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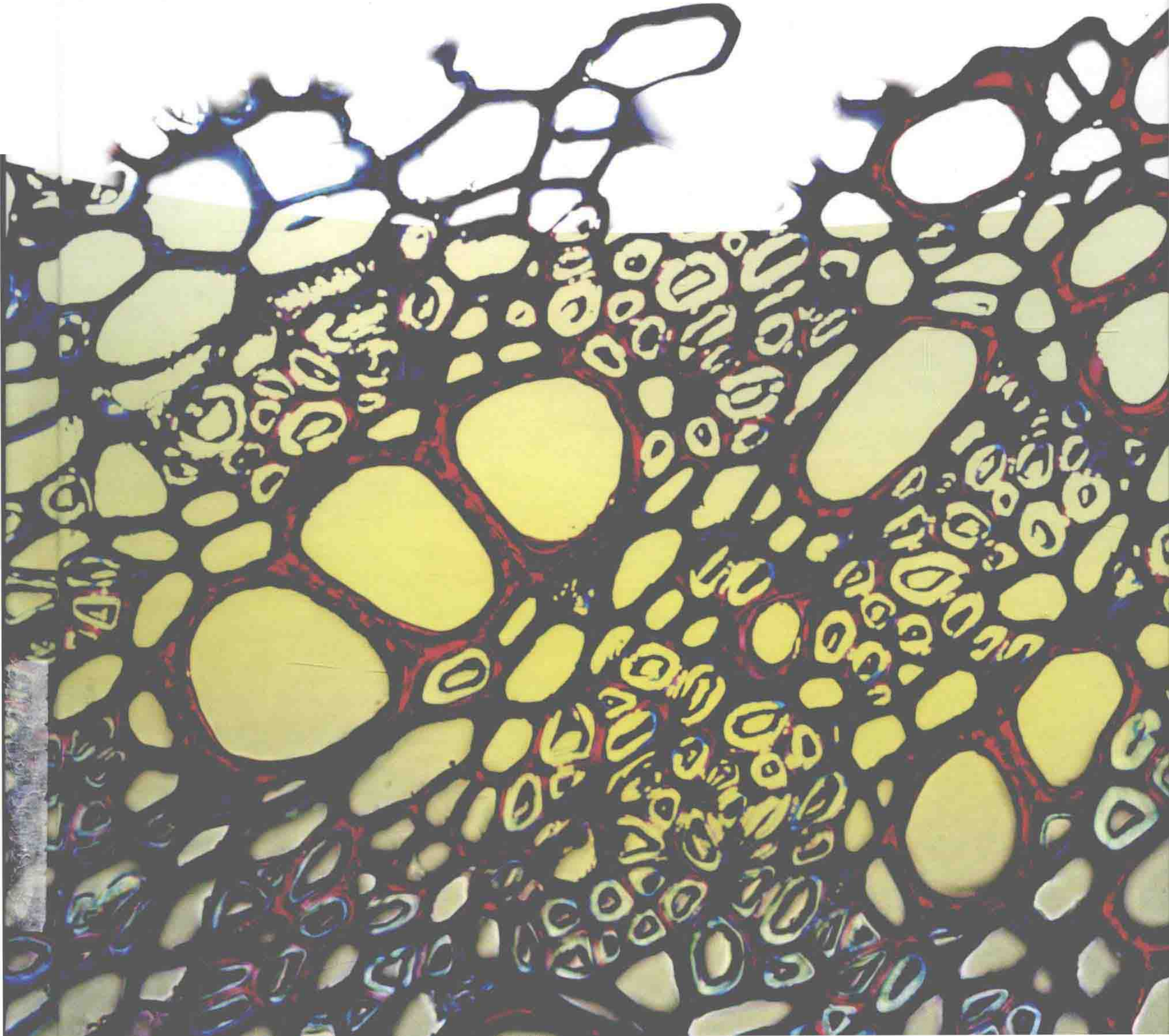
Nonlinear Elasticity and Hysteresis

Fluid-Solid Coupling in Porous Media



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Preface

The subject matter of this book is the description of the behavior of porous materials in the presence of fluids. Porous materials are many, for example, soil or a sandstone, designed material such as a Nuclepore filter or MCM-41, wood fiber, or the cellular solid in the keel of an ice plant. Fluids often occupy the pore spaces in these materials and can alter the geometry/mechanical properties of the porous materials. It is this fluid–solid coupling that is discussed in the chapters herein.

