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A unified Bio-Chemo-Hydro-Mechanical formulation for soil improvement with microbially-induced calcite precipitation

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ABSTRACT

This paper reports recent advances in modelling MICP at the engineering scale, in particular with respect to the stress-strain-strength modelling of bio-cemented soils. A complete Bio-Chemo-Hydro-Mechanical (BCHM) model is presented. The BCH model is based on the advection-dispersion-reaction equation modified to incorporate the behaviour of bacteria. Mechanisms such as bacteria attachment, reaction rate and calcite precipitation are considered. Calcite precipitation leads to a decrease in porosity and permeability which, in turn, modifies flow and transport of reactive species. A new constitutive model has been developed to reproduce the increase in strength and stiffness of bio-cemented sands. The main novelty with respect to previous studies is the unification of the bio-chemo-hydraulic equations with a constitutive model that reproduces the stress-strain-strength response of biocemented sands. In a boundary value problem, the inclusion of such constitutive model reveals the development of plastic strains at the interface between the cemented and non-cemented areas, as a consequence of the heterogeneous strength after treatment. The potential of the model for its use in geotechnical applications is demonstrated with a synthetic case of a shallow foundation.

Keywords: Microbially-Induced-Calcite-Precipitation (MICP); Soil improvement; Numerical Modelling; Multiphysical Coupling.

1 INTRODUCTION

Land scarcity and the increase in natural hazards are expected to drive the need of soil improvement works in many parts of the world. Microbially Induced Calcite Precipitation (MICP) is a promising technique for soil consolidation as an alternative to conventional cement-based improvement techniques. The technique consists in utilising urease-producing bacteria to catalyse the hydrolysis of urea, which produces carbonate. In the presence of calcium, carbonate can precipitate into calcite that, in turn, acts as a binder between soil grains. As a result, the soil strength and stiffness increase with a slight reduction in porosity and permeability. The whole process of MICP involves bio-chemical-hydro-mechanical coupled processes which require the use of numerical tools to assist a proper design and to realize the potential of MICP in geotechnical applications (Terzis and Laloui, 2019a).

This study presents recent advances in modelling MICP at the engineering scale, in particular with respect to the constitutive modelling of bio-cemented soils. A complete Bio-Chemo-Hydro-Mechanical (BCHM) model is presented. The BCH model is based on the advection-dispersion-reaction equation modified to incorporate the behaviour of bacteria. Mechanisms such as bacteria attachment, reaction rate and calcite precipitation are considered. Calcite precipitation leads to a decrease in porosity and permeability which subsequently modifies flow paths and hence the transport of reactive species. A new Mohr-Coulomb type model has been developed to reproduce the increase in strength and stiffness of treated soils. The calcite content is incorporated in the constitutive model as a variable that influences the stress-strain response of bio-cemented sands.

The ultimate goal is to present and verify a numerical tool for the analysis of geotechnical problems in which MICP is involved. For this the calibration of the complete model is discussed with an emphasis on drained triaxial tests. The potential of the model for its use in geotechnical application is demonstrated via a synthetic case of a shallow foundation, where the impact of different treatment strategies on the load-displacement and bearing capacity was studied. Factors that were analysed included the injection protocol, number of injection points and volume of injected fluids.

2 MODEL FORMULATION

2.1 Balance equations

MICP consists in the hydrolysis of urea, catalysed by urease, which produces carbonate and ammonium. This is expressed as:

$$\mathrm{CO(NH_2)_2} + 2\mathrm{H_2O} \xrightarrow{urease} 2\mathrm{NH_4^+} + \mathrm{CO_3^{2-}} \quad (1)$$

When calcium is available, $\mathrm{CO_3^{2-}}$ precipitates into calcium carbonate:

$$\mathrm{Ca^{2+}} + \mathrm{CO_3^{2-}} \rightarrow \mathrm{CaCO_3} \downarrow \quad (2)$$

The above chemical reactions can be expressed as a single reaction as:

$$\mathrm{CO(NH_2)_2} + 2\mathrm{H_2O} + \mathrm{Ca^{2+}} \rightarrow 2\mathrm{NH_4^+} + \mathrm{CaCO_3} \quad (3)$$

The above expression has been shown to be accurate in many instances in which the precipitation occurs significantly faster than the hydrolysis and it is used as the main bio-chemical equation for the model. The derivation of the field equations follows those outlined in Fauriel and Laloui (2013) although some assumptions have been revisited. It is based on the compositional approach that consists in establishing the balance of components in the system of interest as:

$$\underbrace{\frac{\partial}{\partial t}\left(\theta_\alpha \rho_\alpha^\gamma\right)}_{\substack{\text{Mass acumulation}\\ \text{rate in } \alpha \text{ phase and}\\ \gamma \text{ component}}} = -\underbrace{\boldsymbol{\nabla}\cdot\theta_\alpha(\rho_\alpha^\gamma \mathbf{q}_\alpha + \mathbf{j}_\alpha^\gamma)}_{\substack{\text{Advective+diffusive}\\ \text{flux of mass}}} - \underbrace{\Lambda_{\alpha\beta}^\gamma}_{\substack{\text{Net influx}\\ \text{of mass from}\\ \alpha \text{ to } \beta \text{ phase}}} + \underbrace{\Omega_\alpha^\gamma}_{\substack{\text{Net production}\\ \text{of mass}}} \quad (4)$$

