TOWARD SUSTAINABLE LIQUEFACTION MITIGATION: MODELING THE CYCLIC MECHANICAL RESPONSE OF BIOCEMENTED SOILS

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KEYWORDS

Biocementation, Cyclic loading, Liquefaction, Constitutive Model

ABSTRACT

Earthquake-induced liquefaction remains a significant hazard to seismically prone regions. Although traditional mitigation methods, such as compaction, drainage and grouting are effective, they often have significant environmental and economic implications. Biogeotechnical methods, particularly Microbially Induced Calcite Precipitation (MICP), have emerged as a practical and environmentally conscious alternative. Experiments have shown that MICP induced calcite contents as low as 1% can sufficiently increase liquefaction resistance. Yet, there are few attempts to model this behavior, limiting the technique's adoption. This study aims at addressing this gap by introducing Hujeux-BC, a constitutive model for the cyclic behavior of biocemented soils. In this model, the physical mechanisms characterizing biocementation, inter-particle bonding and densification are incorporated independently. The effects of these mechanisms on the mechanical behavior are represented through changes in the material's elastic moduli and relative density as well as the introduction of a bonding parameter. The model performance is evaluated using a cyclic direct simple shear test from the literature that covers a range of cementation levels. The model is able to replicate the soil's behavior at both treated and untreated states using only the calibrated parameters at the untreated state and the biocementation parameters obtained through the measured calcite content and the change in shear wave velocity. Notably, the model is able to estimate the number of loading cycles required to trigger liquefaction reasonably well. This accuracy, combined with the model's straightforward calibration process can pave the way for more tailored liquefaction mitigation techniques using MICP.

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1. INTRODUCTION

In response to the limitation and environmental concern associated with traditional liquefaction mitigation techniques such as compaction, drainage, and grouting, there has been a growing interest in exploring more sustainable, cost-effective, and less intrusive alternatives. Among these, biogeotechnical approaches, particularly Microbially Induced Calcite Precipitation (MICP), have gained attention as promising solutions to enhance soil stability and resistance to liquefaction.

Despite the demonstrated potential of MICP in substantially improving the resistance of soils to liquefaction, as supported by experimental evidence [1], [2], [3], [4], wider application of these techniques is limited by the current lack of models that can accurately describe the cyclic behavior of biocemented soils.

To bridge this gap, this study presents the Hujeux-BC model, a novel cyclic elastoplastic constitutive model for biocemented soils. This model extends the principles of the Hujeux cyclic model [5] by incorporating the influence of biocementation. These adjustments are based on empirical data, including measurements of calcite content and change in shear wave velocity, allowing the model to capture the nuanced effects of biocementation under both monotonic and cyclic loading conditions.

One of the distinguishing features of the Hujeux-BC model is its ability to separately address the mechanical consequences of biocementation, such as densification and inter-particle bonding. This separation is crucial for accurately simulating the degradation of bonds over time, while also considering the lasting effects of densification. Such an approach helps improve our understanding of how biocemented soils respond to repeated cyclic loading over extended periods.

The following sections present the rationale behind the model formulation and the model performance in simulating an undrained cyclic direct simple shear (DSS) test on biocemented soils at varying cementation levels under different cyclic stress ratios (CSR).

2. THE EFFECTS OF BIOCEMENTATION

The model captures the influence of biocementation by examining the underlying physical mechanisms that shape its mechanical response. Key aspects of the mechanical behavior of biocemented soils under monotonic loads, as highlighted by several review articles [6] [7], include enhanced stiffness, increased strength with subsequent softening, and dilatancy. These effects are widely recognized to stem from two principal processes: densification and interparticle bonding [8], [9]. Densification is attributed to calcite accumulation in the pore spaces, a phenomenon readily quantifiable through techniques like acid washing or thermo-gravimetric analysis [10]. In contrast, assessing interparticle bonding is more complex. Although detection is feasible with sophisticated methods such as scanning electron microscopy or X-ray micro-tomography [11], it remains difficult to accurately identify the “active” bonds at a large scale . Alternatively, these bonds are estimated using indirect methods such as the change in shear wave velocity (V_s) [8].

