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Biogeotechnical Mitigation of Earthquake-Induced Soil Liquefaction by Denitrification: A Two-Stage Process

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ABSTRACT

Dissimilatory reduction of nitrate by denitrifying bacteria, or denitrification, shows promise as a two-stage process for mitigating the potential for earthquake-induced soil liquefaction. This biogeotechnical technique may be particularly useful in and around existing facilities due to its non-disruptive and minimally intrusive nature. In Stage 1, mitigation of liquefaction potential is provided by desaturation of the soil due to the generation of biogas (biogenic nitrogen and carbon dioxide). In Stage 2, denitrification induces the precipitation of sufficient amounts of calcium carbonate at particle contacts and in the voids to mitigate liquefaction through increased shear strength and dilatancy. Bench scale column tests with geophysical (p-wave and s-wave) measurements and triaxial and cyclic simple shear tests demonstrate the feasibility of both of these mechanisms. The p-wave measurements show that biogas-induced desaturation commences immediately upon the start of denitrification. The s-wave measurements provide a means of monitoring the improvement in the small strain stiffness of the soil due to carbonate precipitation over time. The triaxial tests show increases in shear strength and dilatancy due to carbonate precipitation. The cyclic simple shear tests show the ability of both desaturation and carbonate precipitation to increase the resistance of the soil to cyclic loading.

Introduction

Earthquake-induced liquefaction can cause significant damage to structures built on or in saturated, cohesionless soil deposits. Liquefaction damage from the M 6.3 Christchurch earthquake of February, 2011 resulted in the abandonment of over 7,000 single family residences with a total value of nearly $3 billion (NZD) (CERA 2013). Available methods to mitigate liquefaction potential beneath or adjacent to existing structures are, in general, either disruptive or prohibitively expensive. Biogeotechnical soil improvement techniques offer the potential for non-disruptive, cost-effective remediation of liquefiable soils (DeJong et al. 2011). Specifically, microbially induced carbonate precipitation (MICP) shows the potential to non-disruptively increase liquefaction resistance (Montoya et al. 2013). MICP occurs when microorganisms alter the geochemistry of the pore water to induce calcium carbonate ($CaCO_3$) precipitation. The most common MICP process used in geotechnical research is microbially-facilitated hydrolysis of urea (ureolysis). Significant improvement in soil shear strength and shear wave velocity, V_s, by MICP via ureolysis has been demonstrated by Whiffin et al. (2007), DeJong et al. (2014), and others in the laboratory and by van Paassen et al. (2010a) in a large scale pilot test.

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Another microbial process, dissimilatory reduction of nitrate (NO_3^-), or denitrification, can also induce $CaCO_3$ precipitation (Karatas et al. 2008). Denitrification is a slower process than ureolysis, so it takes more time to induce significant changes in the mechanical properties of soil (van Paassen et al. 2010b). But, unlike ureolysis (which produces ammonia and ammonium as byproducts), denitrification does not produce toxic byproducts that need to be removed or otherwise managed. Nitrogen and carbon dioxide gas ($N_{2(g)}$ and $CO_{2(g)}$), the non-toxic byproducts of denitrification, can induce significant desaturation in the soil. He et al. (2013) demonstrated that denitrification produces enough biogas within a matter of days to significantly reduce the static liquefaction potential of soil. Okamura and Soga (2006) and Yegian et al. (2007), among others, have demonstrated that desaturation leads to increased liquefaction resistance. Therefore, denitrification has potential as a two stage process for liquefaction mitigation in which desaturation via biogas production provides short term mitigation and MICP via denitrification provides long term mitigation. In this study, bench scale columns and triaxial and cyclic simple shear tests were used to demonstrate the potential use of denitrification as a two stage process for liquefaction mitigation.

