A Bio-hydro-mechanical Model for Propagation of Biogrout in Soils

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ABSTRACT

Conventional soil improvement techniques can lead to permanent soil pollution or emission of carbon dioxide. It is therefore a challenge for engineers to design alternative sustainable and cost-effective grouting techniques. In Microbial Induced Calcite Precipitation (MICP), bacterial activity leading to calcite precipitation is created and the precipitated calcite acts as a cementing agent in the soil. Bacterial strains producing urease can indeed have a major impact on the natural calcite precipitation process when supplied with nutrients and urea.

The miscible and reactive biogrout injection in saturated, deformable soil need to be better described to more effectively design this innovative grouting technique. A comprehensive research work is therefore carried out on this topic. The field equations for biogrout transport are established based on the understanding of the complex processes involved: bio-hydro-mechanical couplings, transport, miscibility, bacterial growth and decay and bacterial attachment and detachment.

The resulting set of field equations is discretized and implemented into an advanced finite element code. Finite element modelling of column injection tests is carried out to validate the formulation and demonstrate the potentiality of the developed model. The simulation results emphasize the significant role of bio-hydro-mechanical processes in the global MICP response of the soil.

INTRODUCTION

As population and living standards follow a global trend of increase, the need for infrastructure continuously expands. Challenges pertaining to new locations and innovative construction techniques therefore multiply. Usually, chemical and cement based grouting products are used for soil improvement; however, they lead to permanent soil pollution or emission of carbon dioxide. More environmentally friendly grouting products such as biogrout are therefore in demand. In the frame of sustainable development, biogrouting is a revolutionary technique based on the injection of a biological solution in soil. There is however a need to develop a comprehensible and highly coupled bio-hydro-mechanical mathematical model able to realistically predict the behaviour of biogrout propagation in soils.

THEORETICAL FRAMEWORK

In the context of advanced grouting fluid transport analysis, among the most recent works are those presented by Bouchelaghem et al. (2001), Saada et al. (2005) and Chupin et al. (2009). Their formulations account for the following phenomena: transport (advection, diffusion and dispersion), miscibility, filtration and hydro-mechanical coupling. As bacteria are living organisms, they are not only subjected to such physicochemical phenomena but they are also governed by a number of strictly biological processes affecting their transport (Sen et al., 2005). Bacteria enriched fluid transport models such as Li et al. (1996), Sen et al. (2005) and Tufenkji (2007) therefore additionally consider factors and mechanisms which influence microbial transport and removal in saturated porous media, such as bacterial transport (random motility and chemotaxis) and growth/decay, but they usually lack the miscibility and the effect of the fluid flow and the porosity variation characterizing advanced grouting fluid transport models. Advanced pollutant transport models such as the one developed by Biver (1993) consider many of the above listed processes: transport, filtration, miscibility and growth/decay. This literature constitutes the starting point of the analysis presented in this paper in which also the processes accounting for the effect of bacterial communities on the elastic strains are taken into account (Figure 1).

The concept of continuous porous media used herein is based on the notion of a Representative Elementary Volume (REV) that allows establishing balance equations at the macroscale. Assuming that the porous medium is saturated, it is composed of two phases, the solid phase *s* consisting of the solid matrix and the fluid phase *f* corresponding to the pore fluid. As the biogrout is injected into the medium, the composition of the phases is altered. Bacteria can indeed attach or stay suspended and, as a result, be considered as two distinguished species; the attached bacteria *sb* belong to the solid phase and the suspended bacteria *fb* to the fluid phase. We define herein two other species: *sg* refers to the solid grains and *fw* to the pore water. The injection solution is supposed to be a part of the pore fluid. Both attached and suspended bacteria can be referred to as biomass and belong to a same component (bacteria).

