

Evaluating injection strategies for a field trial of Microbially Induced Desaturation and Precipitation (MIDP)

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ABSTRACT

A numerical model has been developed to design field trials of microbially induced desaturation and precipitation (MIDP). MIDP offers the potential for a minimally disruptive approach to mitigation of earthquake-induced liquefaction triggering that can be economically applied beneath existing structures over a range of potentially liquefiable soils. The process involves stimulating indigenous nitrate-reducing bacteria to produce nitrogen gas and calcium carbonate mineral precipitates. Numerous studies have illustrated the impact of biogenic gas and biomineral precipitation on the mechanical behavior of treated sand samples in laboratory-scale experiments. However, a key factor in field applications is the spatial distribution of the biogas and carbonate mineral reaction products, which is related to substrate distribution. Substrate distribution, in turn, is related to soil permeability and injection strategies such as the injection well configuration and flow rate. The numerical model developed in this study integrates fluid flow with reactive processes and allows for the prediction of substrate and product distribution and associated changes in soil properties, including porosity, permeability, and degree of saturation, resulting from MIDP treatment. Simulation results of MIDP treatment under various scenarios offer insights into the potential outcomes of proposed field trial designs and allow for optimization of injection strategies.

INTRODUCTION

Microbially induced desaturation and precipitation (MIDP) is an emerging bio-mediated soil improvement technique proposed as an energy-efficient, non-disruptive, and cost-effective method to mitigate liquefaction underneath existing structures. (Kavazanjian et al. 2015; Kwon et al. 2024b; a; O'Donnell et al. 2017) Desaturation resulting from biogenic gas formation can substantially influence soils' hydro-mechanical behavior. Even a small proportion of gas can decrease the bulk stiffness of pore fluids and mitigate pore pressure accumulation during both monotonic and cyclic undrained loading. (Rebata-Landa and Santamarina 2012; Wang et al. 2021).

The performance of MIDP to improve soil has been demonstrated in small-scale laboratory column tests (O'Donnell et al. 2017; Pham 2017), large-scale laboratory tank tests (Stallings Young et al. 2020), and field-scale tests (Moug et al. 2022; Zeng et al. 2022). Numerical reactive transport models have been developed to predict the performance of MIDP treatment and estimate the quantity and distribution of generated gas and biomaterials (Hall et al. 2023; Kwon et al. 2023, 2024b; O'Donnell et al. 2019; Wang et al. 2023). These models can be used to refine treatment protocols for field application (Kwon et al. 2023).

The reactive transport model for MIDP presented herein is implemented using the finite element program COMSOL Multiphysics version 5.5. The model couples fluid transportation with the reaction equations to predict the distribution of substrates, their reacted byproducts, and their effect on the degree of saturation. The model is used to evaluate and optimize design procedures to obtain well-distributed substrates for field applications.

NUMERICAL MODEL DESCRIPTION

The COMSOL Multiphysics® (version 5.5) numerical model couples fluid flow and transport of solute species with a simplified biochemical reaction to predict changes in substrate concentration, porosity, degree of saturation, and permeability in the soil.

Fluid flow was calculated using 'Darcy's law' flow module, which solves the equation:

$$u = -k\nabla H \quad (1)$$

In which u is Darcy flow velocity [m s^{-1}], k is the hydraulic conductivity [m s^{-1}] and H is the hydraulic head [m]. Fluid density is assumed to be constant and effects of gravity and buoyancy-driven flow are neglected.

The reactive transport was simulated using the module 'Transport of diluted species in porous media', which solves the following equation:

$$\theta \frac{\partial C_i}{\partial t} - \nabla(\theta D \nabla C_i) + u \cdot \nabla C_i = \theta r_i \quad (2)$$

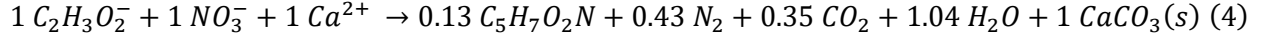
Where C_i = solute concentration of species i [mol m^{-3}], D is diffusion coefficient [$\text{m}^2 \text{s}^{-1}$], r_i = reaction rate for species i [$\text{mol m}^{-3} \text{s}^{-1}$], and θ is the porosity of soil matrix. These equations are explained in more detail by Zeng et al. (2021), who developed a reactive transport model for a field trial using MICP.