Further, the cyclic behavior of biocemented soils has been explored through various laboratory and scaled model experiments, revealing that even low cementation levels markedly enhance liquefaction resistance [1], [2], [3], [4]. These experiments demonstrate that biocementation's cyclic behavior is similar to its monotonic behavior, suggesting identical underlying physical mechanisms. Specifically, biocementation increases resistance, reduces porewater pressure buildup, increases stiffness, and postpones the onset of liquefaction.

The model translates the densification and bonding effects of biocementation into mathematical terms by incorporating specific parameters that reflect changes in the soil's physical properties. This approach not only preserves the original modeling framework’s essence but also ensures coherence and originality in the presentation of the biocementation process and its implications on soil behavior.

Densification

Densification is mainly governed by the change in the void ratio which in turn induces changes in the soil’s density and influences the state of the soil.

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 of the soil, Sr is the degree of saturation, e is the untreated void ratio, $m_{cc} = \frac{m_c}{m_s}$ is the calcite mass 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 and e^* is the void ratio after biocementation

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 velocity before and after calcite precipitation.

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

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

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

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

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 [12].

3. MODEL FORMULATION

The model presented in this study is based on the work of Hujeux (1985) where the detailed equations are described. The following presents the changes due to biocementation.

The change in the elastic behavior due to biocementation is expressed through the elastic cementation factor CF_E which is a combination of the densification and bonding elastic parameters described in the previous section as:

$$CF_E = \xi_{den} \cdot \xi_{bon} \tag{6}$$

The elastic moduli are then expressed as:

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

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 the elastic exponent.

The change in the yield surface to account for the increased strength of biocemented soils is expressed using the mean pressure at the critical state p'_{cs} which evolves to:

$$p'^{*}_{cs} = CF_S \cdot p'_{cs} \tag{8}$$

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

4. MODEL PERFROMANCE

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 [4]. The tests were conducted under a confining pressure of $100\ kPa$ at 5 different cyclic stress ratios $\left(CSR = {}^{\tau_{max}}/_{\sigma_{v_0}}\right)$, $0.1, 0.15, 0.2, 0.25, 0.3$. All of the samples in the test were very lightly cemented with calcite contents below 1 %.

The model parameters were calibrated on the untreated results with the biocementation parameters estimated using the reported calcite content and change in shear wave velocity [4]. The results shown in Figure 1 show the experimentally obtained and model predicted evolution of the excess pore water at a CSR of 0.2. There is a clear alignment between the experimental and model results demonstrating the model's ability to capture the trends during the test as well as the number of cycles needed to reach an r_u value of 0.95. These results highlight the model's potential in predicting liquefaction under cyclic loading.

