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Seismic Characterization of Heterogeneous Sedimentary and Fractured Rocks Based on Biot's Theory of Poroelasticity

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Abstract

Understanding and quantifying seismic energy dissipation, which manifests itself in terms of velocity dispersion and attenuation, in fluid-saturated porous rocks is of considerable interest, since it offers the perspective of extracting information with regard to the elastic and hydraulic rock properties. There is increasing evidence to suggest that wave-induced fluid flow, or simply WIFF, is the dominant underlying physical mechanism governing these phenomena throughout the seismic, sonic, and ultrasonic frequency ranges. This mechanism, which can prevail at the microscopic, mesoscopic, and macroscopic scale ranges, operates through viscous energy dissipation in response to fluid pressure gradients and inertial effects induced by the passing wavefield.

In the first part of this thesis, we present an analysis of broad-band multi-frequency sonic log data from a borehole penetrating water-saturated unconsolidated glacio-fluvial sediments. An inherent complication arising in the interpretation of the observed P-wave attenuation and velocity dispersion is, however, that the relative importance of WIFF at the various scales is unknown and difficult to unravel. An important generic result of our work is that the levels of attenuation and velocity dispersion due to the presence of mesoscopic heterogeneities in water-saturated unconsolidated clastic sediments are expected to be largely negligible. Conversely, WIFF at the macroscopic scale allows for explaining most of the considered data while refinements provided by including WIFF at the microscopic scale in the analysis are locally meaningful. Using a Monte-Carlo-type inversion approach, we compare the capability of the different models describing WIFF at the macroscopic and microscopic scales with regard to their ability to constrain the dry frame elastic moduli and the permeability as well as their local probability distribution.

In the second part of this thesis, we explore the issue of determining the size of a representative elementary volume (REV) arising in the numerical upscaling procedures of effective seismic velocity dispersion and attenuation of heterogeneous media. To this end, we focus on a set of idealized synthetic rock samples characterized by the presence of layers, fractures or patchy saturation in the mesocopic scale range. These scenarios are highly pertinent because they tend to be associated with very high levels of velocity dispersion and attenuation caused by WIFF in the mesoscopic scale range. The problem of determining the REV size for generic heterogeneous rocks is extremely complex and entirely unexplored in the given context. In this pilot study, we have therefore focused on periodic media, which assures the inherent self- similarity of the considered samples regardless of their size and thus simplifies the problem to a systematic analysis of the dependence of the REV size on the applied boundary conditions in the numerical simulations. Our results demonstrate that boundary condition effects are absent for layered media and negligible in the presence of patchy saturation, thus resulting in minimum REV sizes. Conversely, strong boundary condition effects arise in the presence of a periodic distribution of finite-length fractures, thus leading to large REV sizes.

In the third part of the thesis, we propose a novel effective poroelastic model for periodic media characterized by mesoscopic layering, which accounts for WIFF at both the macroscopic and mesoscopic scales as well as for the anisotropy associated with the layering. Correspondingly, this model correctly predicts the existence of the fast and slow P-waves as

well as quasi and pure S-waves for any direction of wave propagation as long as the corresponding wavelengths are much larger than the layer thicknesses. The primary motivation for this work is that, for formations of intermediate to high permeability, such as, for example, unconsolidated sediments, clean sandstones, or fractured rocks, these two WIFF mechanisms may prevail at similar frequencies. This scenario, which can be expected rather common, cannot be accounted for by existing models for layered porous media. Comparisons of analytical solutions of the P- and S-wave phase velocities and inverse quality factors for wave propagation perpendicular to the layering with those obtained from numerical simulations based on a 1D finite-element solution of the poroelastic equations of motion show very good agreement as long as the assumption of long wavelengths remains valid. A limitation of the proposed model is its inability to account for inertial effects in mesoscopic WIFF when both WIFF mechanisms prevail at similar frequencies. Our results do, however, also indicate that the associated error is likely to be relatively small, as, even at frequencies at which both inertial and scattering effects are expected to be at play, the proposed model provides a solution that is remarkably close to its numerical benchmark.