The reaction rate was calculated using:

$$r_i = r_0 \times X_{\text{ta}} \times \frac{C_{\text{Ac}}}{C_{\text{Ac}} + K_{\text{m,Ac}}} \times \frac{C_{\text{NO}_3}}{C_{\text{NO}_3} + K_{\text{m,NO}_3}} \times Y_i \quad (3)$$

Where r_0 is a rate constant [d^{-1}], X_{ta} is the concentration of total active biomass [mmol-X L^{-1}], C_{Ac} and C_{NO_3} are the concentration of acetate and nitrate [mmol L^{-1}], $K_{\text{m,Ac}}$ and $K_{\text{m,NO}_3}$ are half-saturation rate constant of acetate and nitrate [mmol L^{-1}], and Y_i is the yield coefficient for each

component as shown in the reaction equation. The simplified reaction equation adopted in this study, similar to the one used in Wang et al. (2023), is given as:



This reaction equation is derived based on the stoichiometry framework suggested by Rittman and McCarty (2020) and adjusted based on the assumption of equal consumption of nitrate and acetate, as explained by Kwon et al. (2024a) and observed by Pham et al. (2018). Additionally, it is assumed that all the inorganic carbon produced in the metabolic reaction will either end up as carbon dioxide or as calcium carbonate, maintaining charge balance during the reaction, considering that due to the low solubility of calcium carbonate, the concentration of dissolved inorganic carbon in presence of high calcium concentrations is relatively small and all soluble calcium ions will eventually precipitate. This assumption aligns with previous studies on other bio-mediated ground improvement methods such as Microbially Induced Calcium Precipitation (MICP), where the precipitation rate is considered equal to the reaction rate (van Wijngaarden et al., 2011; van Paassen, 2009).

The degree of saturation S_w is calculated from the produced N_2 and CO_2 based on the assumptions described by Kwon et al. (2023), using Henry's law to calculate the ratio between dissolved and gaseous N_2 and CO_2 and the ideal gas law to convert the moles of gas to volume of gas. The gas pressure used in both equations is the sum of water and capillary pressure. The capillary pressure is calculated from bubble radius and surface tension using the Young-Laplace equation.

Porosity θ is calculated following Wang et al (2023):

$$\frac{\partial \theta}{\partial t} = -\frac{\partial C_{CaCO_3}}{\partial t} \times \frac{M_{CaCO_3}}{\rho_{CaCO_3}} - \frac{\partial X_{total\ biomass}}{\partial t} \times \frac{M_{biomass}}{\rho_{biomass}} \quad (5)$$

Where M_{CaCO_3} and $M_{biomass}$, are the molar weights of calcium carbonate and biomass which are 100 [g mol⁻¹] and 24.6 [g mol⁻¹], respectively. ρ_{CaCO_3} and $\rho_{biomass}$ are the density of calcium carbonate and biomass which are 2,710 and 100 [kg m⁻³], respectively. (Wang et al. 2023)

Changes in porosity and degree of saturation affect the hydraulic conductivity. The change in hydraulic conductivity is calculated using a power law equation proposed by Verma and Pruess (1988) and used by Wang et al. (2023):

$$k_r = \frac{k_s}{k_0} = \left(\frac{\theta_s - \theta_{cr}}{\theta_0 - \theta_{cr}} \right)^\eta \quad (6)$$

Where k_r is the relative change in hydraulic conductivity, k_s , and k_0 are the current and initial hydraulic conductivity while θ_s , θ_0 , and θ_{cr} are the current, initial, and critical porosity at which permeability terminates is assumed to be 0 (zero) for this study. η is a fitting constant derived from experimental data. For MIDP treatment, Wang et al. (2023) suggested η ranged between 18 and 320, while Kim (2019) suggested a factor of 20.2 showed a high correlation with the experimental data from experiments using a microfluid chip. For larger-scale two-dimensional tank experiments,

the parameter η was found to be 25 by Kwon et al. (2024) and was the value used in the numerical model described herein.