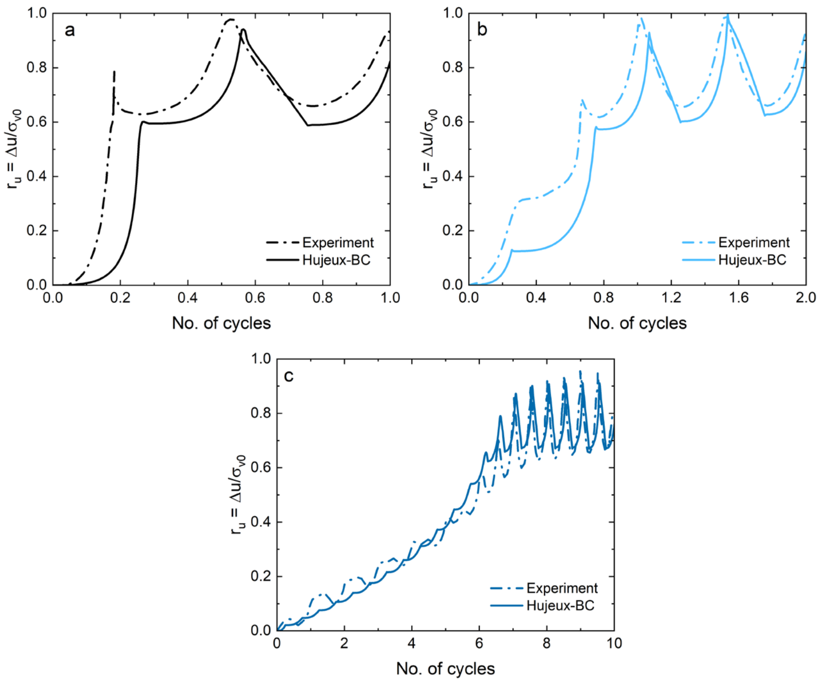

Figure 1. Comparison between experimental and simulations results for an undrained cyclic DSS on MICP-treated sands using Hujeux-BC a) untreated, b) $m_{cc} = 0.14\% - \Delta V_s = 16\ m/s$*, c)* $m_{cc} = 0.43\% - \Delta V_s = 36\ m/s$ *(experimental data from Lee et al (2022) [4])*

Using the same model parameters calibrated on the tests shown in Figure 1, the model was used to estimate the number of cycles required to reach an excess porewater pressure of 0.95 for all of the CSR values. The CSR – N curves shown in Figure 2 show the experimental and model results for the untreated state as well as at two cementation levels. The model predicted curves closely match the experimental ones for high CSR values but start to deviate at lower CSR values. The mean absolute percentage error was calculated at 36% for all of three curves. This slightly large error is mainly due to the large differences predicted at the CSR of 0.1, focusing on the high CSR values, where liquefaction is more likely to occur, the calculated error for the three curves is around 14%. Given the inherent variability of cemented soils, the results offer a reasonable estimation showcasing the model's potential for evaluating MICP based mitigation techniques.

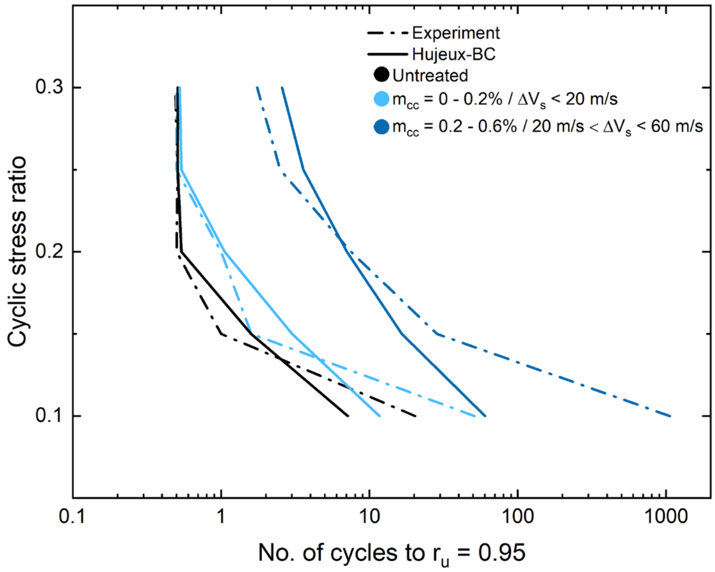

Figure 2. Comparison between simulated and experimental CSR – N curves (experimental data from Lee et al (2022) [4])

5. CONCLUSIONS

This study introduces the Hujeux-BC model, specifically designed for the analysis of biocemented soils, by incorporating the impacts of biocementation through the calcite content and change in shear wave velocity. The model uniquely represents densification and inter-particle bonding independently, giving it the potential to simulate the long-term soil behavior as bonds degrade. The model accurately reflected the behavior of biocemented soils under cyclic loading, successfully generating accurate CSR – N curves for soils with varying cementation levels.

