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## Cyclic behavior of bio-cemented soils using relatively large grains

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### ABSTRACT

Consequences of liquefaction during earthquakes can be disastrous and fatal. During the past decade, bio-mediated methods have gained researchers and engineers' attention, and have been developed to strengthen soils and mitigate liquefaction. Among these methods, a commonly used method — the microbial induced calcite precipitation (MICP) method — has proved to be a potential alternative technique due to its sustainability and relatively environmentally friendly character, with lower carbon emissions compared to traditional methods. In most of the existing studies on cyclic behavior of MICP-treated soils, uniformly graded fine sands like Ottawa 50-70, with a maximum diameter of 1 mm and a narrow grain size distribution, were used. As liquefaction can also occur in soils with larger grain size, it is quite important to study the applicability of MICP method to these soils and to know their behavior after treatment. In this study, we used coarser soils with a maximum grain size of 5 mm. Undrained cyclic triaxial tests were applied to MICP-treated and untreated soils. Cyclic stress ratios (CSR) and number of cycles from 0.25 (300 cycles) to 0.3 (100 cycles), 0.35 (100 cycles), 0.4 (100 cycles), up to 0.5 were applied one after another as long as liquefaction did not occur. The results obtained on one of these soils showed that the untreated soil samples liquefied at a CSR equal to 0.25 after 42 cycles, with an axial deformation around  $\pm 4$  %. For the MICP-treated samples with 8.6 % calcium carbonate content, cyclic resistance increased slightly to 63 cycles at 0.25 CSR, while the axial deformation was in one direction and relatively lower rate of increment. With around 3 % more calcium carbonate content (11.5 %), the MICP-treated soil was like cement which could withstand a much higher cyclic stress ratio (up to 0.5) with many more cycles compared to the untreated soil.

**Keywords:** liquefaction mitigation, cyclic behaviors, MICP

## 1 INTRODUCTION

Liquefaction is a hazard often occurring in loose sand during earthquakes. During liquefaction, the ground will partially or completely lose its strength, which can cause massive destruction, such as damage of buildings, roads, pipes, embankments, dams, etc. (Kumari and Xiang, 2019). Traditional methods for soil improvement, for example, compaction or soil replacement, are energy-consuming and disruptive to the surroundings, which is not suitable for sensitive environment and low-carbon economy (Huang and Wen, 2015). Recent progresses in applying microbiological techniques, like microbial induced calcite precipitation (MICP) method, have given engineers and researchers a potential alternative in liquefaction mitigation (Yu et al., 2020).

There are some studies that prove the efficiency of liquefaction mitigation using bio-methods, such as Van

der Ruyt and Van der Zon (2009), Montoya et al. (2012), Xiao et al. (2018), Wang et al. (2021), etc.. For cyclic behaviour of bio-cemented soils, results showed increased cyclic resistance and smaller strain accumulation. In centrifuge model studies, reduced excess pore pressure generation at different levels of shaking was obtained in MICP-treated samples using Ottawa 50-70 sand ( $d_{50}$  0.22,  $C_u$  1.4), while undesired increase in the maximum accelerations at ground surface was also observed (Montoya et al., 2014). Smaller shear strain accumulation (0.01-0.7 %) was found in MICP-treated samples (using Ottawa F-65 sand,  $d_{50}$  0.199,  $C_u$  1.6) before triggering liquefaction than in untreated samples (0.01-1.04 %). Larger peak base accelerations were needed to trigger liquefaction in MICP-treated samples compared to untreated samples. These improvements increased with increasing cementation level (Darby et al., 2019). In cyclic triaxial studies,

reduced build-up of excess pore pressure was also observed. For axial strains over 0.5 %, the bonds between grains (Keisha No. 4 sand,  $d_{50}$  0.825) started degrading, which caused higher rate of increase in excess pore pressure (Simatupang and Okamura, 2017).

In the existing articles, most of the researchers used similar soils grain size distributions, usually with grains smaller than 1 mm or with very low contents of grains > 1 mm. However, in real sites, grain size distribution may vary a lot and liquefaction can also occur in grains > 1 mm. It is quite important to have an idea of the cyclic behaviour of bio-cemented soils prepared with different grain size distributions. In this study, we used soils grains with diameters comprised between 1 mm and 5 mm. Different  $\text{CaCO}_3$  contents in bio-cemented samples were obtained by changing the number of MICP treatments. Undrained cyclic triaxial tests were conducted on both treated and untreated soil samples.