BOUNDARY CONDITIONS AND INPUT PARAMETERS

Boundary conditions and input parameters were chosen to represent a proposed field trial investigating the application of MIDP. This field trial is planned on a square domain measuring 20 meters by 20 meters. The targeted layer is about 8 m thick and consists mainly of sand. A total of 13 wells evenly distributed within a 15 x 15 m plot will be installed in one of two configurations: either a triangular grid with a well distance of about 4.3 m or a rectangular grid with a well distance of about 3.5 m, as depicted in Figure 1. Figure 1 presents a bird's-eye view of the site. The outer boundary of the domain is defined as an open boundary, allowing solutions to pass through.

The wells will be operated using a closed water balance similar to that reported by Zeng et al (2022), wherein a relatively small volume of a concentrated substrate solution is mixed in line with extracted groundwater to reach a target concentration of 50 mol L⁻¹ and then is injected back into the ground. To maximize the flow rate while limiting the increase in pressure at the injection wells and the drawdown of the water table at the extraction wells, the number of injection wells and extraction wells will be balanced, resulting in a total of 7 injection wells and 6 extraction wells. The wells are placed so that the flow rate can be periodically reversed to optimize the distribution of nutrients.

The input parameters for the numerical model that are used in the simulations are summarized in Table 1. The reaction rate constant and initial biomass concentration were adopted from a previous study (Kwon et al. 2024). To balance the cumulative injection and extraction flow rate, the flow rate for each injection well was 1 m³ hr⁻¹, while the extraction flow rate was 1.17 m³ hr⁻¹. The injection and extraction wells were switched to test the effect of reversing the flow direction, and the flow rates were adjusted accordingly. In the numerical simulation, the total injection phase was approximately 105 hours for both the original and switched well configurations. This simulation aimed to evaluate the impact of switching the well functions on the overall flow dynamics.

The target desaturation level to mitigate earthquake-induced liquefaction ranges from 10% to 20% (Hall et al. 2022; O'Donnell et al. 2017); At field site, the targeted treatment volume is 15 x 15 x 10 meters with a target saturation of 80%. Approximately one pore volume of substrate solution with a concentration of 50 mmol L⁻¹ is required to achieve this goal (van Paassen et al. 2017) It was assumed that the flow velocity was constant along the depth of the targeted layer and that all biogas, biomass, and biominerals remained at the position where they were formed.

