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Phase field modeling of partially saturated deformable porous media

Giulio Sciarra

Dipartimento Ingegneria Chimica Materiali Ambiente, Università di Roma La Sapienza, Via Eudossiana 18, 00184 Rome, Italy

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ABSTRACT

A poromechanical model of partially saturated deformable porous media is proposed based on a phase field approach at modeling the behavior of the mixture of liquid water and wet air, which saturates the pore space, the phase field being the saturation (ratio). While the standard retention curve is expected still^ to provide the intrinsic retention properties of the porous skeleton, depending on the porous texture, an enhanced description of surface tension between the wetting (liquid water) and the non-wetting (wet air) fluid, occupying the pore space, is stated considering a regularization of the phase field model based on an additional contribution to the overall free energy depending on the saturation gradient. The aim is to provide a more refined description of surface tension interactions.

An enhanced constitutive relation for the capillary pressure is established together with a suitable generalization of Darcy's law, in which the gradient of the capillary pressure is replaced by the gradient of the so-called generalized chemical potential, which also accounts for the "force", associated to the local free energy of the phase field model. A micro-scale heuristic interpretation of the novel constitutive law of capillary pressure is proposed, in order to compare the envisaged model with that one endowed with the concept of average interfacial area.

The considered poromechanical model is formulated within the framework of strain gradient theory in order to account for possible effects, at laboratory scale, of the micro-scale hydro-mechanical couplings between highly localized flows (fingering) and localized deformations of the skeleton (fracturing).

1. Introduction

The constitutive characterization of partially saturated porous media became of interest at the beginning of the last century when scientific research started to face fundamental problems in geotechnics and petroleum engineering, concerning modeling the response of partially imbibed soils, during imbibition/drainage cycles (see Buckingham, 1907; Richards, 1931), or modeling the behavior of sedimentary reservoir rocks, when a multi-phase fluid flows through the porous network. Starting from the analysis of basic static problems, it became clear that the balance between capillary and driving forces, in particular gravitational forces, would have been the central subject of modeling efforts. This pushed the research in the direction of finding out simple relations between the curvature of the wetting/non-wetting fluid interface and the average content of the wetting fluid, over a suitably defined Representative Volume Element (RVE). The main ideas of this

E-mail address: giulio.sciarra@uniroma1.it

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identification have been clearly sketched by Coussy (2010, Chapter 6) for a partially saturated truncated conical pore, specifying the infinitesimal variation of the interfacial energy in terms of the infinitesimal variation of the volume occupied by the wetting fluid (saturation). This naturally provided the well-known definition of macro-scale capillary pressure, as the derivative of a macro-scale capillary energy. In Leverett (1941), Brooks and Corey (1964), in the summarizing contribution by Bear (1972), in VanGenuchten (1980), etc., different semi-empirical relations, between macro-scale capillary pressure and saturation have been stated, in order to specify the retention properties of the porous skeleton. These retention curves typically exhibit hysteresis during imbibition/drainage cycles, so as to fit with experimental evidence.

At the same time the pioneering papers by Cahn and Hilliard (Cahn and Hilliard 1958, 1959; Cahn, 1959) established the basic framework within which modeling of multi-phase fluid flow is formulated in terms of space and time evolution of the mass concentration or, in the general case, of a phase field which can vary continuously over thin interfacial layers. Beyond the original formulation due to Cahn and Hilliard (1958) one can refer to Jacqmin (2000) and Kim (2012) for general reviews, as well as to Lowengrub and Truskinovsky (1998), Boyer and Lapuerta (2006), Boyer et al. (2010) or Lamorgese et al. (2011). Surface tension is recovered, in this context, considering the integral, through the thickness of the layer, of the concentration gradient (or the gradient of the phase field). This approach progressively attracted more and more interest, in particular within the framework of fluid mechanics, because of its advantages for numerical calculations which do not necessitate adaptive interface fitting grids, see e.g. Jacqmin (2000), Kim (2012) and Gomez and Hughes (2011). Surprisingly however limited contributions attempted at incorporating these ideas into modeling of unsaturated porous media, one can refer for instance to Papatzacos (2002) and Papatzacos and Skjoeveland (2004) and more recently to Cueto-Felgueroso and Juanes (2008, 2009a,b) and Gomez et al. (2013).

