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Coupled multiphase flow and elasto-plastic modelling of in-situ gas injection experiments in saturated claystone (Mont Terri Rock Laboratory)

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ABSTRACT

Understanding gas migration in host rock is one of the most important issues to consider in the final disposal of radioactive waste in deep geological formations. In order to investigate gas transport in water-saturated argillaceous rock, constant gas pressure injection tests on the samples from the Mont Terri Rock Laboratory (Switzerland), as well as pulse injection tests with a stepwise increasing of gas pressure, were carried out. During gas migration, desaturation and hydraulic mechanical interaction can be observed. To simulate gas migration in water-saturated porous media, a coupled multiphase flow and mechanical method within the FEM code family OpenGeoSys (OGS) was developed including the van Genuchten function for the relationship between capillary pressure and water saturation, the approach of Mualem for the relative permeability of both gas and water phases, and an elasto-plastic deformation model. Two approaches were applied, taking into consideration the permeability change by pore gas pressure and by deformation, respectively. Both permeability approaches are based on experimental observations and allow for the significant increase in permeability when gas pressure exceeds the minimal stress. The material parameters for the multiphase model are determined using the measured data from laboratory experiments under well-defined test conditions. With the calibrated model parameters, the in-situ experiment was simulated. Good agreement between the numerical results and the experimental data is achieved.

1. Introduction

Gas transport processes are becoming more and more important to the research of nuclear waste disposal in geological formations. During the post-closure phase of a repository, gases can be produced through different processes. For example, the anaerobic corrosion of a metal container and radiolysis of water will generate H_2. The degradation of organic substances will produce CO_2 and CH_4. Due to the accumulation of generated gases, the pressure in a repository will increase. Under high gas pressure the safety function of the repository, especially the waste isolation and radionuclide retention functions, may be impaired by permeability enhancement of the engineered barrier system and the host rock, which may lead to the release of radioactive gases and the intrusion of groundwater. Fig. 1 shows several possibilities for gas flow paths out of a repository: 1) along the excavation induced micro fractures with high permeability, 2) through insufficient sealing material, and 3) into the host rock through pore space. To this end, the investigation and study of gas transport in the repository system is one of the most important issues for the long-term safety analysis of a final disposal project.

This paper focuses on gas migration in argillaceous rock, which is considered a potential geological formation for radioactive waste disposal in Europe and has been extensively investigated. Based on current understanding, gas transport in argillaceous rock can be described phenomenologically by four mechanisms from hydraulic and mechanical perspectives (NAGRA, 2008).

1) Under low gas pressure, the gas migration process is dominated by diffusion and advection of dissolved gas in pore water.
2) When gas pressure exceeds the gas entry pressure of the host rock, gas begins to displace pore water and the two-phase flow process takes place. Although, diffusion and advection of the dissolved gas exist at any level of gas pressure, in comparison to the two-phase flow process, the amount of transported dissolved gas is minute.
3) If gas pressure continues to increase and exceeds the minimal in-situ principal stress, the path way dilatancy-controlled gas migration will take place. Due to the low tensile strength of argillaceous rock, micro-cracks will occur and the hydraulic properties of the host rock will be altered; e.g. porosity and permeability, which are important parameters for the safety analysis.
4) If gas pressure continues to increase, macroscopic fractures can appear. In this case, the gas transport through macro fractures becomes a single-phase flow process.

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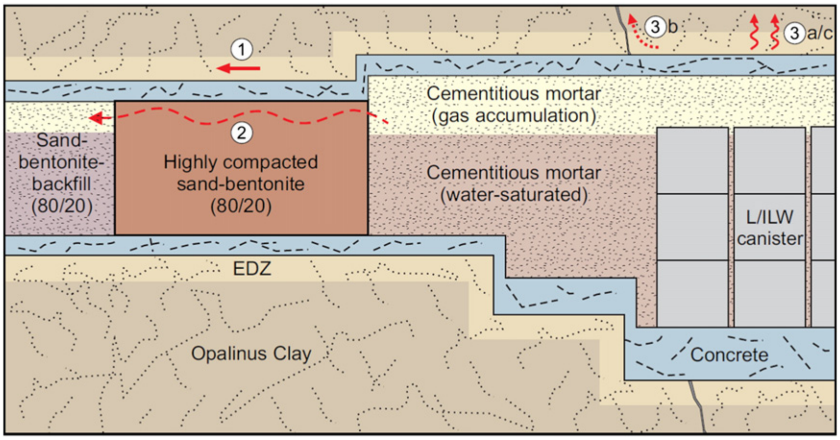

Fig. 1. Schematic description of gas migrations in a nuclear waste repository by NAGRA (2008).

