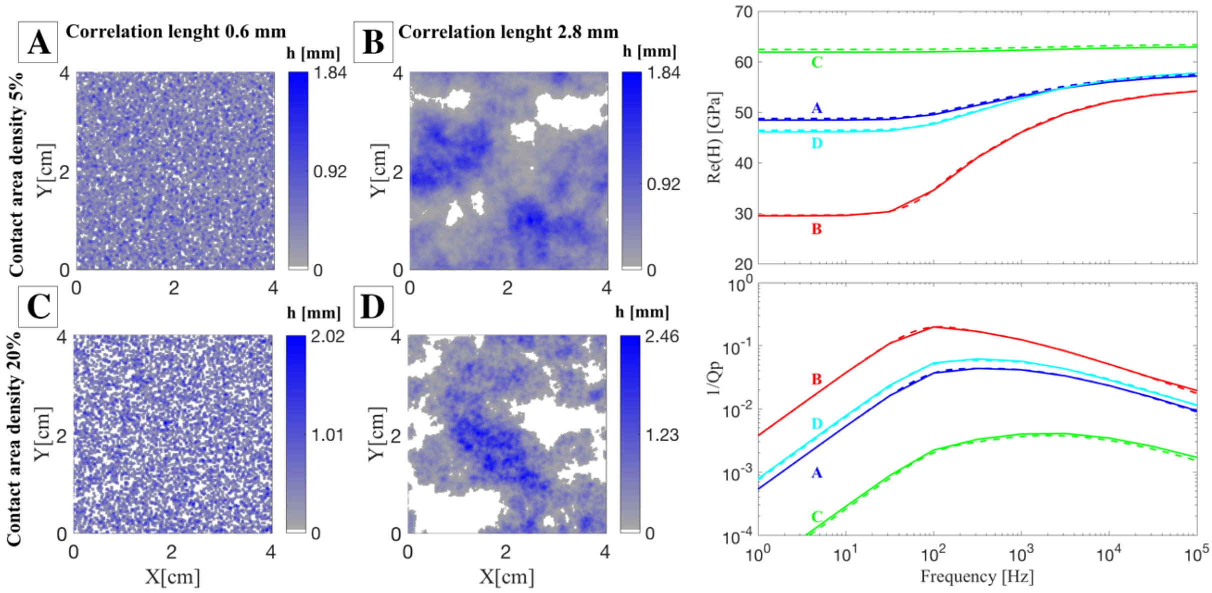

Figure 1: (a) Fracture aperture distributions. Upper models have a lower contact area density than lower ones. Models on the left have a lower correlation length than those on the right. All models have a mean aperture of 0.4 mm. (b) Real part of P-wave modulus (H) and attenuation ($1/Q_P$) normal to the fractures. Solid lines correspond to complex fracture models illustrated in (a), while dashed lines correspond to models of a simple fracture geometry characterized by constant apertures and using equivalent fracture properties.

Conclusions

As a main outcome, we showed that a fracture represented as a thin layer with constant thickness and appropriate equivalent properties yields results for seismic attenuation and P-wave modulus that approximate well those of a fracture with a much more intricate geometry which includes contact areas. Our results validate the use of simple planar thin layers for approximating the behaviour of fractures having realistic aperture distributions in order to reduce the computational costs of the corresponding numerical simulations.

Acknowledgements

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