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Innovations in liquefaction mitigation: Modelling the mechanical cyclic behavior of biocemented soils

Innovations dans l'atténuation de la liquéfaction: Modélisation du comportement mécanique cyclique des sols biocimentés

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ABSTRACT: Liquefaction remains a major geotechnical hazard in seismically active zones. Traditional mitigation methods while effective, frequently have significant environmental and economic impacts and may not be suitable for existing structures. Biogeotechnical methods, notably Microbially Induced Calcite Precipitation (MICP), offer a sustainable alternative. Experiments reveal that MICP enhances liquefaction resistance, even at low calcite contents. However, the lack of models capturing this behavior hinders the design and adoption of these techniques. This study presents Hujeux-BC, a mechanical constitutive model for the cyclic behavior of biocemented soils. It independently incorporates the main characteristics of biocementation, densification and interparticle bonding. This is done by modifying the materials elastic parameters and relative density, as well as the addition of a bonding parameter. Using the measured calcite content and change in shear wave velocity, the model is able to simulate the cyclic behavior of biocemented soils. Notably, in an undrained cyclic direct simple shear (DSS) test, the model can simulate the porewater pressure generation, accurately estimating the number of cycles needed to trigger liquefaction. This accuracy and the model's straightforward calibration process provide a powerful tool for designing and optimizing MICP-based mitigation techniques, leading to more targeted and sustainable solutions.

RÉSUMÉ: La liquéfaction demeure un risque géotechnique majeur dans les zones sismiques. Les méthodes d'atténuation traditionnelles, malgré leur efficacité, ont des impacts environnementaux et économiques et ne conviennent pas toujours aux structures existantes. Les méthodes biogéotechniques, comme la Précipitation de Calcite Induite par Microbes (MICP), représentent une alternative durable. Les essais montrent que la MICP augmente la résistance à la liquéfaction, même à faible teneur en calcite. Cependant, l'absence de modèles constitutifs adéquats limite leur adoption. Cette étude introduit Hujeux-BC, un modèle constitutif pour le comportement cyclique des sols biocimentés. Il intègre séparément les caractéristiques principales de la biocimentation : la densification et la liaison entre particules. Ceci est fait en modifiant les paramètres élastiques du matériau, la densité relative, et en ajoutant un paramètre de liaison. En se basant sur la teneur en calcite et la vitesse des ondes de cisaillement, le modèle reproduit le comportement des sols biocimentés. Notamment, dans un essai cyclique non-drainé de cisaillement simple il permet de simuler la génération de la pression interstitielle, estimant le nombre de cycles nécessaires pour déclencher la liquéfaction. Cette précision, et la calibration simple des paramètres du modèle, en font un outil essentiel pour optimiser les techniques basées sur la MICP, menant à des solutions plus ciblées et durables.

Keywords: Liquefaction; biocementation; constitutive model; cyclic loading.

1 INTRODUCTION

Despite our increased understanding of liquefaction and the developed prevention methods, recent earthquake events highlight that liquefaction remains a threat to infrastructure (Cubrinovski et al., 2012), emphasizing the ongoing need to explore liquefaction mechanisms and preventative measures.

Traditional mitigation methods such as compaction, drainage, and grouting while effective, are often costly and invasive making them unsuitable for many existing structures. The need for more environmentally conscious, low-cost and non-invasive methods is therefore ever-present (Towhata, 2008). Biogeotechnical methods have emerged as a possible solution for this persistent hazard, particularly Microbially Induced Calcite Precipitation (MICP).

To assess the effectiveness of MICP based techniques, a combination of experiments and models is essential. Numerous experiments were conducted to observe the dynamic behavior of biocemented sands showing that biocementation greatly increased the liquefaction resistance, with highly cemented soils becoming virtually un-liquefiable (Montoya et al., 2013; Sasaki and Kuwano, 2016; Zamani et al., 2021; Lee et al., 2022). Yet, the shortage of models for biocemented soils' cyclic behavior limits the technique's widespread use.

This study introduces Hujeux-BC, a cyclic elastoplastic constitutive model for biocemented soils. The model is based on the Hujeux (1985) cyclic model framework and integrates the observed changes in behavior of biocemented soils under both monotonic and cyclic loading. This is done by the addition of new biocementation parameters that are calibrated through the measured calcite content and the change in the shear wave velocity.

The model uniquely considers biocementation's mechanical effects, densification and inter-particle bonding, separately which enables it to simulate the bond degradation and the lasting densification impact of biocementation independently making it a valuable tool for studying the long-term behavior of biocemented sands subjected to repeated cyclic loading.

The following sections present the model formulation and performance in simulating an undrained cyclic DSS test on biocemented soils at varying cementation levels under different Cyclic Stress Ratios (CSR).