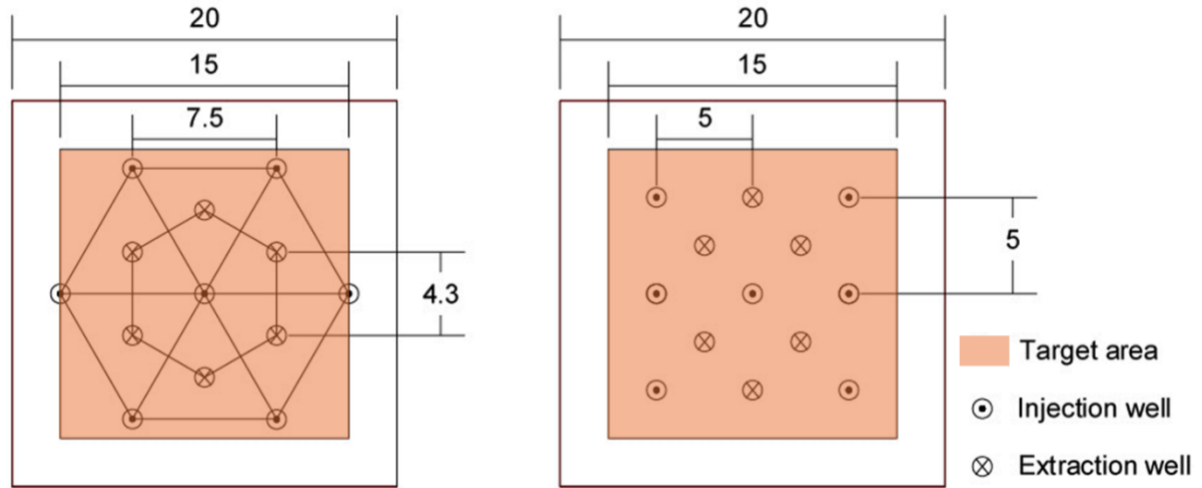


Figure 1. Well configuration based on the triangular pattern and rectangular pattern

Table 1. Input parameters for numerical analysis.

Parameter	Value	Description
Q_{in} (m ³ hr ⁻¹)	1,1.17	Injection flow rate per well
Q_{out} (m ³ hr ⁻¹)	1,1.17	Extraction flow rate per well
H_w (m)	10	Height of the injection well
R_w (m)	0.15	Radius of the well
K_m (mmol L ⁻¹)	0.01	Half-saturation constant of nitrate and acetate
r_0 (h ⁻¹)	0.1	Reaction rate constant
C_{s_0} (mmol L ⁻¹)	50	Initial substrate concentration (Acetate, Nitrate, Calcium)
C_{x_i} (mmol L ⁻¹)	1	Initial denitrifying biomass concentration in the subsurface
K_{target} (m s ⁻¹)	4.0×10^{-4}	Initial hydraulic conductivity of the target layer
d_{50} (mm)	0.27	Assumed mean particle radius of soil
ε_p	0.4	Initial porosity of the soil

RESULTS

Comparison of well configuration

To achieve an 80% target saturation within the 15 x 15-meter area, approximately 105 hours of injection are necessary when employing seven injection wells at a constant flow rate of $1 \text{ m}^3 \text{ hr}^{-1}$. Figure 2 presents the nitrate distribution resulting from triangular and rectangular well configurations at 105 hours. The spatial distribution of injected nitrate appears to correlate with the distribution of generated byproducts, including biogas (N_2 and CO_2), biomass, and biominerals. As shown in Figure 2, the triangular pattern (Figure 2a) showed a relatively uniform distribution among the wells, but limited substrates in the corners where no extraction wells were present. In contrast, the rectangular pattern shows more substrates in the system around the four extraction wells in the middle, with limited substrates near the extraction wells at the top and bottom of the plot (along the middle column of wells). Area analysis revealed that the triangular pattern treated 59% of the target area within 105 hours, while the rectangular pattern achieved a broader treatment of 78% during the same timeframe. By reversing the injection and extraction wells, the gap in treatment at the top and bottom of the middle column of wells can be filled in.