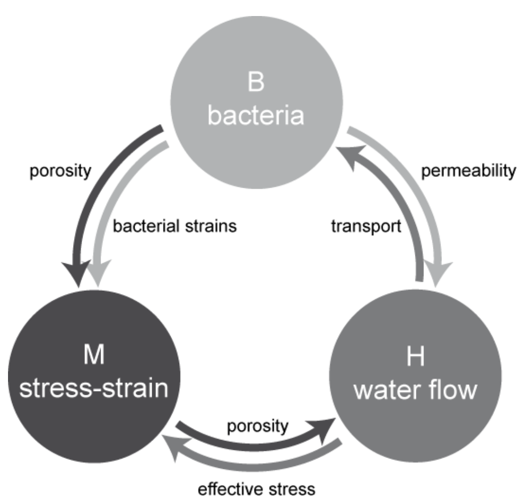

Figure 1. Biogrout transport in porous media.

BIO-HYDRO-MECHANICAL MODEL

Model development

A series of assumptions are made in the development of the balance equations: i. the porous media is saturated by one fluid phase; ii. the dispersive and diffusive fluxes are neglected for the phases as spatial variations in the phases density are small (the fraction of bacteria within the fluid and solid phases is assumed to be small in comparison to the homogeneously distributed pore water and solid grains); iii. the dispersive and diffusive fluxes are neglected for the attached bacteria; iv. no internal production of solid grains or pore water occurs; v. a linear equilibrium isotherm is assumed between the concentration of attached and suspended bacteria; vi. growth and decay rates are considered equal in both solid and fluid phases and vii. random mobility and chemotaxis are neglected for both attached and suspended bacteria.

Balance equations

As the velocity distribution within the fluid phase is needed as input information for the component transport problem and that interaction between the hydraulic flows and the mechanical behaviour of the solid matrix is taken into account, the mass balance of the fluid and solid phases carrying the bacteria and the momentum balance of the mixture need to be solved along with the mass balance of the bacteria. The balance equations needed in the development of the model are therefore the following: i. solid phase and fluid phase mass balances to evaluate the velocity distribution through a flow equation; ii. total momentum balance to evaluate the hydro-mechanical coupling; and iii. bacteria mass balance to derive a transport equation. Mass balance of each species composing the porous media is first expressed, adopting the compositional approach (Panday and Corapcioglu, 1989). From these, all needed equations are derived.

Mass balance equations are derived respectively for solid and fluid phases considering the assumptions listed previously:

$$\frac{\partial}{\partial t}\left(\left(1-n\right)\rho^{s}\right)=-\nabla\cdot\left(\left(1-n\right)\left(\rho^{s}\boldsymbol{V}^{s}\right)\right)+k_{att}\left(nC\right)-k_{det}\left(\rho^{b}S\right)+k_{g}\left(\rho^{b}S\right)-k_{d}\left(\rho^{b}S\right)$$

$$\frac{\partial}{\partial t}\left(n\rho^{f}\right)=-\nabla\cdot\left(n\left(\rho^{f}\boldsymbol{V}^{f}\right)\right)-k_{att}\left(nC\right)+k_{det}\left(\rho^{b}S\right)+k_{g}\left(nC\right)-k_{d}\left(nC\right)$$

Momentum balance is established for the mixture:

$$\nabla\cdot\boldsymbol{\sigma}+\rho\boldsymbol{F}=0$$

Mass balance is finally established for the bacteria combining mass balance of attached and of suspended bacteria:

$$\frac{\partial}{\partial t}\left(\rho^b S + nC\right) = -\nabla\cdot\left(\left(\rho^b S + nC\right)\boldsymbol{V}^s\right) - \nabla\cdot\left(n\left(C\boldsymbol{V}^r - \boldsymbol{D}\nabla C\right)\right) + \left(k_g - k_d\right)\left(\rho^b S + nC\right)$$

with n the porosity, ρ^s the solid phase density, $\boldsymbol{V}^s$ the macroscopic velocity of the solid phase, C the suspended bacteria concentration, S the attached bacteria density, ρ^b the dry bulk density of the porous media, k_{att}, k_{det} respectively the attachment and detachment rates of bacteria, k_d, k_g respectively the growth and decay rates of bacteria, ρ^f the fluid phase density, $\boldsymbol{V}^f$ the macroscopic velocity of the fluid phase, $\boldsymbol{\sigma}$ the volume averaged stress, $\rho\boldsymbol{F}$ the total body force per unit volume of porous medium at a macroscopic point, $\boldsymbol{V}^r$ the macroscopic relative velocity of the liquid phase with respect to the solid phase and D the hydrodynamic dispersion tensor.

