Modeling unstable gas infiltration through initially saturated geomaterials

keywords: CO_2 sequestration; geological storage; partially saturated porous media; instability; phase field modeling

Context

Modeling unstable gas infiltration through a saturated rock formation is a paramount issue in a wide range of engineering problems especially in the fields of energy storage, greenhouse gas sequestration and radioactive waste disposal. The common feature in all these contexts is the possible leakage of gas through pre-existing and re-activated cracks or newly developed paths through the geological/engineered formations that form the sealing barrier.

Underground gas storage can be associated to a broad spectrum of engineering applications in the field of civil & environmental engineering but also chemical engineering, nuclear power plants etc. Among others we refer to i) energy that is produced by any kind of renewable energy (wind, solar or hydraulic power plant) and is to be stored in the form of synthesized methane or hydrogen, and as well to ii) the last step of CCS (Carbon Capture & Storage) process, that is finalizing the CO_2 capture via its underground sequestration, into depleted hydrocarbon reservoirs, aquifers rocks or manmade underground caverns. Moreover critical interaction between a gas and a geological formation can also be encountered in geological disposal of radioactive wastes when the corrosion of the storage canister implies a gas release and a consequent pressure build-up, leading possibly to the fracturation of the engineered barriers or the host formation.

Approach

The project aims to develop and implement a new numerical approach for multi-phase fluid flow through porous media allowing to capture complex topological changes in liquid-gas interactions as fingering, pinching and coalescence of one phase against the other and to investigate their effects on the mechanical response of the porous skeleton. These phenomena have been experimentally observed since the fifties as occurring in mixtures of heterogeneous fluids and characterized as instabilities of an evolving fluid-fluid interface. However only recently their effects on the behavior of the porous solid have started to be experimentally investigated and numerically simulated.

Extending previous results already developed within the research team advising the present thesis, a phase field approach modeling a partially saturated porous media will be formulated in the case of non-passive phases, heterogeneously mixed in the porous network. In the framework of continuum poromechanics, this will be done introducing a suitable non-convex potential energy of the phase concentration, whose two limit values are associated to the phases of the mixture. The non-convex nature of the functional will be regularized with the help of an energetic contribution penalizing the concentration gradient, in a similar way as in the case of Cahn-Hilliard non-uniform fluids. As no restriction to the nature of the fluids saturating the pore space are assumed, an higher-order diffusion equation coupled with at least one conservation law will be formulated to describe space-time evolution of the two phases. Considering in particular the case of a gas infiltrating a porous medium initially saturated by a liquid phase, the gas compressibility will also be taken into account.

The target of the research project being the characterization of the effect of fluid instabilities on the (irreversible) deformations and more generally the material reorganization of the porous skeleton, a plastic model, for instance of the Cam-Clay family, together with a regularizing strain gradient term will be adopted. This will allow to modeling strain localization in the vicinity of fluid fingering instabilities.

The constitutive model will be implemented within the LAGAMINE Finite Element code, developed since the nineties at Université de Liège, also in collaboration with Ecole Centrale Nantes, to characterize the behavior of saturated and partially saturated geomaterials. The implementation will be based on a mixed approach, thus reducing the higher-order diffusion equation, describing the fluid flow through the porous network, to two second-order diffusion equations.

Numerical simulation of representative case studies involving interaction of a gas front with a soil/rock formation initially saturated by a defending fluid will be developed in the framework of the above mentioned applications.

Expected results

The project deliverables will be:

- Development of the constitutive model of partially saturated porous media based on the phase field approach.
- Coding of the subroutine within the framework of the LAGAMINE Finite Element library implementing the constitutive model.
- Numerical simulation of at least a case study: either interaction of CO_2, sequestered in underground aquifer rocks, with the sealing caprock, or gas infiltration through engineering barriers in underground radioactive waste disposal.

Required competences

- Competence in continuum mechanics is required.
- Modeling of plastic response of solids is recommended.
- Programming skills using FORTRAN and/or C++ coding are strongly recommended.

Additional information & Contacts

The thesis will be co-tutored between Ecole Centrale de Nantes and Université de Liège; the PhD student will spend half the time of his/her doctorate course in Nantes and the other half in Liège.

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N.B. A Curriculum Vitae, a motivation letter and the transcript of records must be uploaded on the website of Thèses en Bretagne Loire in order to be considered for candidature. Further, an e-mail can be sent to siddhartha-harsha.ommi@ec-nantes.fr for confirmation of reception of candidature, or for any queries.