This paper follows the research path traced by these authors to model partially saturated deformable porous media, considering the pore network infused with a two-phase fluid. Also the constitutive characterization of the solid will be generalized with respect to the classical poromechanical model, in order to describe the coupling between highly localized flows and (possibly localized) strains.

For long time the above mentioned constitutive characterization of the macro-scale capillary pressure in terms of the corresponding hysteretic retention curve has been the only relation used for describing the hydraulic flow through partially saturated porous media, being also the pivot of the hydro-mechanical coupling with the constitutive law of the porous skeleton. Due to the coarse simplification provided by this model, however, it was finally recognized the existence of several problems in which the relation between capillary pressure and saturation is not sufficient to describe at the same time surface tension, between the wetting and the non-wetting fluid, and the retention properties of the porous skeleton, due to its texture. As a matter of fact what is understood by this constitutive law is, as already mentioned, that no variation of the capillary pressure can be observed if no change of the saturation is induced by external forces. This is due to the rough upscaling rule, from the micro to the macro-scale, which assumes the variation of the area of interfaces proportional to the volume occupied by the fluids, see Coussy (2010). On the other hand, as originally pointed out by Morrow. (1970), redistribution of the fluids within a porous medium can occur also keeping constant the saturation, and instabilities can even arise from fluid interfaces that are unable to change curvature smoothly with variations in pressure ("Haines jumps"). In other words, different micro-scale configurations of interfaces between a wetting and a non-wetting phase are possible for a given saturation.

In more refined macro-scale formulations the specific cumulative measure of interfaces, between the wetting and the non-wetting phase, say the specific interfacial area, is also introduced to account for the micro-scale features of the fluids within the RVE, see Hassanizadeh and Gray (1993) and the related literature, e.g. Reeves and Celia (1996), Papatzacos (2002) and Niessner and Hassanizadeh (2008). In order to clarify the meaning of this additional macro-scale state parameter, one can think of the effect of the saturation degree, on the macro-scale capillary pressure, as that which coarsely accounts for the retention characteristics of the porous skeleton, depending on its texture, and consider on the other hand the effect of the cumulative measure of interfaces as a suitable corrective term, which allows for describing different admissible coexistence configurations of the saturating fluids. Within this framework, several experimental campaigns have been carried out, based on laboratory tests, see e.g. Dalla et al. (2002), Culligan et al. (2004) and Costanza-Robinson et al. (2011), and also pore network micro-scale numerical simulations have been implemented, see e.g. Joekar-Niasar et al. (2010), in order to characterize the constitutive relation among capillary pressure, saturation and specific interfacial area.

Consider now the behavior of the porous skeleton, it is almost standard in continuum poromechanics to introduce a constitutive prescription of stress in terms of strain and saturation, both in the case of elastic and elasto-plastic deformations; one can refer among others to the seminal paper by Alonso et al. (1990) and the related literature, see e.g. Olivella et al. (1996) and Alonso et al. (1999), to the systematic formulation by Lewis and Schrefler (1998), see also Sanavia et al. (2002, 2006), to the approach based on the generalized Bishop effective stress, see e.g. Houlsby (1997), Gens et al. (2006), Buscarnera and Einav (2012), Jommi (2000), Tamagnini (2004), etc., or to some recent contributions within the range of finite deformations of the porous skeleton, see Borja et al. (2013) and Song and Borja (2014). Possible modifications of these constitutive models, in order to account for the effect of the specific interfacial area, concern the improvement of the retention curve provided within the approach to multi-phase mechanics proposed by Hassanizadeh and Gray (1990, 1993), in which velocities of phases and interfaces are employed to describe fluid flow and skeleton deformation, see also Gray and Schrefler (2001), Gray et al. (2009) and Nikooee et al. (2013). Within this framework, however, several phenomena, related to micro-structure remodeling, cannot be captured, exactly as several phenomena related to the spatial distribution of fluids within the pores could not be described only in terms of saturation evolution. The typical case is that of localized