Constitutive equations

The balance equations introduced so far are independent of material properties and rheology. Constitutive conditions are needed to complete the description of the material behaviour.

The mechanical constitutive law is developed as follows. The biological part of the deformation is linked to the amount of attached bacteria on the grain surface:

$$\boldsymbol{\sigma}' = \boldsymbol{D}^e : \boldsymbol{\varepsilon}^e = \boldsymbol{D}^e : \left(\boldsymbol{\varepsilon}^e_{mec} + \boldsymbol{\varepsilon}^e_{bio}\right) = \boldsymbol{D}^e : \left(\boldsymbol{\varepsilon}^e_{mec} - \alpha_{bio}\Delta S\boldsymbol{I}\right)$$

The relative fluid-solid velocity is governed by Darcy's Law:

$$n\boldsymbol{V}^r = n\left(\boldsymbol{V}^f - \boldsymbol{V}^s\right) = -K\left(\nabla p^f + \rho^f\boldsymbol{g}\right)$$

with $\boldsymbol{D}^e$ the elastic tensor, $\boldsymbol{\varepsilon}^e$ the solid elastic strain with a mechanical part $\boldsymbol{\varepsilon}^e_{mec}$ and a biological part $\boldsymbol{\varepsilon}^e_{bio}$, α_{bio} the biological expansion coefficient of the solid grains due to the attachment of bacteria, K the permeability defined as $K = k/\mu$ in which k is the intrinsic permeability and μ is the dynamic viscosity.

As stated earlier, linear equilibrium attachment/detachment is assumed in the developments. We consider that the kinetic attachment/detachment processes are active during a very short duration of time only and that apparent equilibrium or steady-state is reached quasi instantaneously. Such process are indeed very fast compared to flow and deformation processes. A linear relation is hence assumed at all times between the concentration of attached bacteria S and the concentration of suspended bacteria C.

An equilibrium relation between S and C can be derived from mass balance:

$$S = \frac{n}{\rho^b}\frac{k_{att}}{k_{det}}C = K_d C$$

with $K_d = \frac{n}{\rho^b}\frac{k_{att}}{k_{det}}$ the partition coefficient.

Field equations

The field equations are obtained by combining the mass balance equations and introducing the related constitutive equations.

Upon combining mass balance equations for solid and fluid phases and introducing Darcy's law, the following flow equation is obtained:

$$\nabla \cdot \boldsymbol{V}^s - \nabla \cdot \left(K \left(\nabla p^f + \rho^f \boldsymbol{g} \right) \right) + n\beta_f \frac{\partial p^f}{\partial t} = \left(k_g - k_d \right) \left(\frac{1}{\rho^f} n + \frac{1}{\rho^s} \rho^b K_d \right) C$$

with β_{fw} the fluid compressibility defined by $\partial_t \rho^{fw} / \rho^{fw} = \beta_{fw} \partial_t p^f$.