## 2 MATERIALS AND METHODS

### 2.1 Sand and soil sample preparation

The sand used is from glacial origin with diameter ranging from 1-5 mm and very low content of calcite. Detailed properties and grain size distribution can be found in Table 1 and Fig. 1.

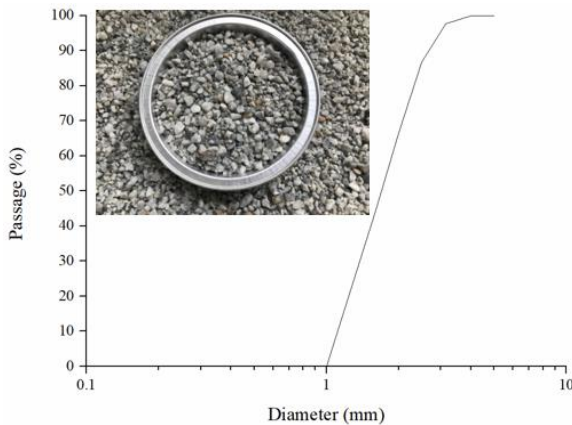


Fig. 1. Grain size distribution of the soil used.

Table 1. Properties of the sand.

Sand	$e_{\max}$	$e_{\min}$	$d_{10}(\text{mm})$	$d_{60}(\text{mm})$	$G_s$	$C_u$	Shape
	0.84	0.62	1.14	1.88	2.7	1.66	sub-angular

For soil sample preparation, the moist tamping method was used for both treated and untreated samples. Wet sand was added and compacted layer by layer (5 layers in total) into the mold to a target initial relative density of 0.3. Untreated soil samples (UT1, UT2) were prepared directly on the base of the triaxial cell with a rigid mold (diameter 10 cm, length 17 cm) and a rubber membrane. For MICP-treated samples (T1, T2, T3), soil columns were prepared in a plastic mold (diameter 9.6 cm, length 17 cm). On both ends, a plastic filter was placed. After preparation, the MICP-treated samples

were taken out from the plastic mold and replaced in the triaxial cell.

### 2.2 Bacteria and cementation solution

For bacterial solution (BS), freeze-dried bacteria (*Sporosarcina pasteurii*) powder provided by Solétanche-Bachy was used in this study. Bacteria powder were hydrolyzed sufficiently (by stirring with magnetic stirrer during hydrolysis) in Crystalline water with 3 g / L or 10 g / L NaCl. The final optical density of the BS used was around 3 at 600 nm ( $\text{OD}_{600}$ ).

Cementation solutions (CS) were prepared by dissolving 1.4 mol urea (ACROS) and 1.4 mol calcium chloride (VWR) in 1 L tap water.

### 2.3 MICP process

For MICP treatment process, at first, 1.5 PV BS was injected upwards and retained in the column for around 1 h. Then 1.2 PV CS was injected and retained for 1 d. The process was repeated until the desired amount of  $\text{CaCO}_3$  was reached. Finally, 1.5 PV water was injected to flush out the solution before triaxial tests.

Properties of the samples were shown in Table 2. For T1, both BS and CS were injected at around 50 mL/min. For T2 and T3, BS was injected at around 50 mL/min, CS was injected at around 30 mL/min.

For T1, 3 g/L NaCl was used in BS. For T2, 10 g/L NaCl was used in BS. For T3, 10 g/L NaCl was used in the first time BS and 3 g/L was used from the second to the last BS.

### 2.4 Undrained cyclic triaxial tests

The undrained cyclic triaxial tests were carried out under a series of cyclic stress ratio (CSR) at 0.1 Hz. First 300 cycles at CSR 0.25 were applied, followed by 100 cycles at 0.3, 0.35, 0.4 and 0.5, in sequence. The test was stopped when the soil sample liquefied.