Abiotic Experiments

Cyclic Simple Shear Testing

To demonstrate the impact of desaturation on liquefaction potential, Ottawa 20-30 crystal silica sand was tested in cyclic simple shear at relative densities (D_r) of 45% and 75% and degrees of saturation (S) of 100%, 99%, and 97%. Specimens 40 mm-tall were air pluviated into a latex membrane-lined stack of 100 mm-diameter stainless steel rings and purged with CO_2 for ten minutes. The specimens were then permeated with roughly two pore volumes of de-aired water. An effective confining stress of 50 kPa was applied and the specimens were backpressure saturated ($S = 100\%$, $B > 0.95$). Once saturated, an effective vertical pressure of 100 kPa was applied and the specimens were allowed to consolidate for 30 minutes. For the tests at $S < 100\%$, the saturated specimens were allowed to equilibrate for 30 minutes with a standpipe containing a predetermined volume of air to bring the soil-standpipe system to the desired degree of saturation. Cyclic stress controlled tests at a frequency of 1 Hz were then performed at varying cyclic stress ratios (CSRs) to develop cyclic strength curves for each of the target S values. Liquefaction was defined in these tests as the point where the pore pressure ratio (r_u) was equal to 1.0 and cyclic strains rapidly increased. The results of the abiotic cyclic simple shear tests are presented in Figure 1. As seen in Figure 1, the specimens at $S = 97\%$ show a minimum increase of 40% in cyclic strength (i.e. liquefaction resistance) compared to saturated specimens.

Simple Shear Tests for Correlating P-Wave Velocity and Degree of Saturation

Simple shear specimens were prepared at $D_r = 45\%$ using specialized pedestal and top caps containing bender elements capable of measuring both compression wave (P- wave) and S-wave velocity. Specimens were prepared at five different degrees of saturation: 100%, 97.5%, 90%, 60% and 0%. The $S=100\%$ specimen was backpressure saturated to $B > 0.95$. The specimen at $S = 97.5\%$ was generated by permeating the soil from the bottom without applying any backpressure. The $S = 90\%$ specimen was made by premixing the appropriate amounts of soil and water in a bowl and them tamping them into the mold to a relative density of 45%. The S = 60% specimen was prepared by allowing a saturated specimen to drain under gravity for fifteen minutes. The P-wave velocity of each of these specimens was measured at four different confining stresses to produce the family of curves shown in Figure 2. As shown in Figure 2, the P-wave velocity at all confining pressures stays relatively constant (at a value representative of the dry soil) for S < 90% but then rapidly increases as S increases to a value representative of water at S = 100%.

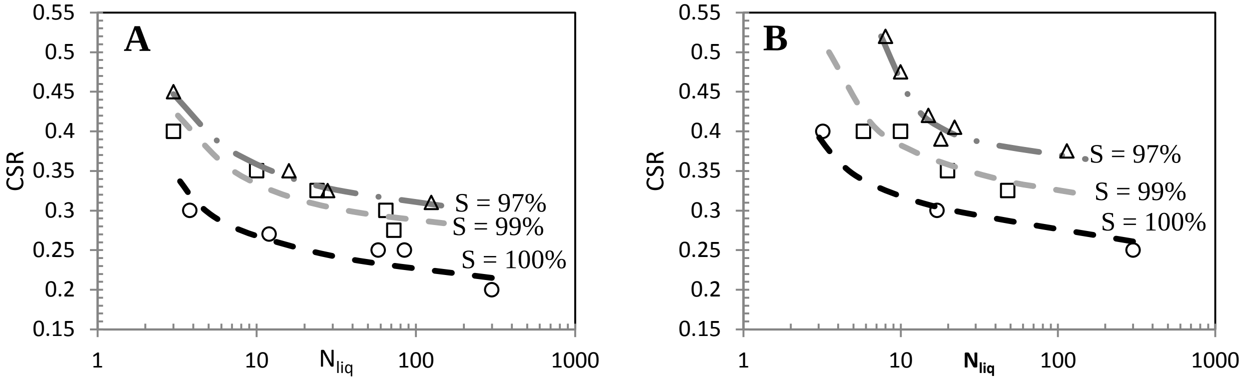

Figure 1. Cyclic strength curves for Ottawa 20-30 sand at degrees of saturation of 100%, 99%, and 97% and relative densities of 45% (A) and 75% (B). Liquefaction defined as r_u = 1.0