where subscripts α and γ refer to the phase and the species respectively, θ is the relative volume of the phase, ρ is the density, $\mathbf{q}$ is the advective flux, $\mathbf{j}$ is the diffusive flux, $\Lambda_{\alpha\beta}^\gamma$ is the influx due to phase change from α to β of the species γ, and Ω represents the net production of mass due to external exchange or chemical reactions. A water-saturated porous medium is considered in which the state variables are the displacements of the solid skeleton, pore fluid pressure, attached bacteria concentration, calcite concentration, suspended bacteria concentration, suspended urea and calcium (reactants) concentration, and suspended ammonium (by-product) concentration.

2.2 Constitutive relationships

The main constitutive equations used to express the balance equations in terms of the primary variables are described in this section. Water flow is expressed through Darcy's law:

$$\mathbf{q}_w = -\mathbf{K}_w\left(\boldsymbol{\nabla} p_w + \rho_f g \boldsymbol{\nabla} z\right) \quad (5)$$

where $\mathbf{K}_w$ is the hydraulic conductivity tensor and z is the depth. The hydraulic conductivity evolves with the porosity following the Kozeni-Carman equation:

$$\mathbf{K}_w = \mathbf{K}_0 \frac{(1-n_0)^2}{n_0^3} \frac{n^3}{(1-n)^2} \quad (6)$$

where $\mathbf{K}_0$ is the initial permeability and n_0 is the initial porosity.

Non-advective fluxes are modelled as $\mathbf{j}^{\gamma} = -\mathbf{D}^{\gamma}\nabla c^{\gamma}$, where $\mathbf{D}^{\gamma}$ is the hydrodynamic dispersion coefficient of component γ. This coefficient accounts for diffusive and dispersive fluxes as:

$$\mathbf{D} = D_{\gamma}\mathbf{I} + \frac{(\alpha_L - \alpha_T)(\mathbf{v}_w \cdot \mathbf{v}_w)}{|\mathbf{v}_w|} + \alpha_L|\mathbf{v}_w|\mathbf{I} \quad (7)$$

where D_{γ} is the molecular diffusion coefficient and α_L and α_T are the lateral and transversal dispersion coefficients respectively.
Attachment of bacteria is assumed to follow an equilibrium isotherm with a maximum attached concentration. The reaction rate is taken as a Michaelis-Menten form:

$$k_{rea} = U_{max}\frac{R}{R + K^{m}} \quad (8)$$

Where U_{max} is the maximum urease activity that depends on the bacteria concentration.

2.3 Stress-strain elastoplastic model

Calcite precipitation modifies the mechanical response of soils as a result of the inter-particle bonding and the densification (Terzis and Laloui, 2019b). In particular, and with respect to untreated sands, some of the salient features are: (i) increase of stiffness in the initial loading phase; (ii) a higher peak strength for the biocemented samples; (iii) brittle response upon failure of the biocemented sand; and (iv) similar strength at residual state. The main features and hypotheses of the constitutive model implemented is presented in the following.

The model is based on elastoplasticity, with an explicit distinction between reversible (elastic) and irreversible (plastic) strains. Linear elasticity is used to compute elastic strains:

$$\mathrm{d}\epsilon_v^e = \frac{\mathrm{d}p'}{K}, \qquad \mathrm{d}\epsilon_q^e = \frac{\mathrm{d}q}{3G} \quad (9)$$

where K is the bulk modulus and G is the shear modulus. The elastic moduli evolve with the total precipitated calcite content according to the expression proposed by Fauriel and Laloui (2012).

Most MICP treatments target sands and silty-sands, the strength of which can be represented by means of a cohesive-frictional yield function:

$$f_Y = q - \eta(p' + c) \quad (10)$$

Where c is the isotropic tensile strength and η is the shear strength ratio at failure, which is established as a function of Lode's angle. To account for the increase in peak strength with calcite content, c is established as a function of the current calcite content. Shear strains beyond the peak strength result in plastic deviatoric strains which induce a strength decrease in treated samples by means of irreversible decrease in c.

3 MODEL PERFORMANCE

The above formulation has been implemented in the finite element code Lagamine (Biver 1993, Collin et al. 2002) following the procedure outlined in Fauriel and Laloui (2012). The main novelty with respect to previous studies is the unification of the bio-chemo-hydraulic equations with a constitutive model that reproduces the stress-strain-strength response of biocemented sands. To demonstrate the performance of the constitutive model, Figure 1 shows experimental results from Feng and Montoya (2016) of drained triaxial tests on Ottawa sand. These include untreated and treated specimens and three different confining pressures are reported, which exhibited some differences. In particular, cemented specimens display significantly higher strength and dilatancy.