2 MODELLING FRAMEWORK

2.1 Theoretical background

The model development draws from observations of the physical mechanisms that govern the behavior of biocemented soils under both monotonic and cyclic loading. The main characteristics of the monotonic mechanical behavior of biocemented soils as detailed in numerous review papers (Terzis and Laloui, 2019; Fu et al., 2023) can be summarized as: i) increased soil stiffness, ii) increased soil strength and softening post peak, iii) dilatant behavior. Experimental data consistently attribute this behavior to two mechanisms: i) densification and ii) interparticle bonding(Nafisi and Montoya, 2018; Harran et al., 2023). Densification occurs due to the presence of calcite in the pore space which can be easily determined through acid washing or thermos-gravimetric analysis among other methods. Bonding on the other hand is more difficult to quantify. While it can be detected using advanced techniques like scanning electron microscopy or X-ray micro-tomography, it remains difficult to accurately identify the "active" bonds. Alternatively, these bonds can be estimated using indirect methods such as the shear wave velocity V_s (Nafisi and Montoya, 2018).

The cyclic behavior of biocemented has been investigated through different laboratory and scaled model tests where it was found that even low levels of cementation result in a dramatically increased liquefaction resistance (Montoya et al., 2013; Sasaki and Kuwano, 2016; Zamani et al., 2021; Lee et al., 2022). These studies identify the effects of biocementation on the cyclic behavior as: i) increased resistance, ii) reduced porewater pressure generation, iii) increased stiffness and iv) delayed onset of liquefaction. These observations align with the change in behavior under monotonic loading implying that the physical mechanisms inducing these changes are the same.

2.2 The effects of biocementation

2.2.1 Densification

A densification parameter for the elastic behavior is introduced as:

$$\xi_{den} = \frac{\rho_{cc}(G_s + eSr) + m_{cc}(G_s - Sr)}{\rho_{cc}(G_s + eSr)} \tag{1}$$

where G_s is the specific gravity, Sr is the degree of saturation, e is the untreated void ratio, $m_{cc} = \frac{m_c}{m_s}$ is the calcite content, and $\rho_{cc} = \frac{\rho_c}{\rho_s}$ is the calcite density ratio.

The effect of densification on the yield surface is introduced through the parameter ψ_{den} expressed as:

$$\psi_{den} = \exp\left(\frac{e - e^*}{\lambda}\right) \tag{2}$$

here, λ is the coefficient of compressibility obtained as the slope of the critical state line (CSL) in the $v - \ln(p')$ plane.

2.2.2 Bonding

The effect of active calcite bonds on the elastic behavior is obtained through the change in shear wave velocity and is estimated as:

$$\xi_{bon} = \frac{(V_s{}^2)^*}{V_s^2} = \frac{(V_s + \Delta V_s)^2}{V_s^2} \tag{3}$$

where V_s^* and V_s are the shear wave velocities before and after calcite precipitation.

The effect of bonding on the yield surface is introduced through the parameter ψ_{bon} expressed as:

$$\psi_{bon} = \left(\psi_{bon_0}\right)^R \quad (4)$$

where ψ_{bon_0} is the initial degree of bonding and R is a debonding function given by:

$$R = \exp\left(-\omega \cdot \varepsilon_v^p\right) \quad (5)$$

Here, ω is the debonding rate and ε_v^p is the plastic volumetric strain. This expression was inspired by the work of Koliji et al. (2010) on structured soils since it was observed that their evolution during loading closely resembles that of biocemented soils.

3 MODEL FORMULATION

The model presented in this study is based on the work of Hujeux (1985) where the full elasto-plastic relationships are described. The following presents the changes due to biocementation.

The effect of biocementation on the elastic moduli is expressed as a combination of the densification and bonding parameters into a cementation factor CF_E given by:

$$CF_E = \xi_{den} \cdot \xi_{bon} \quad (6)$$

The elastic moduli are then expressed as:

$$K(p') = CF \cdot K_{ref} \left(\frac{p'}{p_{ref}}\right)^n \quad (7)$$

$$G(p') = CF \cdot G_{ref} \left(\frac{p'}{p_{ref}}\right)^n \quad (8)$$

where K_{ref} and G_{ref} are the reference bulk and shear moduli, p_{ref} is the mean effective pressure at which the moduli were estimated, p' is the current mean effective pressure, and n is an elastic exponent.

The change in the yield surface is done through the mean pressure at the critical state p'_{cs} which governs the strength response of the soil. p'_{cs} evolves to:

$${p'_{cs}}^* = CF_S \cdot p'_{cs} \quad (9)$$

where $CF_S = \psi_{den} \cdot \psi_{bon}$ is the cementation factor for strength.