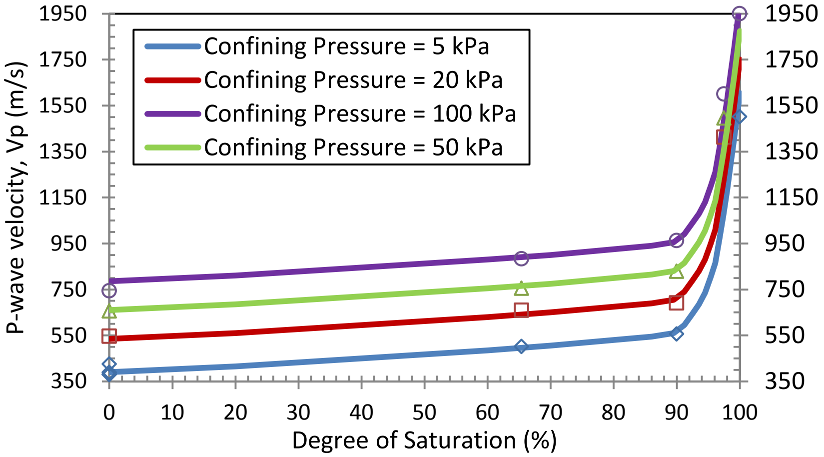

Figure 2. Relationship between P-wave velocity, degree of saturation, and confining pressure

Biotic Experiments

Materials and Methods

Four soil columns were prepared using dry Ottawa 20-30 sand air-pluviated to D_r = 45%. Three of the columns (TRX-1, TRX-2, TRX-3) were prepared using 70 mm diameter triaxial base and top caps with imbedded bender elements for S-wave velocity measurements. The fourth column (SS-1) was prepared using 100 mm diameter simple shear base and top caps with embedded bender elements for measurement of both P- and S-wave velocities. Each column was lined with a latex membrane and encased in a rigid jacket under very low overburden stress (weight of top cap) for the duration of treatment so that it could be subsequently moved into the soil testing equipment. Prior to setting up the columns, the pedestals, top caps, and membranes were alcohol sterilized (70% v/v ethanol) and the sand was autoclaved. After pluviation, the columns were flushed from the top with $N_{2(g)}$ to minimize $O_{2(g)}$ in the soil pores and facilitate denitrification.

Each column was inoculated with a mixed culture of bacteria grown from natural sand and water collected from Bolsa Chica State Beach in Huntington Beach, CA. The inoculum was grown by mixing 2 g of Bolsa Chica sand, 5 mL of Bolsa Chica water, and 95 mL of a solution containing 20 g/L nutrient broth (Difco, BD Brand), 12.5 mM $Ca(NO_3)_2$, and 12.5 mM $Ca(CH_3COO)_2$ in deionized (DI) water and then incubating the mixture for five days at 30°C. A separate solution consisting of 25 mM $Ca(NO_3)_2$, 50 mM $Ca(CH_3COO)_2$, 2 mM $MgSO_4$, and 125 mM anhydrous $CaCl_2$ was prepared to serve as the pore fluid in each column. The pore fluid solution also received 0.5 mL/L of a trace metals solution consisting of 0.5% (w/v) $CuSO_4$, $FeCl_3$, $MnCl_2$, $Na_2MoO_4 \cdot 2H_2O$ to promote microbial growth in the columns. The solution was adjusted to a pH of approximately 8 using 1 M NaOH. The columns were inoculated with 30 mL of the bacterial culture and the pore fluid solution was slowly added to each column via the bottom port until fluid began to exit the top cap (≈ 230 mL for TRX columns, 120 mL for the SS column).

After filling the columns, dialysis bags were connected to the top caps to collect gas produced during denitrification and fluid displaced from the columns. The pore fluid in each column was drained at two week intervals and refilled with fresh pore fluid. While draining, the pore fluid in the columns was replaced with $N_{2(g)}$ so that the columns remained anaerobic. At each refilling interval, the concentration of NO_3^- and acetate in the pore fluid was slowly raised while keeping the ionic strength and calcium (Ca^{2+}) concentration of the added solution constant. So, for instance, after 26 weeks of treatment, the composition of pore fluid injected into Column TRX-3 was changed to 40 mM $Ca(NO_3)_2$, 80 mM $Ca(CH_3COO)_2$, 2 mM MgSO4, and 80 mM $CaCl_2$. Tryptic Soy Broth (Fluka Analytical) was also added in very minimal amounts (0.75 – 1.5 g/L) after twelve weeks of treatment to further promote microbial growth in the soil columns. Column TRX-1 was treated for 10 weeks, Column TRX-2 was treated for 20 weeks, Column TRX-3 was treated for 30 weeks, and Column SS-1 was treated for 12 weeks before testing.