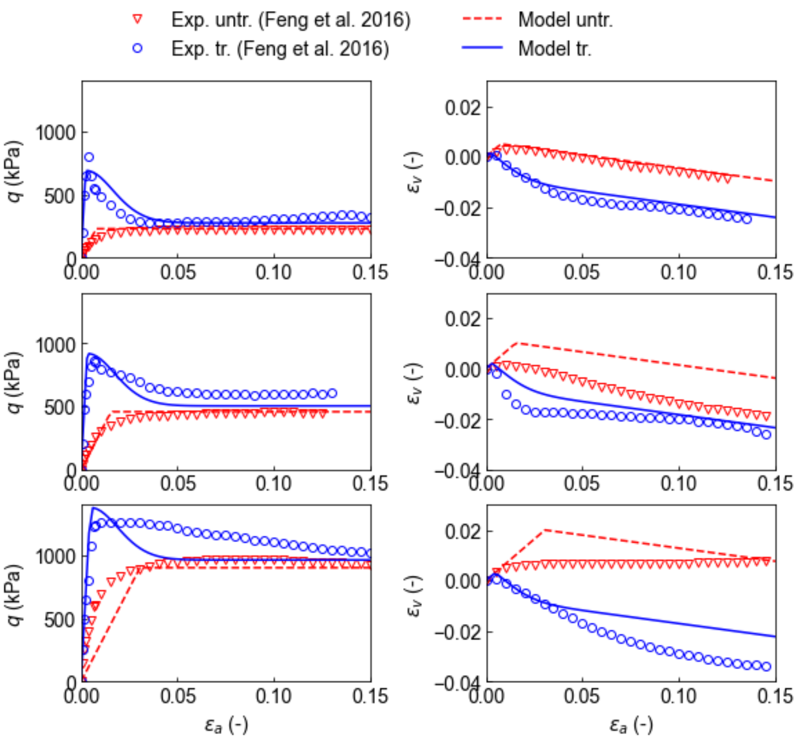

Figure 1. Validation of the constitutive model against treated sands by Feng and Montoya (2016).

As it can be seen, the model reproduces the main trends of both untreated and treated specimens. Given the main aim of the framework, which is to provide a practical tool for the analysis of geotechnical problems, the model results are considered satisfactory.

The performance of the complete formulation was assessed in a synthetic case of a shallow foundation. The foundation is assumed infinitely rigid and it is constructed on a sand layer with the properties of Ottawa sand according to the previous calibration. A series of MICP injections following different protocols is performed below the foundation to increase its bearing capacity. After the injections, the foundation is loaded and the behaviour of the improved sand layer is examined. The final stress distribution and the plastic zones are presented in Figure 2. Higher stresses tend to distribute towards the higher stiffness zones as a result of the high calcite content. The failure zone, as observed by the development of plastic strains, occurs mostly within the untreated soil in this particular case, which indicates that the location of the injection point could have been further optimized.

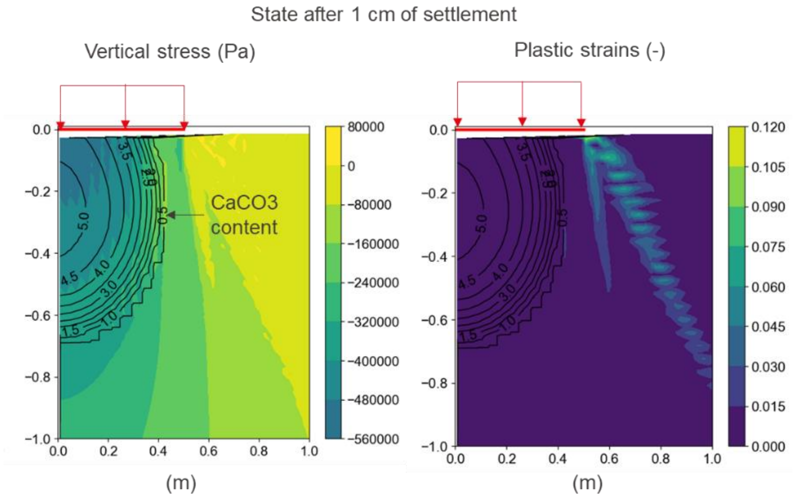

Figure 2. Model prediction due to a 1 cm settlement. Left: vertical stress distribution beneath the foundation. Right: Plastic strains.

4 CONCLUSIONS

This paper presents the development and application of a comprehensive bio-chemo-hydro-mechanical model that can be used for designing MICP treatments with the finite element method. The formulation involves a novel elastoplastic constitutive model based on Mohr-Coulomb that effectively predicts the strength increase of MICP improved soils. The numerical tool presented in this paper enables the interpretation of the highly coupled processes that take place in the application of MICP. The main design factors can be examined to ultimately optimise the injection procedure on a case-by-case basis. A synthetic application case to a shallow foundation strengthening is presented that demonstrates the scope of model application. In particular it demonstrates the impact of the injection strategy on the final cement distribution and the effects in terms of heterogeneous mechanical properties.

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