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A theoretical treatment on the mechanics of interfaces in deformable porous media

Franck J. Vernerey

Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, CO, USA

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ABSTRACT

The presence of interfaces (such as cracks, membranes and bi-material boundaries) in hydrated porous media may have a significant effect on the nature of their deformation and interstitial fluid flow. In this context, the present paper introduces a mathematical framework to describe the mechanical behavior of interfaces in an elastic porous media filled with an inviscid fluid. While bulk deformation and flow are characterized by displacement gradient and variations in the fluid chemical potential, their counterpart in the interface are derived by defining adequate projections of strains and flow onto the plane of the interface. This operation results in the definition of three interface deformation and stress measures describing decohesion, mean tangential strain and relative tangential strain, as well as three interface fluid driving forces and flux representing normal flux, mean tangential flux and relative tangential flux. Consistent with this macroscopic description of interface behavior, a set of governing equations are then introduced by considering the conservation of mass and the balance of momentum in the mixture. In particular, we show that the coupled mechanisms of interface deformation and fluid flow are described by six differential equations for fluid flow and three equations for solid deformation. It is also shown that a simpler set of governing equation can be derived when incompressible constituents are considered. The behavior of the mixture is finally specified through a general linear constitutive relation that relies on the definition of quadratic strain energy and dissipation functions. While a large number of material constants are needed in the general case, we show that under simplifying assumptions, the behavior of the interface can be written in terms of only eight material constants. A summary and discussion is then provided on the proposed formulation and potential applications are suggested.

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1. Introduction

Studies on the mechanics of hydrated porous media (composed of a deformable solid skeleton and an interstitial fluid phase) are of great interest to understand the behavior of a variety of materials such as biological tissues, soils or hydrogels. The theory of porous media, originally introduced by Biot (1941, 1957) in the context of consolidation and later generalized to the theory of mixtures, notably by Bowen (1980), Truesdell (1969) and Rajagopal and Tao (1995) has been very successful at describing the combined fluid flow and solid deformation in porous media. These continuum theories are based on the hypothesis that porous media are composed of a macroscopically homogeneous interconnected porous network and therefore can be macroscopically described in terms of continuous fields (such as solid displacement and fluid velocities). However, the microstructure of porous materials is sometimes characterized by the presence of interfaces, such as cracks, membranes and thin material interfaces, introducing strong and weak discontinuities in displacement fields. These discontinuities may critically affect the mechanical behavior of the medium and the

nature of the interstitial fluid flow within the solid. In this context, the presence of cracks on interstitial fluid flow has been the object of various studies (Barthelemy, 2009; Liolios and Exadaktylos, 2008; Pouya and Ghabezloo, 2008; Ghabezloo and Pouya, 2008), particularly in the situation where the solid phase does not deform. For instance, one strategy consists of modeling interfaces (cracks) as thin ellipsoidal inclusions for which an effective permeability can be derived using self-consistent homogenization techniques (Dormieux and Kondo, 2007; Barthelemy, 2009). An alternative approach was presented by Liolios and Exadaktylos (2008) in which fluid flow in non-intersecting cracks was described in terms of a line of discontinuity. This formulation was more recently extended by Pouya and Ghabezloo (2008) to describe intersecting cracks, which further allowed to estimate the effective permeability of a micro-cracked porous medium. While the above studies provide very good estimations of fluid flows within cracks (and can be extended to arbitrary porous interfaces), they did not consider the effect of solid deformation, as applications mainly focused on rigid media such as rock and concrete.

With different applications in mind, the mechanical deformation of interfaces in elastic solids was explored by Gurtin et al. (1998) within the context of small deformations. Viewing interfaces as lines of discontinuity in displacement and strain fields, various measures

E-mail address: franck.vernerey@colorado.edu