The degree of saturation in each column was evaluated in two ways: 1) in all columns, based upon the assumption that the volume of fluid displaced into the dialysis bag was equal to the volume of gas retained in the pores; 2) in Column SS-1, based upon the measured P-wave velocity and Figure 2. $CaCO_3$ precipitation (presumed to be calcite) in each column was also monitored in two ways. A sample of the pore fluid was taken at each draining interval, filtered through a 0.2 μm screen, and tested using ion chromatography (Dionex ICS-2000) to quantify Ca^{2+} ions in the pore fluid. Mass balance based upon the monitored Ca^{2+} levels in the pore fluid before and after treatment and the total volumes of fluid removed and added during each refilling event was used to estimate the amount of $CaCO_3$ precipitated in each column. $CaCO_3$ content was also quantified in Columns TRX-1 and SS-1 by taking as much of the sand as possible from the column at the end of testing, washing it with four pore volumes of DI water, drying it, weighing it, exposing it to 2 M HCl, and then drying and weighing it again. Effervescence of the samples upon addition of HCl was taken as evidence of the presence of calcite. The difference in mass before and after acid treatment was taken as the mass of $CaCO_3$ in the sand sample.

During treatment, S-wave velocity measurements in each column were used to monitor the evolution of the small strain stiffness of the soil with time. Following treatment, all of the columns were flushed with roughly four pore volumes of DI water to remove any residual salts. Consolidated undrained triaxial tests with pore pressure measurement were then conducted on the three triaxial columns and a consolidated undrained cyclic test was conducted on the simple shear column. All of the triaxial columns were back pressure saturated (B >0.95) at a confining stress of 100 kPa and column SS-1 was backpressure saturated (B >0.95) at a vertical effective stress of 50 kPa prior to testing. After saturation, Column SS-1 was subjected to a vertical effective stress of 100 kPa for 30 minutes before cyclic testing commenced. Triaxial and simple shear tests were also conducted on untreated columns of Ottawa 20-30 sand at D_r = 45% (the same as the initial D_r of the treated columns).

Results

Significant amounts of gas and fluid accumulated in the dialysis bags above all of the columns within days of initial inoculation and within hours after each refilling. The rapid displacement of fluid into each dialysis bag indicates that desaturation occurs quickly. This rapid production of gas and fluid displacement is followed by a period in which the degree of saturation appears to stay relatively constant, as gas continues accumulating in the bag without the fluid level changing. Finally, after approximately 9 to11 days, the fluid levels in the dialysis bags started to decrease slowly, indicating a slow re-saturation of the columns. This trend was consistent with the P-wave velocity measurements of Column SS-1 through a two week cycle shown in Figure 3. Saturation calculated from measurements of fluid displaced into the dialysis bags aligned fairly well with the data from P-wave measurements for Column SS-1 and indicated that the degree of saturation during each treatment cycle fell to between 89% and 96% in the columns.

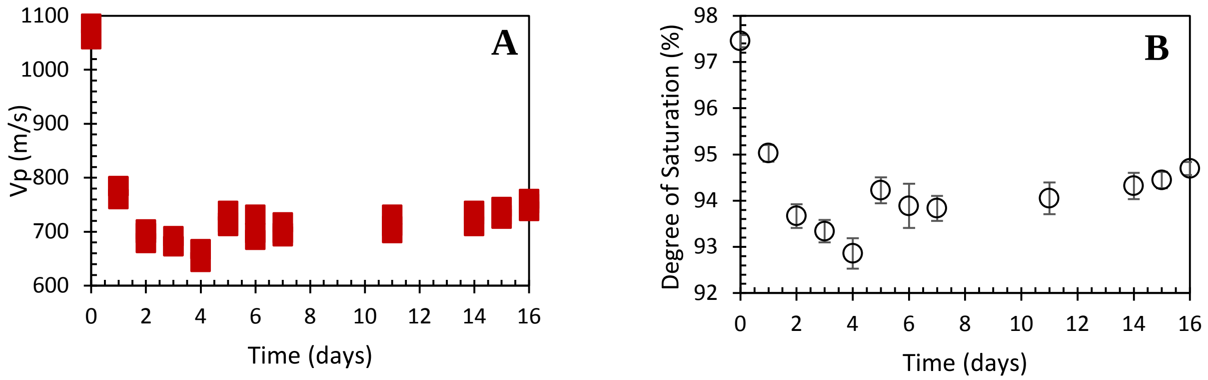

Figure 3. V_P (A) and degree of saturation (B) in column SS-1 for one treatment cycle

