Stress Distribution in Fluid-Saturated Porous Solids: Interactions Between Elasticity, Fluid Flow, and Microstructure

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ABSTRACT

Fluid flowing through the pore-space of porous rocks under non-hydrostatic stress significantly contributes to the deformation of such materials, leading either to the formation of fractures or to dissolution-precipitation processes that modify the pore space geometry. For quantitatively understanding this phenomenon, the stress distribution at the interface between the fluid and the solid is a key component. At the micron scale, regions of high stress become prone to dissolution and crack formation, and the advective transport of solutes through the pore-space leads to precipitation in regions of low stress. This, over time, alters the geometry of the pore space and its transport properties.

In this study, we investigate by numerical means the impact of a fluid steadily flowing through porous solids, considering the solid-fluid interface stress distribution on a timescale where the effect of chemical reactions is negligible. In this regime, a one-way stress coupling from the fluid flow to the elastic field in the solid is sufficient, rendering simulations feasible using the finite element method (FEM) for the solid, and comparing the unstructured lattice-Boltzmann method and FEM Stokes flow for the fluid phase. By varying the flow rate and the externally applied stress, we obtain the probability distributions of the various components of the stress tensor. This approach is validated by using simple 2D and 3D geometries such as a circular or a cylindrical pore embedded into an elastic solid. Then, the numerical method is applied to a digital 3D limestone rock sample scanned using X-ray microtomography and where the pores and the solid matrix could be segmented. The results show how the heterogeneous material distribution in a natural rock controls the stress distribution upon external loading and internal fluid flow and how close to fracturing the rock is when injecting fluid.