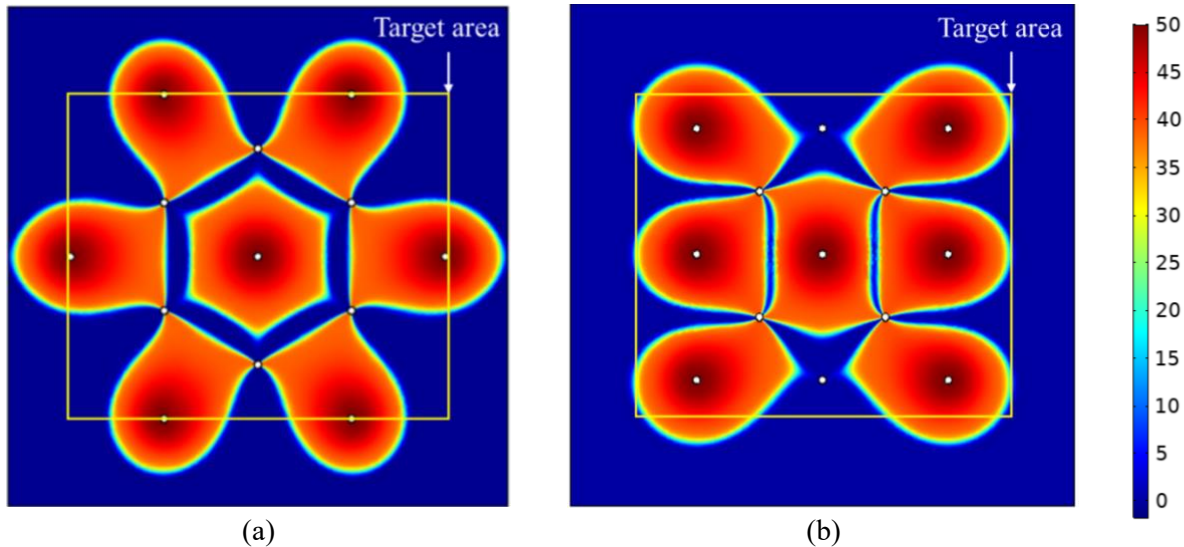


Figure 2. Simulation result of nitrate distribution based on (a) triangular pattern and (b) rectangular pattern at 105 hours of injection

Figure 3 presents the average nitrate breakthrough curves for both rectangular and triangular patterns, as well as the breakthrough curves at different outlet locations within the rectangular pattern. The rectangular pattern exhibited early breakthrough of nitrate from the middle four extraction wells. For the triangular pattern, the nitrate breakthrough was the same for all extraction wells and occurred later than for the rectangular pattern. These results align with the observations on the distribution patterns shown in Figure 2. They can be explained by the distance between the injection and extraction wells, which is about 3.5 m for the middle four outlets in the rectangular

grid, 5 m for the top and bottom outlets in the rectangular grid, and 4.3 m for the outlets in the triangular grid, leading to non-uniform substrate distribution within the targeted area.

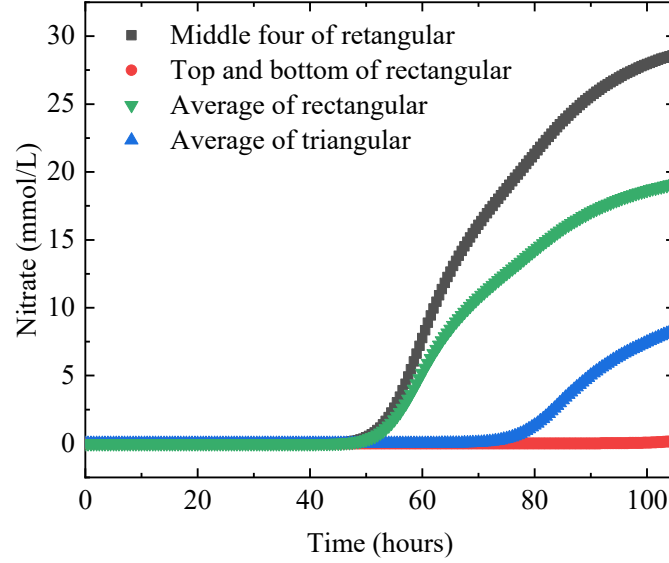


Figure 3. Breakthrough curves of nitrate depending on the outlet location

Effect of well conversion

As depicted in Figure 4, reversing the flow direction results in different substrate distribution patterns and a different coverage area compared to the results shown in Figure 2. The triangular pattern covered 84% of the target area, while the rectangular pattern covered 70%.