4 MODEL PERFORMANCE

The model's performance was tested against a series of undrained cyclic DSS tests conducted by Lee et al. (2022) on Ottawa sand F65 with light cementation levels.

The model was calibrated on the untreated results to determine the main model parameters and then the biocementation parameters were estimated from the reported calcite content and change in V_s. The results shown in Figure 1 align well with the experimental ones, accurately simulating the trends and the cycles needed to reach an excess pore water pressure (r_u) value of 0.95, highlighting the model's potential in predicting liquefaction under cyclic loading. Using the same model parameters calibrated on the tests shown in Figure 1, the model was used to simulate tests at all of the cyclic stress ratios used in the experiment to construct the CSR – N curves for the untreated soil and the two selected cementation levels shown in Figure 2. The simulated curves closely match the experimental ones for high CSRs but underestimate the cycles to liquefaction for lower CSRs. Given the inherent variability of cemented soils, however, the results offer a reasonable estimation showcasing the model's potential for evaluating MICP based mitigation techniques.

5 CONCLUSIONS

This study introduces the Hujeux-BC model, tailored for biocemented soils, that integrates biocementation's effects using the calcite mass content and shear wave velocity as input parameters. The model uniquely represents densification and inter-particle bonding independently, giving it the potential to simulate the long-term soil behavior as bonds degrade. When benchmarked, the model effectively mirrored biocemented soils' response under cyclic loading, particularly producing accurate CSR – N curves for biocemented soils at different levels of cementation.

Despite the complexities involved in modelling biocemented soils, this study shows that by using the reference, untreated state of sands as a starting point and incorporating parameters that reflect the densification and bonding effects, the cyclic behavior of biocemented sands can be understood and replicated, and as experimental observations increase, model calibration can be improved leading to a more robust framework.

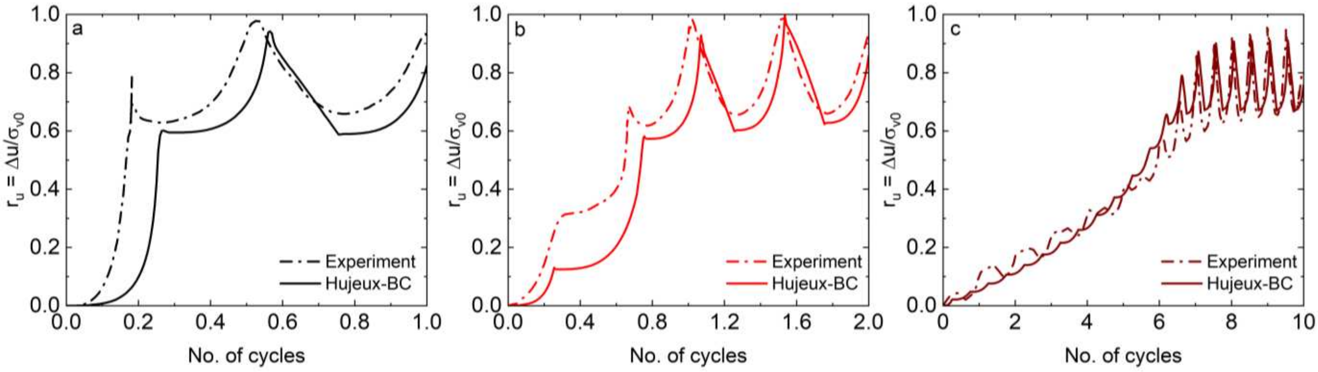

Figure 1. Comparison between experimental and simulations results for an undrained cyclic DSS on MICP-treated sands using Hujeux-BC a) untreated, b) $m_{cc} = 0.14\% - \Delta V_s = 16\ m/s$, c) $m_{cc} = 0.43\% - \Delta V_s = 36\ m/s$ (experimental data from (Lee et al., 2022)).

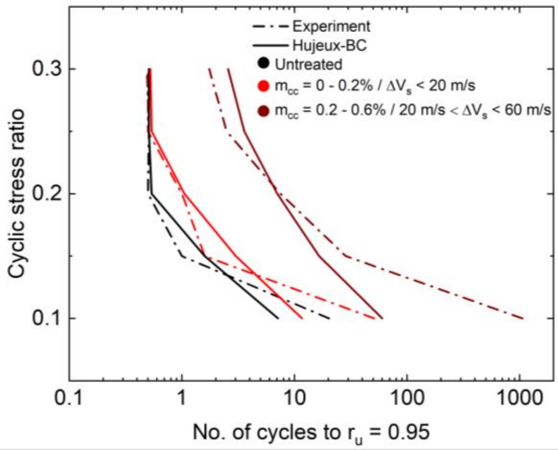

Figure 2. Comparison between simulated and experimental CSR – N curves (experimental data from (Lee et al., 2022))

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