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Study of hydro-mechanical instabilities in geomaterials

Hydraulic and mechanical instabilities in geomaterials refer to a variety of non-linear phenomena that can be triggered by heterogeneities inherent to such materials. Hydraulic instabilities in partially saturated conditions can manifest themselves as heterogeneous fluid invasion causing 'fingering' phenomenon. Mechanical instabilities on the other hand can present themselves as strain localizations and/or fractures. These instabilities and their associated coupling pose a major obstacle for a myriad of applications involving geomaterials like Carbon dioxide(CO_2) sequestration, rain water infiltration and also for reliable predictions such as for contaminant flow in ground waters. Existing classical models do not resolve this behavior due to their lack of pattern-forming ingredients in their formulation and thus being stable against perturbations. The essence of current thesis work is to propose and investigate modeling techniques that allow to describe these instabilities in a simple and natural manner. The constitutive approach adopted in this thesis is that of micro-structured continua, in particular that of enhanced continua with a constitutive law depending on the gradient of so-called phase field variables.

The first part of the work deals with description of a fluid-fluid front that has been modeled as a diffused interface. This has been done by interpreting the presence of two fluids within the pore space as a single non-uniform fluid and the degree of saturation of one of the fluids as the corresponding phase field. While classical one-to-one relation between capillary pressure and saturation degree is expected to describe the retention properties of the porous network due to its texture, an enhanced relation is obtained by prescribing a chemical potential in the spirit of Cahn-Hilliard type modeling of multi-phase fluids. This enhanced relation together with a non-local energy contribution provides the ingredients required to describe fluid-fingering and non-local phenomena such as pinching and coalescence of fluids due to variations in capillary forces. Using asymptotic matching techniques it has been shown analytically, in a one-dimensional setting, that the particular choice of energy contributions employed in the above framework allows to replicate 'overshoot' type non-monotonic saturation profiles during constant-rate infiltration into relatively dry medium. This has been found to match qualitatively with experimental observation. Further, a slight non-convexity introduced into the flux function has been shown numerically to allow the modeling of drainage fronts, besides imbibition, without employing any additional complexities into the model. A careful linear stability analysis(LSA) of the homogeneous solutions against arbitrary perturbations has been done. The growth in time of the amplitude of imposed transverse perturbations is understood as the fingering phenomenon. The predictions of the LSA have been followed-up by two-dimensional simulations portraying the ability of the proposed model to describe fluid fingering and segregation.

In the second part the triggering of a fracture within a drying porous medium has been studied. A prevailing modeling perspective, in the spirit of gradient damage modeling, has been first tested for its ability to replicate periodic fracture formation as observed in representative experiments. Further an investigation is done, starting from the gradient damage modeling framework, but interpreting the presence of a fracture within a drying porous material as a loss of its capillary properties, thus allowing the passage of non-wetting fluid under vanishing capillary pressure. This paradigm is of particular interest in modeling cohesion-less and unconsolidated fine-grained soils, where the resistance against tensile loading is negligible and thus fracturing induced due to development of tensile stresses is not the prevailing phenomenon. Starting from the principles of variational approach used to construct the model, it has been shown that for sufficiently strong desiccation, damage initiates homogeneously on the drying face while progressing into the body with time. The possible occurrence of bifurcations of this base solution has been analyzed, again in the framework of LSA.

This works sets the stage for various possibilities, the most natural one being the study of coupling between the above mentioned instabilities. Apart from that, two-dimensional simulations of fluid-fingering have shown that the model predicts additional features of unstable flow, such as pinching and coalescence of the wetting phase, which need to be investigated using carefully designed experiments. Initiation of damage induced due to evolving drainage finger is also of particular interest in the context of earlier mentioned applications. Lastly, advanced numerical techniques can be sought after for resolution of the above problems with an intent to provide accurate solutions more efficiently.

Mots-clés : partial saturation; geomaterials; phase field modeling; non-uniform fluid; gradient damage;