### 2.5 $\text{CaCO}_3$ content measurement

The  $\text{CaCO}_3$  content was measured after the cyclic tests. 2 g oven-dried treated sand was dissolved in hydrochloric acid (1 M) in a closed system connected with a graduated U-tube with water.  $\text{CO}_2$  gas produced was trapped in the system. The increased volume pushed water in the U-tube and produced height difference. The reaction was considered as finished when the water height was stable in the U-tube. The  $\text{CO}_2$  volume to deduce the mass of corresponding  $\text{CaCO}_3$  was indicated by difference in water height in the U-tube.

Table 2. Properties of tested soil and parameters for the test.

Test No.	NaCl used (g/L)	Number of treatment	B-value	CSR	$N_L$	$\text{CaCO}_3$ (%)
UT1	-	-	0.98	0.25	42	-
UT2	-	-	0.99	0.3	18	-
T1	3	3	0.96	0.25	10	3.2
T2	10	4	0.94	0.25	63	8.6
T3	3, 10	5	0.94	0.2-0.5	700	11.5

### 3 RESULTS AND DESCUSSION

Some details of the tested treated and untreated soil samples are given in Table 2.  $N_L$  represents the number of cycles to liquefaction.

#### 3.1 Effect of different protocols

As shown in Table 2, for T1, 1.1%  $\text{CaCO}_3$  could be formed in the soil column for each treatment, while 2.2% formed in T2 and 2.3% in T3: the efficiency doubled because of the lower injection rate of CS. That means that, to improve the efficiency of MICP treatment, the injection rate of CS is a quite sensitive parameter that needs to be chosen carefully.

It is well-known that increasing ion strength in a bacteria solution might enhance the bacterial adsorption onto the soil. In our limited tests, for T2 and T3, increasing ion strength through adding more NaCl under the experimental conditions of this article seemed not as efficient as reported in (Marzin et al., 2020). This may be because, after finishing 1 cycle of injection, the high concentration solution (much higher ion strength than 10 g/L NaCl) after biomineralization was not flushed out. The BS solution of the next cycle was directly injected into the soil column with this solution of even higher ion strength inside the column. The possible enhancement due to the increase in NaCl concentration was not obvious.

#### 3.2 $N_L$ and excess pore pressure

As shown in Table 2, for untreated samples, UT1 liquefied after 42 cycles at CSR 0.25 and UT2 liquefied after 18 cycles at CSR 0.3. For treated samples, T1 liquefied after 10 cycles and T2 liquefied after 63 cycles at CSR 0.25, while T3 experienced 300 cycles of CSR 0.25, 100 cycles of CSR 0.3, 100 cycles of CSR 0.35, 100 cycles of CSR 0.4 and 100 cycles of CSR 0.5 in sequence.

Fig. 2(a) exhibits the excess pore pressure ratio as a function of the number of cycles, Fig. 2(b) showed rescaled number of cycles for UT1, UT2, T1 and T2. For the untreated samples, the build-up of excess pore pressure was quite swift and violent. For the treated samples, lower pore pressure increments were observed, especially in T2 and T3.