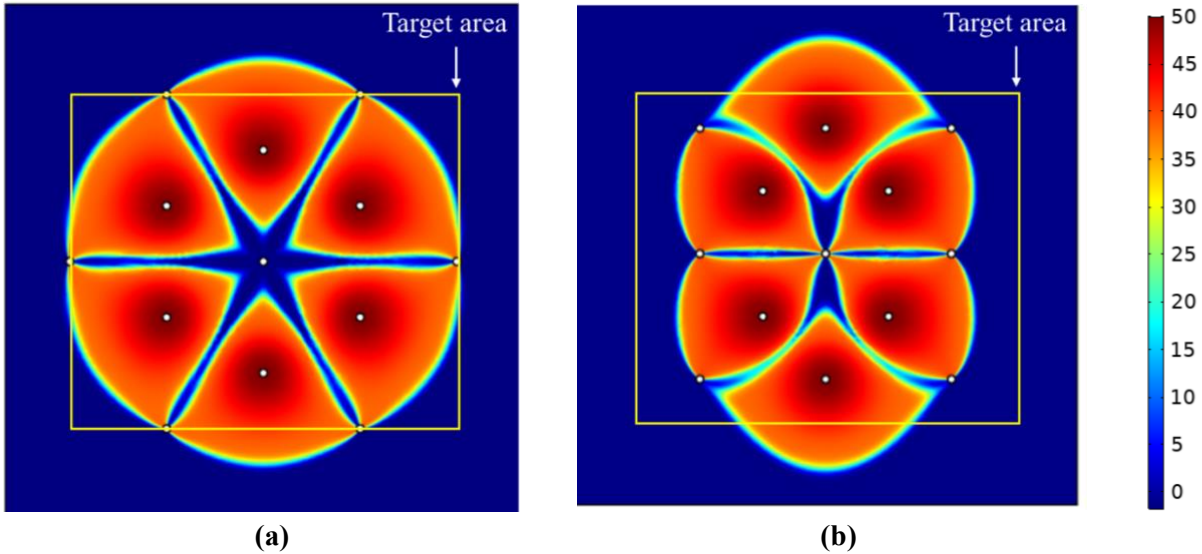


Figure 4. Simulation result of nitrate distribution with converted wells at 105 hours of injection (a) triangular pattern (b) rectangular pattern

Combining the results from Figure 2 and Figure 4 in Figure 5 shows that allowing for reversing flow direction improves the effectiveness of treatment. The substrate distribution is different based on the well configuration, however, both well configurations showed coverage of approximately 95% of the target area.

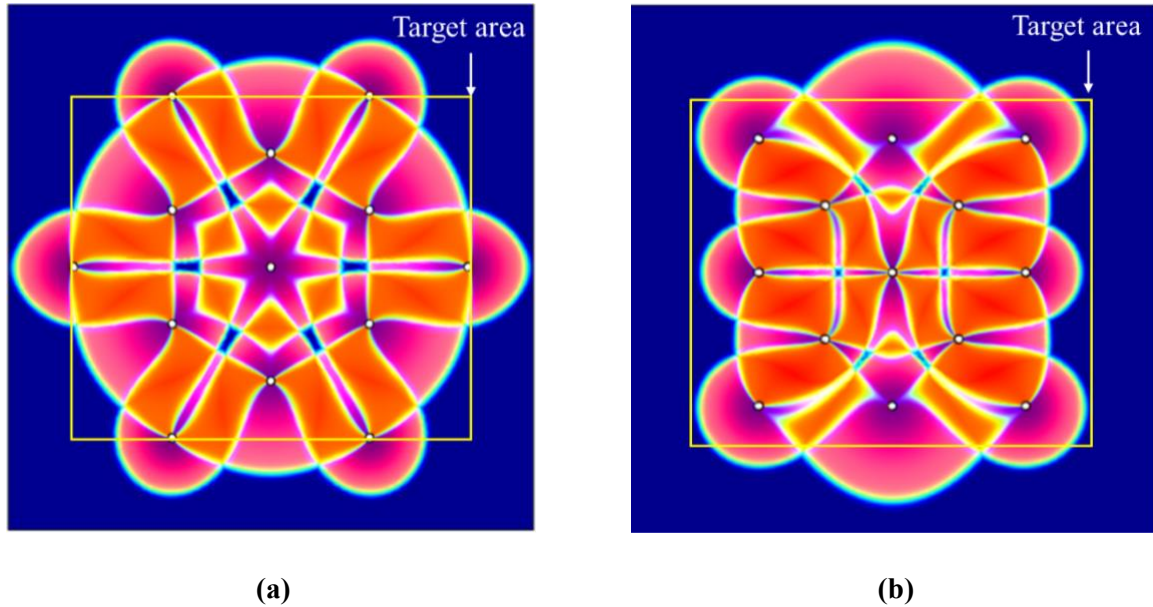


Figure 5. Combined distribution of nitrate based on the combined simulation result from Figures 2 and 4 (a) triangular pattern (b) rectangular pattern

