BARBOSA Nicolás Daniel (2018) : Seismic characterization of fractured rocks based on Biot's theory of poroelasticity

Abstract

The presence of fractures in geological formations tends to dominate their mechanical and hydraulic properties. This makes fractures characterization and imaging an important objective for a wide variety of applications throughout the Earth, environmental, and engineering sciences. Amongst the geophysical techniques having the potential to locate fractures in the subsurface and to provide information on their hydromechanical properties, seismic methods are the most commonly used due to its high resolution and deep penetration. Hence, understanding and quantifying the relation between observed seismic attributes, such as, for example, velocity dispersion, attenuation, and anisotropy, and the elastic and hydraulic properties of fracture networks is of considerable interest. In fluid-saturated fractured rocks, wave-induced fluid flow, or simply WIFF, is known to be an underlying physical mechanism governing the behavior of elastic waves throughout the seismic, sonic, and ultrasonic ranges of frequencies. This mechanism prevails in response to fluid pressure gradients and inertial effects induced by the passing wave fields. The viscous friction associated with the relative fluid-solid motion in the pores of the rock manifests itself in the form of attenuation and velocity dispersion in seismic recordings.

Here, we present theoretical and experimental advances with regard to the seismic characterization of fluid-saturated fractured rocks. On the theoretical side, we organize the analysis according to the relation between the seismic wavelength and the characteristic size of fractures. In the first part of this thesis, we consider fractures whose planar extent as well as their spacing is larger or comparable to the seismic wavelengths and that, hence, must be treated as discrete features. In this scenario, the WIFF resulting in response to fluid pressure gradients between the compliant fractures and the stiffer embedding background produces a frequency-dependent behavior with regard to the stiffening effect of the fluid saturating the fracture. We use numerical solutions of plane-wave propagation to investigate how this WIFF-related effect affects the seismic reflectivity, and hence the seismic visibility, of a fracture. Our results indicate a strong dependence of the fracture reflectivity on WIFF, especially for P-waves and low incidence angles. Most importantly, we find that in common fractured environments WIFF effects can significantly increase the seismic visibility of fractures. Motivated by these results, we developed an analytical model for the effective compliance of a fracture that accounts for the impact of WIFF on the stiffening effect of the fluid saturating the fracture. As a result, the effective compliance of the fracture is complex valued and frequency-dependent. This model is expected to improve the estimation of the mechanical properties of fractures in corresponding inversion schemes compared to classical approaches, which rely on the assumption that fractures are hydraulically sealed with respect to the background. Furthermore, it also allows for extracting information with regard to other practically important parameters, such as, for example, the background permeability.

When fractures are much smaller than the wavelength, seismic wave propagation can be described using an effective homogeneous representation of the fractured medium. In the second part of this thesis, we investigate how the effects that fractures have on the effective anisotropy of seismic waves can be affected by (i) the presence of fracture clustering and (ii) the presence of intrinsic elastic and hydraulic anisotropy in the background rock. In both cases, we follow the principles of

numerical upscaling techniques to obtain an equivalent anisotropic viscoelastic solid of a representative sample of the fractured formation of interest. The fracture clustering effect is studied for the case of aligned fractures by means of a new hybrid approach in which we first use a 1D numerical oscillatory relaxation test to compute effective seismic properties at normal P-wave incidence. Subsequently, we make use of theoretical aspects of the behavior of WIFF between the fractures and the background that permits to extend the 1D numerical results to oblique incidence. A corresponding analysis shows that the presence of clusters of fractures produces an additional attenuation and velocity dispersion regime compared to that predicted for regular or random distributions of fractures. The reason for this is that a fracture cluster behaves as an effective weak layer whose contrast with respect to the unfractured background produces an additional cluster-scale WIFF process. Regarding the study of the impact of WIFF effects on the effective seismic properties of a fractured reservoir that exhibits some degree of intrinsic anisotropy of the background, we extend an existing 2D numerical upscaling procedure. That is, we apply a set of relaxation experiments to a representative sample of the fractured formation to compute its effective anisotropic seismic properties. To account for the intrinsic background anisotropy, we represent this region with a corresponding anisotropic poroelastic medium. Our results indicate that the intrinsic elastic anisotropy of the background plays a fundamental role for WIFF between the fractures and the background as well as for WIFF between fractures that are hydraulically connected. The hydraulic anisotropy of the background mainly affects the characteristics of the effects related to WIFF between fractures and background.

Quantitative fracture characterization from seismic data has been mostly achieved by modelling fractures with a seismic displacement discontinuity model. This model assumes that the average displacement discontinuity across the fracture is equal to the product of the applied seismic stress and the effective mechanical compliance of the fracture. From this effective compliance, other fracture properties, such as, the aperture and contact area distributions or the infill material of the voids between the fracture's interfaces, can be inferred. Given that scattered seismic wave fields from a fracture depend on its compliance, the use of the reflection or transmission response of a fracture has been extensively used to characterize fractures in the laboratory from core or synthetic samples. However, estimations of the compliance of fractures on scales larger than that of core samples are quite scarce. On the experimental side of this thesis, we present estimations of complex-valued fracture compliances from full-waveform sonic (FWS) data acquired in a borehole penetrating multiple fractures embedded in a granodioritic rock mass. To do so, we propose a methodology to compute the P-wave transmission coefficient associated with a given fracture from the corresponding sonic P-wave attenuation and velocity. The thus inferred transmission coefficient can then be directly related to the complex-valued mechanical compliance of the fracture. The complex nature of the fracture compliance allows us to account for the effects of dissipation mechanisms prevailing when the seismic wave deforms the fracture. Our estimations show that the real component of the fracture compliance is in agreement with previously reported estimates available in the literature and that the magnitude of the imaginary component, which is usually neglected, tends to be comparable to its real counterpart.