Over the last decade, many laboratory tests looking at gas flow through rock and bentonite specimens have been carried out, e.g. Popp et al. (2007) and Zhang and Rothfuchs (2004) for the estimate of rock specimen permeability and Horseman et al. (1999) for the study of gas entry and breakthrough via pathway development of the pre-compacted bentonite sample. Meanwhile, large scale in-situ gas migration experiments were also performed by Shao and Schuster (2009) to investigate the hydraulic properties of Opalinus Clay at different gas pressures. To simulate gas migration experiments, different algorithms were implemented into different simulators, such as OGS (Wang et al., 2011a, 2011b; Kolditz et al., 2012b), CODE-BRIGHT (DIT_UPC, 2000), and TOUGH2 (Pruess et al., 1999). However, most simulations were done without considering the interactions between hydraulic and mechanical processes. Gas injection tests were simulated using only a two-phase flow model with a modification for the permeability change, which was dependent on gas pressure. A pressure dependent permeability relationship was implemented in TOUGH2 and defined by an initial pressure for the permeability increase and an upper pressure for the maximum permeability e. g. by Senger et al. (2006). In only a few studies have the mechanical processes been involved and the permeability changed based on the mechanical influence, e.g. by Olivella and Alonso (2008). In their H^2M coupled model the permeability increase was induced by fracture opening, which was calculated by mechanical process. With the elasto-plastic mechanical model, the fracture opening was assumed due to extension, which was induced by tension or dilatancy (shearing). A threshold value of strain was defined in order to control the start of permeability increase in the fracture. The permeability was calculated by Cubic law. For the stage before the plastic strain appeared the permeability changed due to the deformation of pore spaces, which was not considered in the study by Olivella and Alonso (2008), but CODE-BRIGHT allow for involving this phenomenon in the model.

An international cooperative project has been established to research the gas migration process in argillaceous rock. Two research groups from Germany (Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) & Helmholtz Zentrum für Umweltforchung (UFZ)) and Canada (Canadian Nuclear Safety Commission (CNSC) & University of Ottawa (UO)) are involved. Both groups developed their own numerical model with different methods to simulate the same laboratory and in-situ experiments. The aim of this work was to develop a new method of investigation for gas transport processes in argillaceous rock and their hydro-mechanical influence on host rock properties. A two-phase flow and mechanics coupled numerical model (H^2M) was implemented in the FEM code OGS (OpenGeoSys). In this model displacement, gas pressure, and capillary pressure were defined as primary variables. In the simulation an elasto-plastic mechanical model was applied, in which both shear and tension failure were considered, the relationship between capillary pressure and water saturation was described by the van Genuchten function, and the approach of Mualem was used for relative permeability for both the gas and water phase. As an important coupling factor, the intrinsic permeability was changed along with mechanical and hydraulic conditions during the gas migration process. To describe the development of permeability, two approaches are applied: 1) permeability was dependent on gas pressure only and 2) permeability was controlled by deformation. In the gas pressure dependent approach the permeability changed slightly at low gas pressure. If the gas pressure was higher than the predefined threshold value, the permeability changed rapidly. In the deformation dependent approach the permeability was determined by deformation, which was comprised of both elastic and plastic strain. In the case of plastic strain, the permeability increased significantly. Two laboratory experiments were used for the model calibration and parameter determination. The specimens of Opalinus Clay for the laboratory tests were taken from the Mont Terri Rock Laboratory in Switzerland, where the in-situ test was carried out. The developed model was then applied for the in-situ experiment. Good agreement between the calculated results and the measured data was obtained.

2. Governing equations

To model the laboratory and in-situ gas transport experiments, coupled numerical H^2M analysis is required. The primary variables of the problem are capillary pressure p^c, gas pressure p^g and solid displacement $\mathbf{u}$. The porous medium is assumed as a continuum and homogenous. Fig. 2 schematically describes the porous system, which consists of three phases: liquid (water), gas, and solid phases (Kolditz et al., 2012a).

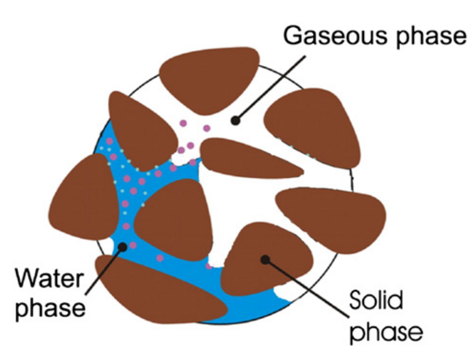

Fig. 2. Porous system with two-phase flow (Kolditz et al., 2012a).