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Pore-fabric induced seismic anisotropy and poroelastic coefficients

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Introduction

In most relevant geological settings, seismic anisotropy is present. Biot (1955) developed a theory for anisotropic poroelasticity. Therein, anisotropy is parameterized through drained and undrained compliances and the components of the Skempton tensor (e.g., Cheng (1996)). However, links to the elastic constants of the constituents and contributions to the macroscopic anisotropy due to the fabric of the microstructure are lacking from Biot's stress tensors. Moreover, in this framework, shear stiffening because of pore fluid is also not accounted in an apparent manner.

On the basis of Sahay et al. (2001), in this work, the connection of pore-fabric induced seismic anisotropy to poroelastic material coefficients is presented.

Methodology

Practitioners consider anisotropic poroelasticity impractical, as the material constants are not easily identifiable from experiments. This lack of applicability is of particular importance for porous matrix with uneven distribution of pores and interfaces. The change in the fabric of the porous matrix due to the interfacial strain tensor (Fig. 1) is the key to understand the impact of anisotropy on the kinematic response. In contrast to the Biot theory, the signature of interfacial strain tensor does manifest explicitly in Sahay et al. (2001). That makes the description of anisotropy transparent. It permits the factorization of the contributions of macroscopic anisotropy due to change in the fabric of the microstructure (pore-fabric induced seismic anisotropy) from the end members' elasticity. Furthermore, this framework also has explicitly a porosity perturbation equation as a part of its constitutive equations. Therein, by allowing porosity to change in a shear deformation, this framework accounts for dependence of shear modulus on the compressibility of pore fluid in a transparent manner.

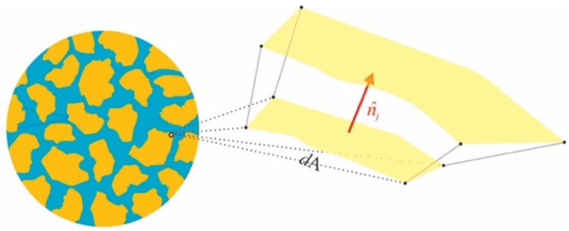

Figure 1: A magnified view of solid-fluid interfacial surface element, before and after deformation. Displacement of surface element in the normal direction to itself (red arrow) amounts a volume swept away. Summation of such motion over all surfaces that lie within the unit volume is the pore-space volume change, i.e., porosity change. Likewise, displacement of interfacial surface element in tangential direction amounts to pore-interface stretch and the sum of such motion over all surfaces within the unit volume is the pore-space shape change. These, respectively, constitute the dilatational and deviatoric parts of the interfacial strain tensor.

Sahay et al. (2001) is a general framework of inhomogeneous and anisotropic poroelasticity. In the present work, at first, the general framework is specialized to a specific homogeneous and anisotropic case wherein material properties for the two constituents end members are homogeneous and isotropic, unperturbed porosity is spatially uniform, but pores and interfaces are preferentially oriented within representative volume element. Clearly, herein, the fabric tensor of the architecture of the microstructure is anisotropic, even in the unperturbed state. Thus, in this case, the seismic anisotropy is solely due to change in the fabric tensor, i.e., pore-fabric induced seismic anisotropy.

Results

For this case, by analyzing the interfacial strain tensor, one finds that the anisotropy tensor (A_{lnrt}) associated with the pore boundary motion can be represented in terms of grain (L^{s}_{jkln}) and dry frame (L^{dry}_{jkrt}) elasticity tensors in the following manner

$$L^{dry}_{jkrt} = \phi_0 \, L^{s}_{jkln}(I_{lnrt} - A_{lnrt}), \tag{1}$$

where $\phi_0 = 1 - \eta_0, \eta_0$ is the unperturbed porosity and $I_{lnrt} = \frac{1}{2}(\delta_{lr}\,\delta_{nt} + \delta_{nr}\delta_{lt})$ is the fourth rank identity tensor. An additional parameter 'n', which is also associated with the pore boundary motion, enters through the effective stress equation for porosity, as defined below

$$\eta - \eta_0 = a_{rt}\left(\bar{\sigma}^{s}_{rt} + n\,\bar{p}^{f}\,\delta_{rt}\right). \tag{2}$$

Here, $\bar{\sigma}^{s}_{rt}$ is the macroscopic solid stress tensor and $\bar{p}^{f}$ is the macroscopic fluid pressure. n is the coefficient of effective stress for porosity and

$$a_{rt} = \phi_0\left(\phi_0\left(L^{dry}_{kkrt}\right)^{-1} - \left(L^{s}_{kkrt}\right)^{-1}\right). \tag{3}$$

Discussion

Both, the fourth rank anisotropy tensor, A_{lnrt}, and effective stress coefficient for porosity, n, are dimensionless quantities. It is apparent from eqn. 1 that A_{lnrt} is the measure of decrement of solid-frame elasticity tensor over solid grain. From eqn. 2 one finds that, in the porosity change process, the parameter n is the measure of non-reciprocal interaction between macroscopic pressures of the two phases. Also, eqn. 2 suggests how porosity changes due to shearing on account of the trace-free part of parameter a_{rt}, which has the dimension of stiffness. Thus, by allowing porosity to change in a shear deformation, this framework accounts for shear stiffening due to the compressibility of pore fluid. Together with the two constituents end members' material coefficients and effective stress coefficient for porosity, the anisotropy tensor A_{lnrt} describes the full set of poroelastic material coefficients.

Conclusions

Here an alternative view on seismic anisotropy in porous rocks is developed.

Acknowledgements

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