We identify two important components of the fluid–solid interaction at the interface of solid and pore space. One relates to the phase change of fluid and the other relates to change of the mechanical state of solid. These changes depend on the thermodynamic state defined by (P, σ, T), that is, the fluid is at pressure P, the solid is at stress σ, and both are at temperature T. The pressure P is the pressure of the fluid that is far from the pore walls. At low fluid pressure, the pore space is filled with unsaturated vapor (Figure 1a). As the fluid pressure increases (moving up the dotted line in Figure 1a), the fluid on approaching the pore walls is inhomogeneous, evolving from gas to gas–liquid coexistence and eventually to liquid, because of forces exerted by the solid on the fluid. On further increase in the fluid pressure, the liquid near the pore wall solidifies. This evolution is depicted in the one-dimensional pore space of Figure 2. The x-axis indicates a physical pore space discretized for illustrative purposes in layers. The fluid pressure increases from Figure 2a–d, and the fluid near the pore wall undergoes phase changes. At fluid pressure equal to the saturated vapor pressure, Figure 2d, the fluid far from the pore wall is bulk liquid and the fluid close to the wall, which has not become solid, is at an effective pressure greater than the saturated vapor pressure. The fluid at the pore wall has become solid at an effective pressure, which is much greater than the saturated vapor pressure. While this evolution of the fluid in response to the fluid pressure is taking place, the solid, at stress σ, is almost unchanged.

The second component of the fluid–solid interaction is the development of a mechanical force system in the solid. At the pore wall, the solid pulls on the fluid, causing the inhomogeneous fluid arrangements in Figure 2a–d. In reaction, the fluid pulls on the solid causing a stain field in the solid. This is illustrated in Figure 3, a pore space in one dimension (for simplicity) bounded by solid on either

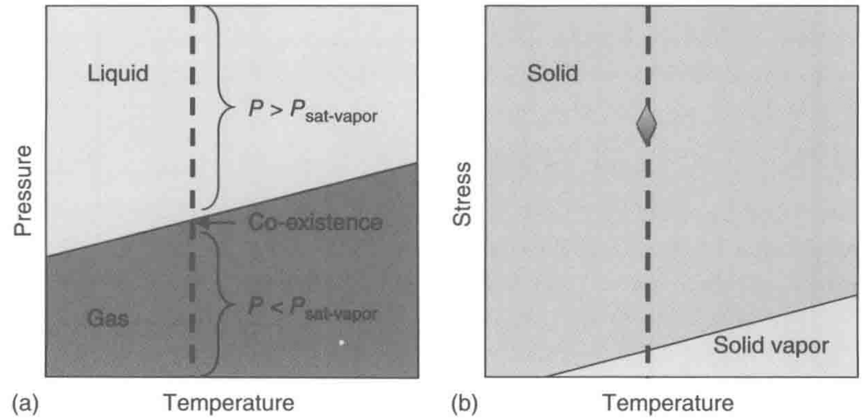

Figure 1 (a, b) Phase diagrams of the material in a porous media system. The fluid is in principle at (P, T) and the solid, able to be addressed independently of the fluid, is in principle at (σ, T).

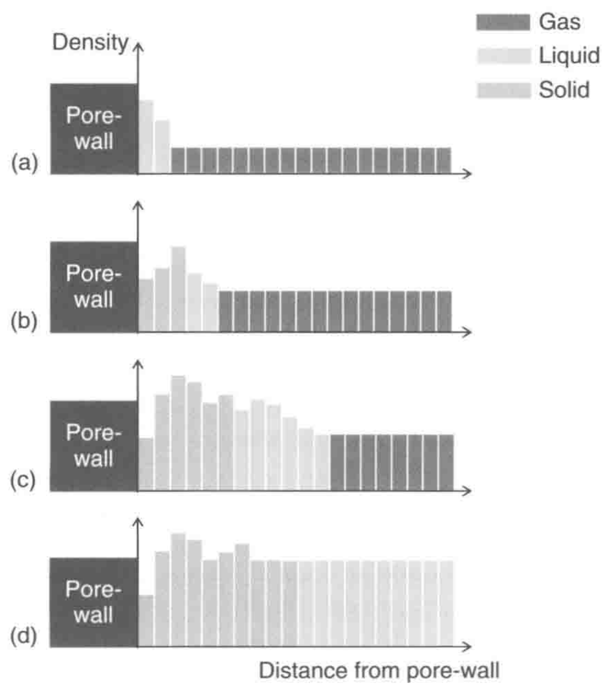

Figure 2 Fluid configuration in a pore space near a wall as pressure increases from (a) to (d). (a) Pressure is far from the saturated vapor pressure; (b) pressure is increasing; (c) pressure is approaching the saturated vapor pressure; and (d) pressure is at saturated vapor pressure.