Considering Terzaghi's effective stress (Terzaghi, 1936), the following equation accounting for the hydro-mechanical coupling is derived from momentum balance of the mixture:

$$\nabla \left(\boldsymbol{D}^e : \left(\boldsymbol{\varepsilon}^e_{mec} - \alpha_{bio} K_d \Delta C \boldsymbol{I} \right) - p^f \boldsymbol{I} \right) + \rho \boldsymbol{g} = 0$$

Mass balance of bacteria is developed considering Darcy's law. This yields the following transport equation:

$$\frac{\partial}{\partial t}\left(\left(\frac{\rho^b}{n} K_d + 1 \right) C \right) = -\nabla \cdot \left(\left(\frac{\rho^b}{n} K_d + 1 \right) C \boldsymbol{V}^s \right) - \nabla \cdot \left(-C \frac{K}{n} \left(\nabla p^f + \rho^f \boldsymbol{g} \right) \right)$$
$$+ \nabla \cdot \left(\boldsymbol{D} \nabla C \right) + \left(k_g - k_d \right) \left(\frac{\rho^b}{n} K_d + 1 \right) C$$

NUMERICAL RESOLUTION

The final system is composed of the three previous equations that allow determining the three principal unknowns (solid displacement, pore water pressure and bacteria concentration in the fluid phase). Conventional hydro-mechanical coupling is supplemented by a bio-mechanical and bio-hydrological coupling as attached bacteria modify the porosity and induce bio-elastic deformations.

$$\begin{cases} \nabla \cdot \dfrac{\partial \boldsymbol{u}^s}{\partial t} - \nabla \cdot \left(K \left(\nabla p^f + \rho^f \boldsymbol{g} \right) \right) + n\beta_f \dfrac{\partial p^f}{\partial t} - \left(k_g - k_d \right) \left(\dfrac{1}{\rho^f} n + \dfrac{1}{\rho^s} \rho^b K_d \right) C = 0 \\ \nabla \left(\boldsymbol{D}^e : \left(\dfrac{1}{2} \left(\nabla \boldsymbol{u}^s + \nabla \boldsymbol{u}^{sT} \right) - \alpha_{bio} K_d \boldsymbol{I} \Delta C \right) - p^f \boldsymbol{I} \right) + \rho \boldsymbol{g} = 0 \\ \dfrac{\partial}{\partial t} \left(R_d C \right) + A_d C + \nabla \cdot \left(R_d C \dfrac{\partial \boldsymbol{u}^s}{\partial t} \right) - \nabla \cdot \left(C \dfrac{K}{n} \left(\nabla p^f + \rho^f \boldsymbol{g} \right) \right) + \nabla \cdot \left(-\boldsymbol{D} \nabla C \right) = 0 \end{cases}$$

with $R_d = \left(\dfrac{\rho^b K_d}{n} + 1 \right)$ the retardation factor and $A_d = \left(k_d - k_g \right) R_d$.

These equations are implemented in the finite element code LAGAMINE (Charlier, 1987 and Collin, 2003). For such an advanced coupled problem, a two-step method is applied; the transport problem is solved for each step and the obtained bacteria concentration in the fluid phase values are injected in the flow and equilibrium equations.

NUMERICAL RESULTS

To test the validity of the developed biogrout transport formulation, numerical simulations of column injection tests are carried out. The geometrical model of the column injection test consists of a vertical straight pipe (Figure 2). Results are given for a drained column with free concentration at its top under rapid injection (increase of concentration from 0 to 1 kg/m^3 during 10 s followed by constant injection during 2000 s). The column is considered packed with Jossigny silt (Cui and Delage, 2009 and Nuth, 2009) and all bacterial parameters are based on the literature data.

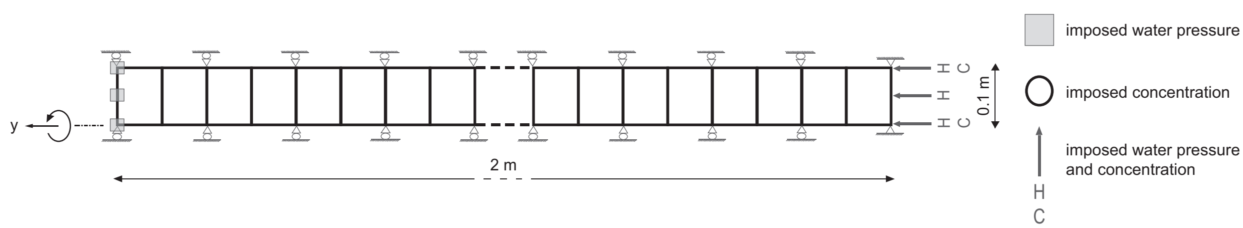

Figure 2. 1D column used for injection tests.

