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Upscaling Theory for Coupled Hydro-Mechanics in 3D Fractured Porous Rock (Application to Damaged Claystone around a Drift)

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Introduction and summary

A methodology for upscaling 3D coupled Hydro-Mechanical (HM) properties of fractured porous rocks is developed theoretically, then tested on synthetic fractured rock samples, and finally, applied to a damaged and fractured claystone around a drift (the GMR gallery located in the 400 m to 600 m deep layer of Callovo-Oxfordian claystone at the Meuse/Haute-Marne Underground Research Laboratory operated by ANDRA). We focus on the Mechanical and coupled Hydro-Mechanical (HM) properties of fractured porous rock (Darcy permeability was upscaled separately in *Ababou, Cañamón Valera et al. 2011, JPCE*). In the application, the geometric structure of the EDZ (Excavation Damaged Zone) around the GMR gallery is described by a hybrid model comprising (i) a set of 10 000 statistical fissures with radially inhomogeneous statistics (size, thickness and density increase near the wall), and (ii) a deterministic set of large curves fractures (“chevrons”), periodically spaced along the axis of the gallery according to a 3D chevron pattern. The upscaled HM coefficients are obtained theoretically and calculated for different cases (synthetic samples, and application to the GMR drift). They include scalars, 2nd rank, and 4th rank tensors. The “3D” and “2D transverse” distributions of the upscaled coefficients are analyzed (displayed using spheres or ellipsoids). Global values are obtained by upscaling over the entire damaged/fractured annular zone around the drift. Equivalent isotropic coefficients are also extracted from these tensors: Young modulus E , bulk modulus K , Lamé shear modulus μ , Poisson ratio ν , and HM coupling coefficients: Biot coefficient B (stress/pressure) and Biot modulus M (pressure / fluid production). Theoretical expressions are provided in the tensorial case, and in the simplified case of statistically isotropic cracks. The isotropic expressions are tested by running 3D “upscaling experiments” on synthetic Poissonian crack systems with isotropic orientations. The impact of fissuring/fracturing on equivalent stiffnesses and HM couplings is analyzed. References: *Cañamón, Ababou et al. 2019 (to appear in IJRMMS)*; *Ababou, Cañamón et al. 2014 (Geol. Soc. London, Spec. Publi., v.400)*.

Theory

The equivalent (upscaled) system of continuum equations involves the following macroscale tensorial laws and coefficients. The first law is the hydro-mechanical Hooke / Biot stress-strain-pressure law, called here “first Biot constitutive equation”: $\sigma_{ij} = R_{ijkl} \Delta \varepsilon_{kl} - B_{ij}^{(1)} \Delta p$ where R_{ijkl} [Pa] is

the stiffness tensor; $B_{ij}^{(I)}$ is the tensorial “Biot” coupling coefficient. Its reciprocal law expresses strain vs. stress and water pressure: $\varepsilon_{ij} = C_{ijkl}\Delta\sigma_{kl} + \bar{B}_{ij}\Delta p$, where C_{ijkl} [Pa⁻¹] is the compliance tensor, and \bar{B}_{ij} [Pa⁻¹] is a “reciprocal” Biot coefficient representing strain/pressure coupling (also known as the poro-elastic expansion coefficient). The second law is the hydro-mechanical coupling (called here “2nd Biot constitutive equation”), which relates water production $\Delta\xi$ (increment of fluid content [m³ of water / m³ of clay rock]) to water pressure variation Δp and to global strain ε_{ij} , as follows: $\Delta\xi = B_{ij}^{(II)}\varepsilon_{ij} + \Delta p/M^{(II)}$, where $B_{ij}^{(II)}$ is a dimensionless tensorial “Biot” coupling coefficient (called here “2nd” Biot coefficient), and $M^{(II)}$ is the dimensionless Biot modulus (called here “2nd” Biot modulus). Concerning water transport (‘Hydraulics’), the equivalent conductivity tensor K_{ij} was obtained earlier by upscaling based on flux superposition under fixed hydraulic gradient (Ababou, Cañamón Valera et al. 2011, JPCE). Thus, we may focus now strictly on M/HM processes.

The above-stated M/HM macroscale laws were obtained theoretically, in this work, by a method that accounts explicitly for the 3D geometric/statistical structure of the fractured porous rock. Briefly, the method is based on the superposition of matrix strain and crack displacements under fixed total stress, assuming a fluid-filled isotropic porous matrix, and fluid-filled cracks obeying Terzaghi or Biot elasticity. This theory generates in particular two Biot coefficients and two Biot moduli, due to the “dual” nature of the porous/fractured medium (Cañamón, Ababou et al. 2019, to appear in IJRMMS).

Sample results and discussion

Fig. 1 presents frontal views of locally upscaled 3D coefficients around the drift: $B_{ij}^{(0)}$ (ellipsoids) and $1/M^{(0)}$ (spheres) are shown in the first transverse layer (Y,Z) at axial position $X \in [-10.0 \text{ m}, -9.5 \text{ m}]$. The upscaling subdomains are cubes of side 0.5 m. Superscript (0) indicates that the plotted coefficients are calculated *relatively* to the coupling effects of fissures and fractures. The global coefficients of the EDZ around the drift were also isotropically upscaled. Comparing them with the intact rock matrix, it was concluded that the global Biot coefficient (B) increases with damage (while staying below unity as it should), and the global Biot modulus (M) decreases with damage. This is as expected physically, since damaging and fracturing should weaken the rock.

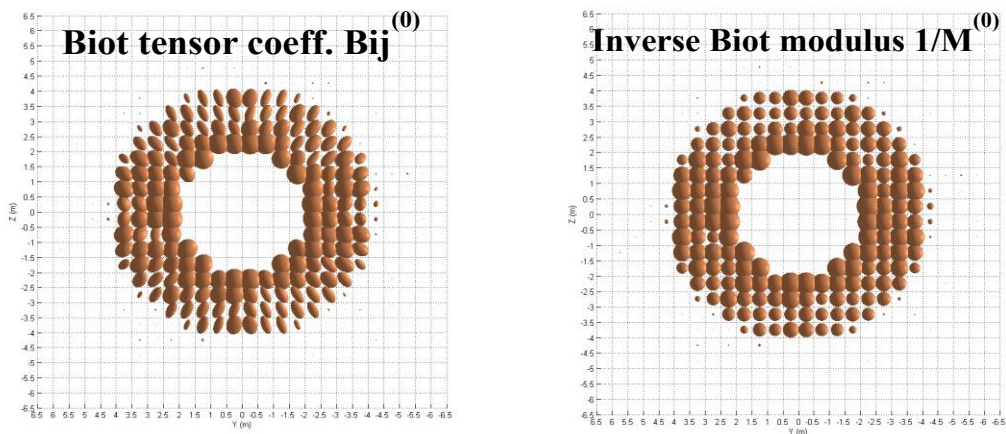


Fig. 1. Frontal views of 3D upscaled coefficients $B_{ij}^{(0)}$ (ellipsoids) and $1/M^{(0)}$ (spheres) around the drift.

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