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Research Paper

Modeling the strain localization around an underground gallery with a hydro-mechanical double scale model; effect of anisotropy

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ABSTRACT

This paper concerns the application of a finite element squared approach for modelling hydromechanical coupling in the simulation of gallery excavation in the context of radioactive waste repositories. The micromechanics of Callovo-Oxfordian claystone is modelled at the microscale, taking into account the interaction of different mechanical constituents and its interaction with pore fluid. In a framework of computational homogenization, the micromechanical behaviour is coupled to the macroscale boundary value problem of a poromechanical continuum with local second gradient paradigm. The simulations concern several cases of the "Transverse action" benchmark by Andra, in the context of which the model is used.

1. Introduction

In a recent paper [29], the framework of computational homogenization was extended to hydromechanical coupling and used in combination with a model for microstructural solid-fluid interaction to numerically derive the constitutive relations for a macroscale poromechanical boundary value problem. The application of the framework of computational homogenization provides a computationally efficient scale transition and has allowed the application of the FE^2 method for hydromechanical coupling on (semi-) engineering problems. This paper presents the application of the FE^2 model for hydromechanical coupling on the simulation of gallery excavations as part of the "Transverse action" benchmark by Andra [26].

The developments of the doublescale model in van den Eijnden et al. [29] are based on a first-version microscale model for solid-fluid interaction at the grain scale. This microscale model, based on the work of Frey et al. [15], captures some basic physical processes to represent degradation of geomaterials. No further conceptual improvements are made with respect to this model and therefore certain limitations with respect to capturing physical phenomena can be expected. The objective of this paper is to explore the capabilities qualitative performance of the doublescale framework with the first-version microscale model in capturing characteristic behaviour of an excavation fractured zone (EFZ). Without conceptual modifications of the model, it is by no means the objective of this paper to quantitatively reproduce the in-situ measurements related to the benchmark project and for this reason, no quantitative comparison is made with in-situ measurements. Instead, the results are used to evaluate the possibilities and restrictions of the model and evaluate the effects of anisotropy introduced by the microstructure.

The double scale model is introduced in Section 2 with a description of the macro and micro field equations, the framework of scale transition and description of the algorithm for generating microstructure models. Section 3 gives a calibration example of the microscale model against experimental data. The boundary value problem of the 'Transverse action' benchmark is presented in Section 4 and results of different dry and wet cases are resumed in Sections 5 and 6, respectively. A discussion on the performance of the model close the paper.

2. Double scale model with fully saturated hydro-mechanical coupling

The employed multiscale modelling framework is the so-called finite element squared (FE^2) method [27,14]. In this method the

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constitutive behaviour of each individual integration point in the macroscale finite element computation is derived from a boundary value problem (BVP) on a representative elementary volume (REV) at the microscale. The boundary conditions of this microscale BVP are dictated by the local kinematics of the macroscale problem. The homogenized response of the REV to the enforced global kinematics serves as a numerical constitutive relation at the macroscale. For deriving this homogenized response and its consistent linearization around the updated state without relying on numerical finite difference approximations which tend to be expensive, the framework of computational homogenization by static condensation was developed first for mechanical computation [18] and later extended for several types of coupled problems [24,16]. An extension for hydromechanical coupling was proposed recently [29]. This extension allows deriving a hydromechanical coupled constitutive relation for a poromechanical continuum from a REV containing details of the material microstructure (see Fig. 1). The REV contains a granular assembly of solid parts interacting with pore fluid that can percolate through the pore network formed by the granular microstructure. The macroscale poromechanical continuum is enriched by means of a local second gradient paradigm to obtain mesh objective results in case of softening behaviour.

2.1. Macro-scale formulation of a poromechanical second gradient continuum

On the macroscale, a poromechanical continuum with hydromechanical coupling in a saturated porous medium is defined. For assessing material softening and localization phenomena in a finite element method without losing the objectivity of solutions due to the well-know mesh-dependency effects, a local second gradient paradigm [10,13] is used for regularization. For the mechanical balance equations, this leads to the introduction of the double stress $\boldsymbol{\Sigma}$ with components Σ_{ijk} as a dual to the microkinematical gradient $\boldsymbol{v}$, which in the so-called *local* second gradient models is constrained to be identical to the second gradient of displacement. This constraint in the strongest form leads to the balance equation for any kinematically admissible variation of displacement $u_i^\star$:

$$\int_\Omega \left(\sigma_{ij} \frac{\partial u_i^\star}{\partial x_j} + \Sigma_{ijk} \frac{\partial^2 u_i^\star}{\partial x_j \partial x_k} \right) d\Omega - \int_\Gamma \left(\bar{t} u_i^\star + \bar{T}_i \frac{\partial u_i^\star}{\partial x_j} \right) d\Gamma = 0 \qquad (1)$$

with $\boldsymbol{\sigma}$ the Cauchy stress and $\bar{t}$ and $\bar{T}$ the boundary traction related to the first and second gradient parts. To solve this equation in a finite element method, without relying on higher continuous elements, the constraint on v is weakened by means of Lagrange multipliers, introducing fields of Lagrange multipliers as additional variables to solve for [10,22]. The balance equation for the fluid phase remains classical. For fluid mass flux $\vec{m}$ and fluid mass density M the balance equation for any kinematically admissible variation of pore pressure $p^\star$ over an arbitrary domain Ω is written as

$$\int_\Omega \left(m_j \frac{\partial p^\star}{\partial x_j} - \dot{M} p^\star \right) d\Omega - \int_\Gamma \bar{q} p^\star d\Gamma = 0, \qquad (2)$$

where $\bar{q}$ is the fluid mass flux over domain boundary Γ. $\dot{M}$ is the time derivative of fluid mass M. Finite element discretization allows solving these nonlinear field equations for prescribed boundary conditions in an iterative way. The algorithm was implemented in the finite element code Lagamine [11,13]. The local second gradient paradigm provides the assumption of decoupling between the classical part of the model and the second gradient part, which is of vital importance to the coupling with the framework of computational homogenization; the first and second gradient part of the model can therefore be formulated independently. A general expression of the constitutive relations, with coupling between solid and fluid phases in the first gradient part, can therefore be formulated as

$$\begin{bmatrix} C_{ijkl} & A_{ijl} & B_{ij} \\ E_{ikl} & G_{il} & H_i \\ K_{kl} & L_l & N \end{bmatrix} \begin{Bmatrix} \frac{\partial \delta u_k}{\partial x_l} \\ \frac{\partial \delta p}{\partial x_l} \\ \delta p \end{Bmatrix} = \begin{Bmatrix} \delta \sigma_{ij} \\ \delta m_i \\ \delta \dot{M} \end{Bmatrix} \qquad (3)$$

and

$$D^{SG}_{ijklmn} \frac{\partial \delta v_{lm}}{\partial x_n} = \delta \Sigma_{ijk} \qquad (4)$$

The latter is formulated as a phenomenological relation between increments of the microkinematical gradient tensor to increments of the double stress in the framework of micromorphic continuum [17], for which only an elastic relation [23] is considered here. When restricted to isotropy of the second gradient model, the sixth-order tensor $\boldsymbol{D}^{SG}$ can be expressed through a single parameter $D[N]$, implicitly controlling the width of strain localization bands [9,6]. This parameter needs calibration against the constitutive relation and the mesh size in order to guarantee mesh-objective results in case of localization phenomena.

Eq. (3) is the general expression of the classical part of the model, which is coupled to the micromechanical model in the framework of first order computational homogenization. The left hand matrix, containing the tangent operators, is derived from the microscale material response to a variation of the kinematics increments through computational homogenization (see van den Eijnden et al. [29] for details). The consistency of these tangent

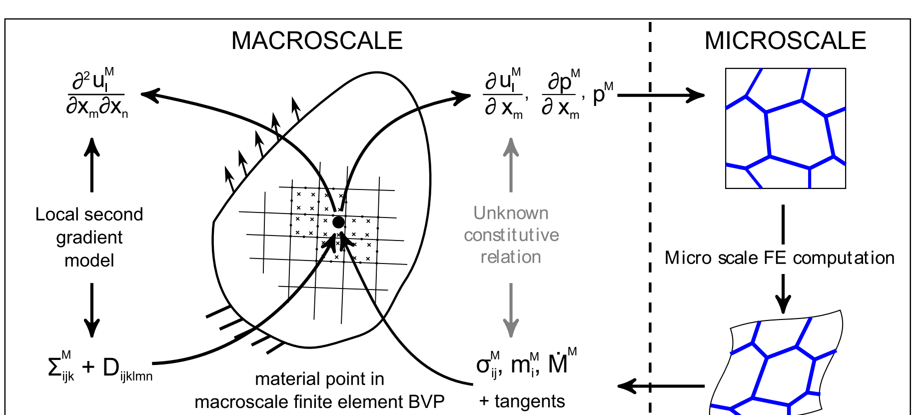

Fig. 1. Schematic representation of the FE^2 method for hydromechanical coupling with a local second gradient paradigm.