Despite the inherent challenges in modeling biocemented soils, this study successfully demonstrates that beginning with the untreated, natural state of sands and including factors for densification and bonding impacts allows for an accurate representation of their cyclic behavior. Additionally, as experimental data becomes more available, model calibration can be improved leading to a more robust framework.

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REFERENCES

[1] B. m. Montoya, J. t. Dejong, and R. w. Boulanger, "Dynamic response of liquefiable sand improved by microbial-induced calcite precipitation," *Géotechnique*, vol. 63, no. 4, pp. 302–312, Mar. 2013, doi: 10.1680/geot.SIP13.P.019.

[2] T. Sasaki and R. Kuwano, "Undrained cyclic triaxial testing on sand with non-plastic fines content cemented with microbially induced CaCO3," *Soils and Foundations*, vol. 56, no. 3, pp. 485–495, Jun. 2016, doi: 10.1016/j.sandf.2016.04.014.

[3] A. Zamani, P. Xiao, J. T. DeJong, R. W. Boulanger, D. W. Wilson, and T. J. Carey, "MICP Treatment to Mitigate Soil Liquefaction-Induced Building Settlements," *IFCEE 2021*, pp. 308–317, May 2021, doi: 10.1061/9780784483411.030.

[4] M. Lee, M. G. Gomez, M. El Kortbawi, and K. Ziotopoulou, "Effect of Light Biocementation on the Liquefaction Triggering and Post-Triggering Behavior of Loose Sands," *J. Geotech. Geoenviron. Eng.*, vol. 148, no. 1, p. 04021170, Jan. 2022, doi: 10.1061/(ASCE)GT.1943-5606.0002707.

[5] J.-C. Hujeux, "Une loi de comportement pour le chargement cyclique," in *Genie Parasismique*, Paris: Presse de l'ENPC, 1985, pp. 287–302.

[6] D. Terzis and L. Laloui, "A decade of progress and turning points in the understanding of bio-improved soils: A review," *Geomechanics for Energy and the Environment*, vol. 19, p. 100116, Sep. 2019, doi: 10.1016/j.gete.2019.03.001.

[7] T. Fu, A. C. Saracho, and S. K. Haigh, "Microbially induced carbonate precipitation (MICP) for soil strengthening: A comprehensive review," *Biogeotechnics*, p. 100002, Mar. 2023, doi: 10.1016/j.bgtech.2023.100002.

[8] A. Nafisi and B. M. Montoya, "A New Framework for Identifying Cementation Level of MICP-Treated Sands," *IFCEE 2018*, pp. 37–47, Jun. 2018, doi: 10.1061/9780784481592.005.

[9] R. Harran, D. Terzis, and L. Laloui, "Mechanics, Modeling, and Upscaling of Biocemented Soils: A Review of Breakthroughs and Challenges," *International Journal of Geomechanics*, vol. 23, no. 9, p. 03123004, Sep. 2023, doi: 10.1061/IJGNAI.GMENG-8446.

[10] S.-G. Choi, S.-S. Park, S. Wu, and J. Chu, "Methods for Calcium Carbonate Content Measurement of Biocemented Soils," *J. Mater. Civ. Eng.*, vol. 29, no. 11, p. 06017015, Nov. 2017, doi: 10.1061/(ASCE)MT.1943-5533.0002064.

[11] D. Terzis and L. Laloui, "3-D micro-architecture and mechanical response of soil cemented via microbial-induced calcite precipitation," *Sci Rep*, vol. 8, no. 1, Art. no. 1, Jan. 2018, doi: 10.1038/s41598-018-19895-w.

[12] A. Koliji, L. Laloui, and L. Vulliet, "Constitutive modeling of unsaturated aggregated soils," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 34, no. 17, pp. 1846–1876, 2010, doi: 10.1002/nag.888.