DISCUSSION

The results shown in Figures 2 to 5 are based upon idealizations of the actual field conditions and depend on the selected boundary conditions, soil properties, and flow parameters. For example, a higher flow rate, closer well distance, or thinner targeted layer will reduce the breakthrough time. The flow rate is typically limited by the maximum allowable injection pressure to prevent a blowout, which in turn is a function of the soil permeability (Kwon et al, 2023). The initial reaction rate determines at what rate substrates are consumed during and after transport. The reaction rate will gradually increase as the amount of biomass increases. If the flow rate is too low all substrates will be consumed before they reach the outlet. The production of biomass, biogas, or biominerals will reduce porosity, permeability, and hydraulic residence time (at a constant flow rate), increasing the injection pressure and reducing the hydraulic residence time. Heterogeneity along the depth of the treated layer or hydraulic fracturing near the injection well may result in some preferential flow paths causing heterogeneity in the distribution of substrates. For optimal performance, a balance between the flow rate and the reaction rate is required to allow for the substrates to be well distributed throughout the target layer. In case of heterogeneity along the depth of the treated layer, higher flow rates could be used to allow more substrate solutions to flow through zones with lower permeability. Changing the well configuration would affect the substrate distribution patterns.

Finally, the model did not account for gas migration which could significantly influence the accuracy of Microbially Induced Desaturation and Precipitation (MIDP) treatment predictions. Future research should incorporate gas migration modeling to enhance the predictive capabilities of this approach.

CONCLUSION

Simulations using a numerical model that was developed to evaluate injection strategies for a field trial of Microbially Induced Desaturation and Precipitation (MIDP) clearly demonstrate that the distribution of substrates (and their resulting products, though not shown in this paper) is affected by the well configuration, well distance, flow rate, and reaction rate. The well configuration should aim for a constant distance between injection and extraction wells to obtain a homogeneous distribution of substrates. The strategy of alternating the flow direction clearly results in a more uniform substrate distribution in both triangular and rectangular patterns.

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REFERENCES

- Hall, C. A., L. A. van Paassen, S. Kamalzare, D. Parmantier, and E. Kavazanjian. 2022. “Techno-Economic Assessment of Liquefaction Mitigation by Microbially Induced Desaturation.” *Lifelines* 2022, 91–100.
- Kavazanjian, E., S. T. O’Donnell, and N. Hamdan. 2015. “Biogeotechnical Mitigation of Earthquake-Induced Soil Liquefaction by Denitrification: A Two-Stage Process.” *In Proceedings of 6th International Conference on Earthquake Geotechnical Engineering*, 20–28.
- Kim, D. 2019. “Pore-scale Study of Bio-mineral and Bio-gas Formations in Porous Media.” 15 (2): 1–23.
- Kwon, P., D. Karmacharya, E. Kavazanjian, C. E. Zapata, and L. A. van Paassen. 2024a. “Microbial-induced desaturation and precipitation in stratified soils with fine sand and silt layers.” *Acta Geotech.* <https://doi.org/10.1007/s11440-024-02324-w>.
- Kwon, P., D. Karmacharya, and L. A. Van Paassen. 2023. “Reactive Transport Model to Evaluate Process Performance of Bio-Mediated Liquefaction Mitigation underneath Existing Structures.” *Geo-Congress 2023*, 80–88.
- Kwon, P., D. Karmacharya, L. A. Van Paassen, and E. Kavazanjian. 2024b. “Numerical Analysis of Two-Dimensional Tank Experiment of Microbially Induced Desaturation (MID) in Layered Silts and Sands.” *Geo-Congress 2024*, 254–263.