Figure 3 (a) presents the evolution of the front of concentration along the column. The short injection duration results in a fast propagation of the concentration. In the formulation, the propagation of the concentration is a combination of advection, dispersion and diffusion. The variation of the dispersivity and of the diffusivity and the relative correlation between water flow and biogrout transport lead to the conclusion that the transport of biogrout is mainly managed by the advective process.

The evolution of the porosity along the column is presented in Figure 3 (b) (the initial porosity of 0.5 is uniform throughout the column). It can be noticed that the porosity profile is quite symmetrical to the concentration profile (Figure 3 (a)).

The main part of the porosity variations can therefore be attributed to bio-affected porosity variations, in addition to those attributed to the flow.

Biological induced stresses are finally presented in Figure 3 (c). As the lateral dilatation is prevented and a bio-elastic law is considered, an increase in biogrout concentration leads to an increase of lateral compressive stresses. Axial displacements on the other hand are free as the top of the column is not blocked. Therefore, no variations of axial effective stresses are observed due to the injection.

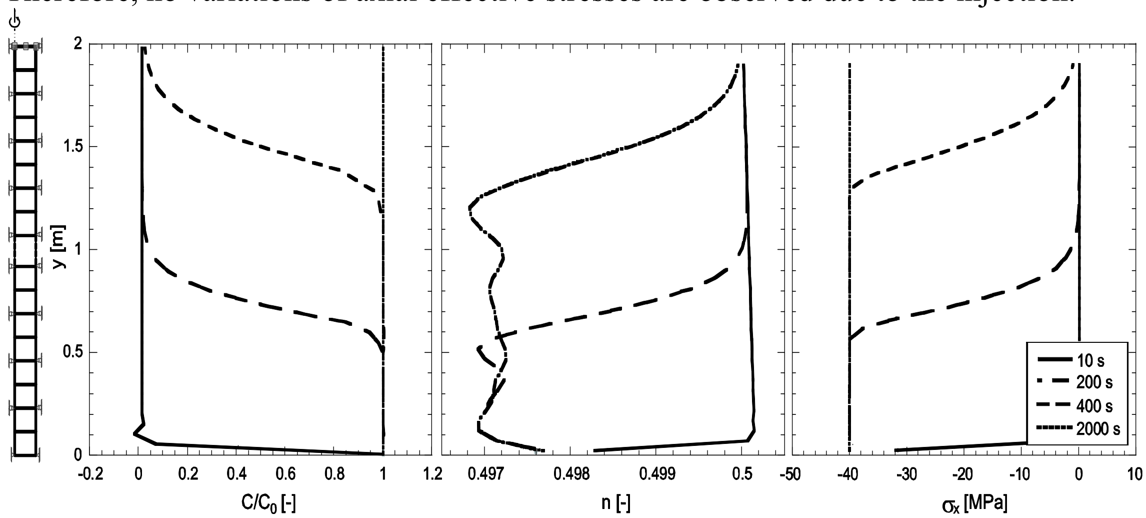

Figure 3. (a) Biogrout concentration profile, (b) porosity profile and (c) biologically induced stresses profile.

CONCLUSION

Field equations have been developed for the case of propagation of miscible and reactive biogrout injection in a saturated and deformable porous medium. The numerical implementation of the formulation has been carried out in a finite element code. Finite element modelling of column injection tests is carried out to demonstrate the potentiality of the developed model. The propagation of the concentration front is well represented in these trials. The bio-hydro-mechanical model will be further used to design foreseen laboratory tests and also in-situ injections.

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