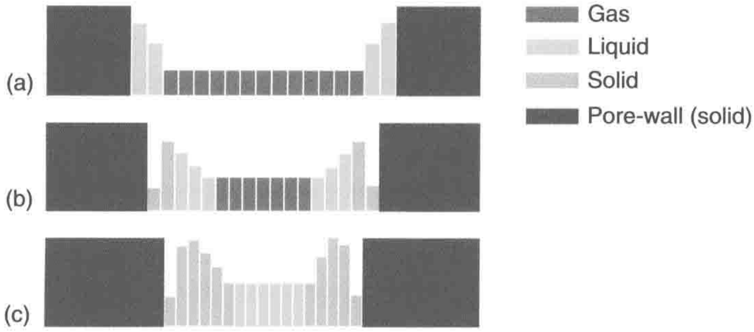

Figure 3 Fluid configuration in a pore wall system. The phase changes within the fluid and the strain induced in the pore wall are illustrated. The fluid pressure increases from (a) very low to (c) the saturated vapor pressure.

side. As pressure approaches P_{sat}, phase changes occur that are shown in Figure 2. The solid phase of the fluid appears on the pore wall due to densification as a result of forces exerted by the pore wall system. Concomitantly, the fluid pulls the pore walls into the pore space. A strain develops in the solid. This strain, often assumed to be small and able to be neglected, is driven by the fluid and can be a complex function of the history of the fluid configurations.

The solid could be under no stresses except that caused by forces from the fluid. However, it is, in principle, possible to have a stress field in the solid that is set independent of the forces from the fluid. This possibility, illustrated in Figure 1b, is the domain of Biot theory. For the most part, this subject area is not developed in this book. An exception is the paper by Vandamme *et al.* in Chapter 5.

The interaction of fluid and solid in porous materials at local scale manifests itself as complex nonlinear phenomena at global scale. One interesting nonlinear phenomenon that this book draws attention to is hysteresis. Hysteresis can be in the response to mechanical probes such as the stress–strain curve of a dry Berea sandstone, discussed in Chapter 1. The mechanical state of a typical sandstone evolves slowly over time following finite frequency excitation. Chapter 1 presents the mechanical experiments that interrogate the internal strain of the grains using a neutron beam and reveals important features of the behavior of rocks, that is, consolidated granular media.

There are also many systems in which the coupling between fluid and solid brings about the complex behavior, and some hysteresis can arise only as a result of the coupling. Chapter 2 is an experimental and theoretical study of mesoporous silicon material and presents a thermodynamic model at the fluid–solid interface. It reports adsorption-induced strain in the solids and the reciprocal stress effect on the adsorption process. Chapter 3 develops a theory to describe the fluid–solid coupling at the local scale. The manifestation of this interaction is described and investigated using a finite element model. The inhomogeneous system composed of fluid and solid elements can accommodate a variety of circumstances such as bulk fluid in the pore space of a rock, fluid in the wall fabric of wood or a cellular solid, and fluid in the polymeric filling of a cellular solid framework. Chapter 4 continues to present a theoretical study that formulates a model for stress–strain behavior of dry quasi-brittle materials allowing damage to be created. The Preisach model is used to model the damages at microscale, and this is translated as density to the macroscopic elastic elements to interpret the macroscopic behavior in terms of evolving populating of microscopic elements. The dry quasi-brittle material model is then modified to include moisture by allowing fluid–solid coupling in the form of an effective internal stress. Chapter 5 focuses on coal that serves as a valuable model of saturated porous material. The particularly interesting feature of coal is the range of length scales of the pores from macroscopic to mesoscopic, cleats, and matrix pores. This is modeled combining thermodynamic description of two pore systems, the macroscopic cleat system and the mesoscopic matrix system, which are coupled by a Darcy flow that is driven by a pressure gradient. Chapter 6 brings an alternative perspective on mechanics of porous materials by developing a multifield model and applying it to a series of foams. The particular interest here is the behavior of coupled fluid–solid systems under dynamic loading.

Chapter 7 examines the fluid–solid coupling in the context of wood swelling. The experimental observations are obtained by the modern X-ray tomography technique at a micrometer scale, and strains at multiple scales of hierarchical wood tissues are studied as a function of moisture content. This is accompanied by a parallel modeling study that explores the role of materials' structure as moisture content changes. The final chapter, Chapter 8, also investigates biological cellular materials, that is, plants. The authors employ this coupling in numerous ways from the analog of "blowing up a balloon" to a "mechanical" thermostat. Systems that exhibit this wide range of behaviors are described, for example, systems based on inner cell pressure, systems based on water uptake into the cell wall, systems based on a differential swelling of cell wall layers, and systems that illustrate the capacity of water as a plant movement actuator.

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