- Moug, D. M., K. R. Sorenson, A. Khosravifar, M. Preciado, E. Stallings Young, L. van Paassen, E. Kavazanjian, B. Zhang, K. H. Stokoe, F. M. Menq, and Y. Wang. 2022. "Field Trials of Microbially Induced Desaturation in Low-Plasticity Silt." *Journal of Geotechnical and Geoenvironmental Engineering*, 148 (11). American Society of Civil Engineers (ASCE). [https://doi.org/10.1061/\(asce\)gt.1943-5606.0002890](https://doi.org/10.1061/(asce)gt.1943-5606.0002890).
- O'Donnell, S. T., B. E. Rittmann, and E. Kavazanjian. 2017. "MIDP: Liquefaction Mitigation via Microbial Denitrification as a Two-Stage Process. I: Desaturation." *Journal of Geotechnical and Geoenvironmental Engineering*, 143 (12): 04017094. [https://doi.org/10.1061/\(asce\)gt.1943-5606.0001818](https://doi.org/10.1061/(asce)gt.1943-5606.0001818).
- van Paassen, L. A., V. Pham, N. Mahabadi, C. Hall, E. Stallings, and E. Kavazanjian. 2017. "Desaturation via Biogenic Gas Formation as a Ground Improvement Technique." *PanAm unsaturated soils 2017*, 244–256.
- Pham. 2017. "Bio-based ground improvement through Microbial Induced Desaturation and Precipitation (MIDP)." Delft University of Technology.
- Pham, V. P., L. A. van Paassen, W. R. L. van der Star, and T. J. Heimovaara. 2018. "Evaluating Strategies to Improve Process Efficiency of Denitrification-Based MICP." *Journal of Geotechnical and Geoenvironmental Engineering*, 144 (8). American Society of Civil Engineers (ASCE). [https://doi.org/10.1061/\(asce\)gt.1943-5606.0001909](https://doi.org/10.1061/(asce)gt.1943-5606.0001909).
- Rebata-Landa, V., and J. C. Santamarina. 2012. "Mechanical Effects of Biogenic Nitrogen Gas Bubbles in Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 138 (2): 128–137. American Society of Civil Engineers (ASCE). [https://doi.org/10.1061/\(asce\)gt.1943-5606.0000571](https://doi.org/10.1061/(asce)gt.1943-5606.0000571).
- Rittman, B., and P. McCarty. 2020. *Environmental Biotechnology: Principles and Applications*,. McGraw-Hill Companies.
- Stallings Young, E. G., C. E. Zapata, and L. Van Paassen. 2020. "Unsaturated fluid flow through granular soils treated with microbial induced desaturation and precipitation." *E3S Web of Conferences*, 195. <https://doi.org/10.1051/e3sconf/202019505003>.
- Verma, A., and K. Pruess. 1988. "Thermohydrological conditions and silica redistribution near high-level nuclear wastes emplaced in saturated geological formations." *J Geophys Res Solid Earth*, 93 (B2): 1159–1173.
- Wang, K., J. Chu, S. Wu, and J. He. 2021. "Stress-strain behaviour of bio-desaturated sand under undrained monotonic and cyclic loading." *Geotechnique*, 71 (6): 521–533. ICE Publishing. <https://doi.org/10.1680/jgeot.19.P.080>.
- Wang, L., L. van Paassen, V. Pham, N. Mahabadi, J. He, and Y. Gao. 2023. "A (Simplified) Biogeochemical Numerical Model to Predict Saturation, Porosity and Permeability During Microbially Induced Desaturation and Precipitation." *Water Resour Res*, 59 (1). John Wiley and Sons Inc. <https://doi.org/10.1029/2022WR032907>.
- Zeng, C., L. A. Van Paassen, J. jie Zheng, E. G. Stallings Young, C. A. Hall, Y. Veenis, W. R. L. Van der Star, M. Konstantinou, and E. Kavazanjian. 2022. "Soil stabilization with microbially induced

desaturation and precipitation (MIDP) by denitrification: a field study.” *Acta Geotech*, 17 (12): 5359–5374. Springer Science and Business Media Deutschland GmbH.
<https://doi.org/10.1007/s11440-022-01721-3>.