Initial and final shear wave velocities, as well as final mass percentages of carbonate (m% $CaCO_3$) from IC analysis and acid digestion are presented in Table 1. The significantly higher value for $CaCO_3$ precipitation found from acid digestion of Column TRX-1 following 10 weeks of treatment may be attributed to sand lost during acid digestion and rinsing. The slightly higher values of $CaCO_3$ precipitation found in ion chromatography analysis of column SS-1 are most likely due to precipitation of $CaCO_3$ onto the latex membrane as well as the base and top caps.

Table 1. Shear wave velocity and $CaCO_3$ mass (m) data for each column.

Column	Duration of Treatment (weeks)	Initial Vs (m/s)	Final Vs (m/s)	m% $CaCO_3$, mass balance	m% $CaCO_3$, acid digestion
TRX-1	10	135	180	0.090	0.316
TRX-2	20	175	356	0.495	Not Tested
TRX-3	30	176	422	0.646	Not Tested
SS-1	12	124	291	0.420	0.343

In Figure 4, the change in S-wave velocity with $CaCO_3$ content for the four denitrification columns described herein is presented along with data for soil improved via microbial ureolysis from DeJong et al. (2014). The soil treated via microbial denitrification showed almost twice as much improvement in V_S as that treated through microbial ureolysis for the same $CaCO_3$ content. It is hypothesized that the denitrification specimens show more improvement due to the fact that denitrification is a much slower process than ureolysis, leading to larger crystal sizes. The larger crystal sizes may, in turn, lead to greater improvement in soil properties compared to specimens with smaller crystal sizes (Cheng et al. 2014). However, the difference may also be due to the fact that different sand was used in the two sets of experiments.

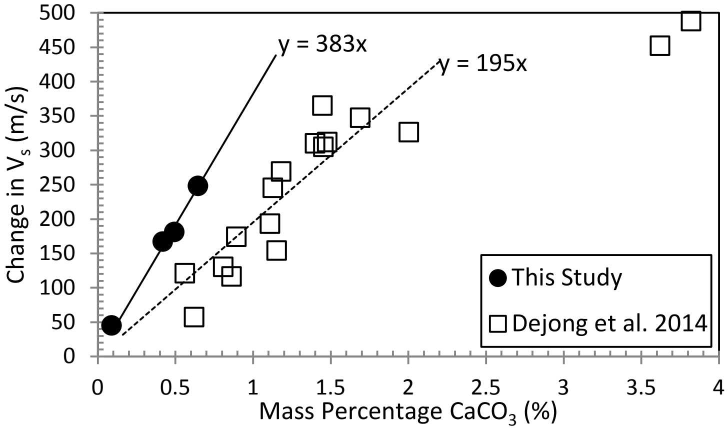

Figure 4. Change in shear wave velocity with $CaCO_3$ content for denitrification columns from this study (closed circles) and soil treated via ureolysis (open squares) from DeJong et al. 2014

The triaxial test results are presented in Figure 5. Triaxial testing of all three treated columns (TRX-1, TRX-2, and TRX-3) showed a significant increase in stiffness when compared to the untreated specimen. The treated columns also showed an increase in dilatancy (as evidenced by larger negative pore pressures). Columns TRX-2 and TRX-3 ($CaCO_3$ content by mass balance 0.50% and 0.65%, respectively) displayed slightly higher peak strength than the untreated column while column TRX-1 (estimated $CaCO_3$ content by mass balance 0.09%) did not show any increase in peak strength. The increased peak strength shown by columns TRX-2 and TRX-3 suggests that cementation had begun to strengthen the interparticle contacts.

Cyclic simple shear testing of column SS-1 ($CaCO_3$ content by mass balance 0.42%), presented in Figure 6, showed a roughly 40% increase in cyclic resistance after treatment when compared to untreated saturated soil at D_r = 45% and superior cyclic resistance to that of the untreated saturated soil at D_r = 75%. Since Column SS-1 was treated under very low overburden stresses (weight of top cap) and only subjected to a vertical effective stress of 100 kPa 30 minutes before testing (the same as the untreated specimens), the difference in cyclic shear strength may be entirely attributed to MICP treatment and does not reflect an influence of time under consolidation. The increases in stiffness, dilatant behavior, and cyclic resistance with relatively small amounts of $CaCO_3$ precipitation and no visible inter-particle soil cementation may be a result of $CaCO_3$ precipitating in the soil pore spaces and roughening of the sand grain surfaces by the precipitated carbonate (Santamarina and Cho 2004).

