

Pore Scale Simulations of Rock Deformation, Fracture, and Fluid
Flow in Three Dimensions

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Abstract

The pore-scale examination of rock deformation and fluid flow consisted of three separate tasks. 1) New laboratory measurements were made of poroelastic properties of Berea sandstone and a new method was developed to measure both the poroelastic constants and the hydraulic conductivity on the same sample of rock in a single test. 2) The second task was to develop constitutive theories of elastic and poroelastic properties of dual-porosity rocks and rocks with cracks. The new constitutive relations explain wave-velocity dispersion in fluid-saturated rock and the stiffening of shear modulus when dry rock is saturated. 3) The third task involved pore-scale percolation modeling of two-phase fluid flow in granular media. The model properly simulates fractal geometries of nonwetting clusters and saturations for flow in unstable gradients. The percolation model was coupled with a water-vapor diffusion model to produce saturation maps in a rock core during evaporative drying. The realistic patchy saturation was used in a heuristic model for predicting elastic properties of partially-saturated rock, which mimicked laboratory results.

Laboratory Measurements

Few experimental measurements have been made of poroelastic constants and hydraulic flow parameters on the same rock. By measuring strain during a transient hydraulic flow test, we demonstrated a method for determining four independent poroelastic constants — drained and undrained bulk compressibility, Skempton's B coefficient, and three-dimensional specific storage — together with the hydraulic conductivity. Additional experimental work consisted of measurements on Berea sandstone of linear compressibilities and Skempton's B coefficient at thirteen pore pressure and confining pressure pairs under drained, undrained, and unjacketed pore-fluid boundary conditions. The measurements showed that Berea sandstone is anisotropic at low effective stresses but becomes isotropic at higher effective stresses. The anisotropy is due to preferential alignment of pre-existing microcracks. The unjacketed pore compressibilities are consistently greater than the unjacketed grain compressibilities, thereby putting in question a common assumption that the two compressibilities are equal.

Theoretical Poroelasticity

The Biot-Gassmann theory of poroelasticity predicts that shear modulus should be the same for dry and saturated rock when this is sometimes contrary to observation (when chemical effects are not a factor). Similarly, Biot's theory of wave propagation in fluid-saturated rock predicts smaller amounts of velocity dispersion and wave attenuation than is observed at ultrasonic frequencies. This theoretical work extends the quasistatic double-porosity model of Berryman and Wang (1995) to the dynamic case. Effects that are usually attributed to squirt flow under partially-saturated conditions can be explained alternatively in terms of the double-porosity model. Stiffening of the shear modulus at high frequency occurs because unequal pore pressures are induced in cracks with different orientations, which requires that pore-fluid equilibration does not occur between cracks and between cracks and porous matrix.

Percolation Modeling of Two-Phase Flow

Two-phase flow in a porous medium occurs in many geologic processes. The basic problem addressed is that many two-phase flow phenomena in an unstable flow conditions, such as buoyancy-driven flow, must be addressed at the pore scale, and not by a multiphase generalization of Darcy's law based on a continuum approach in which the system properties are averaged over a representative elementary volume (REV). Recent advances in the physics of disordered media demonstrate that percolation behavior, such as capillary fingering, is manifested by intriguing geometric flow patterns and by power-law scaling of nonwetting, fluid-cluster saturations. Fingering and other manifestations of instability are captured by an invasion-percolation-in-a-gradient (IPG) model, which was developed and implemented to incorporate all relevant forces — buoyancy, capillary, and viscous. The computational results correctly depict the geometry, including fractal behavior, of the nonwetting fluid cluster and the fluid saturations associated with it.

In one application the IPG model was coupled with a continuum model for water vapor diffusion to create a simulated tomographic image of water distribution within a rock core during drying. As drying proceeds, the initial, continuous water cluster breaks up into smaller and smaller clusters with an increasing surface-area-to-volume ratio. Drying times are a function of the number and location of boundary surfaces, but the surface-area-to-volume ratio is approximately the same for a given saturation. By applying a Voigt volume average of the elastic properties of water-filled and air-filled cells, and by introducing the *ad hoc* rule that water-filled pores on the air-water interface of a cluster behave in a drained manner, we find elastic moduli as a function of saturation that mimic laboratory experimental data.

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