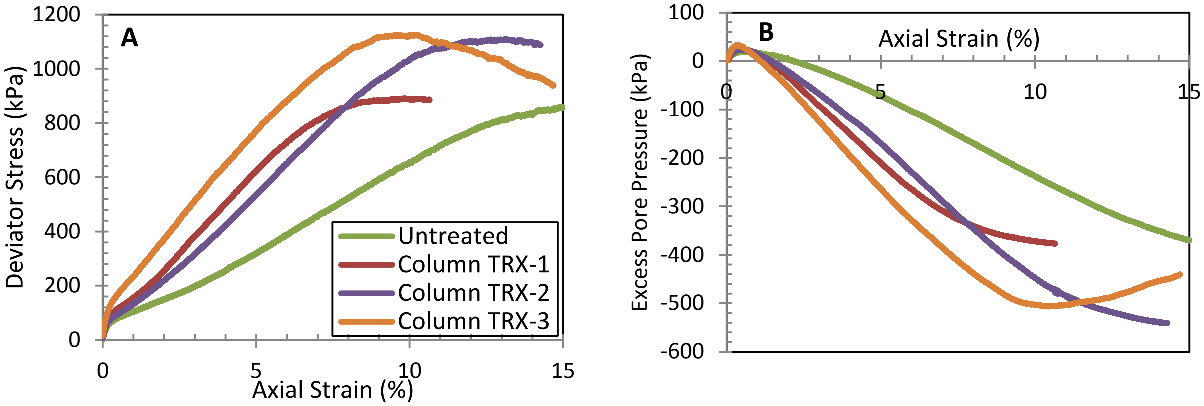

Figure 5. Deviator stress (A) and excess pore pressure (B) of treated columns compared to untreated column at relative density of 45%

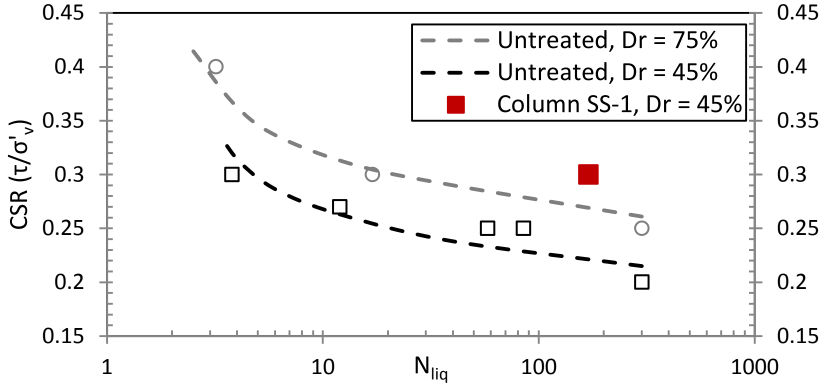

Figure 6. Cyclic strength of untreated and treated saturated sand (liquefaction defined as r_u = 1.0)

Conclusions

Abiotic cyclic simple shear testing shows that significant increases in cyclic resistance (upwards of 40%) can be achieved through very small amounts of desaturation (1-3%). Biotic column testing with P-wave measurements demonstrates that this level of desaturation can occur via denitrification within a matter of 2-4 days. This demonstrates the ability of denitrification to induce enough desaturation in a short amount of time to significantly improve liquefaction resistance. S-wave velocity measurements and triaxial testing showed increases in stiffness, dilatant behavior, and peak strength with small amounts (less than 1% by weight) of denitrification-induced $CaCO_3$ precipitation (presumably calcite). Cyclic simple shear testing showed a roughly 40% increase in cyclic resistance with a small amount (less than 0.5% by weight) of $CaCO_3$ precipitation. Together, these data indicate that MICP via denitrification shows potential for the mitigation of liquefaction potential as a two-stage process, with short term mitigation via desaturation and long term mitigation via MICP.

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