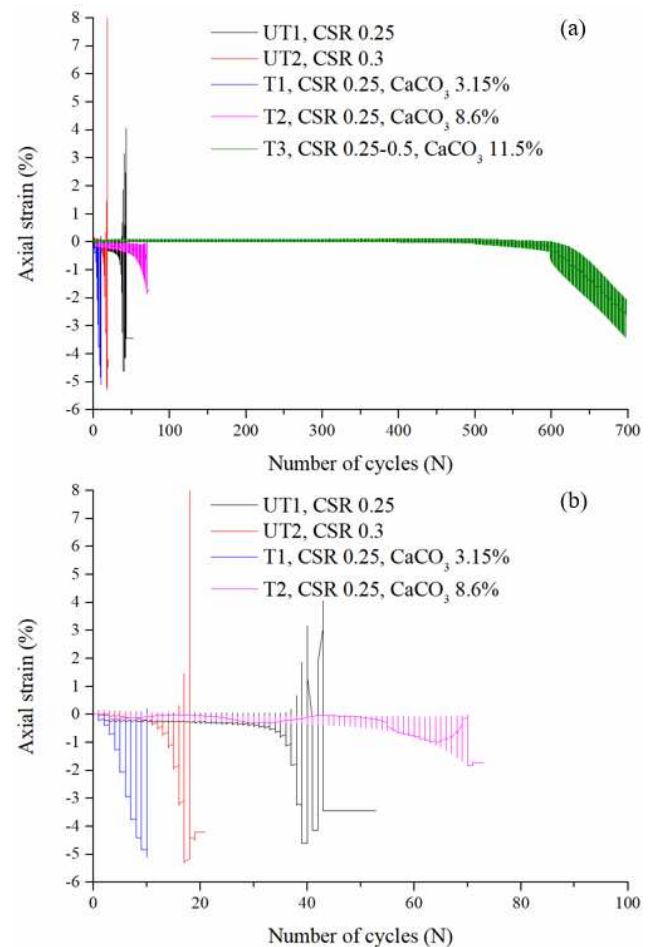


Fig. 2. Excess pore pressure ratio versus number of cycles.

#### 3.3 Axial strain

As shown in Fig. 3(a) and rescaled Fig. 3 (b), the change in axial strain was quite different between treated and untreated samples. For untreated samples, the axial strains were symmetrical. On the contrary, extensions were mainly observed in treated samples. Even in the case of T1, which did not show improvement in cyclic resistance, the strain behavior was in one direction as in the other relatively well-treated samples. One thing in common between treated and untreated samples is that, after 0.5% axial strain was achieved, the rate of increment of axial strain increased. For untreated samples, after 0.5% axial strain, larger strains (up to around 5%) were obtained in the following several cycles. The number of cycles needed for treated samples to achieve 5% axial strain after 0.5% axial strain was larger than in untreated samples. For T2, it seems that bonds degraded fast whereas, for T3, some intact bonds subsisted, which lowered the range of longitudinal displacement.

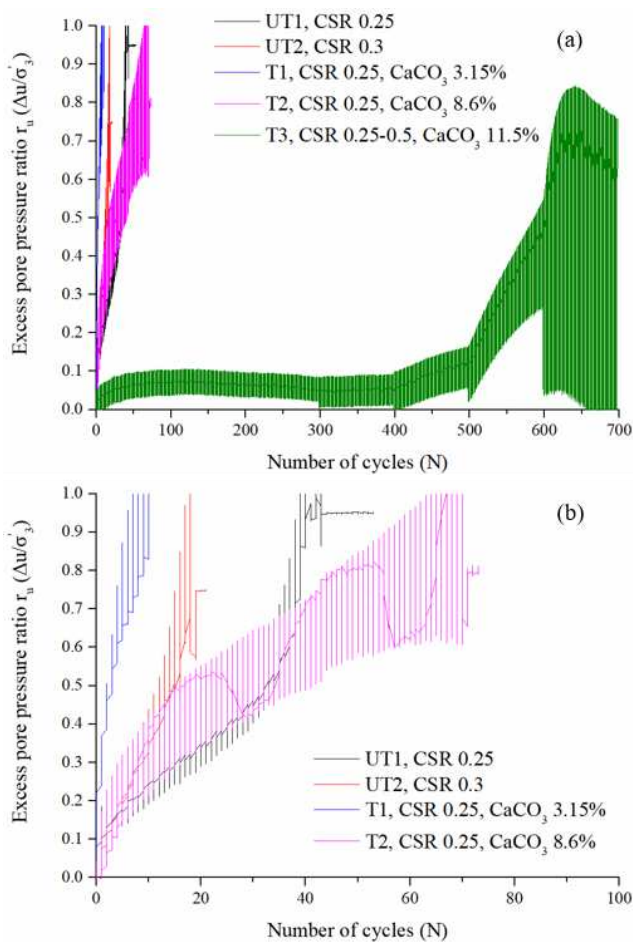


Fig. 3. Axial strain versus number of cycles.

### 3.4 CaCO<sub>3</sub> content

It was reported in Almajed et al. (2019), that even a small amount of calcite precipitation (around 1 %) gave large improvement (peak strength of 1700 kPa in UCS tests) in Ottawa 20/30 sand ( $d_{50}$  0.6). They concluded that the formation of calcite focused at the contact points between particles contributed to the effective treatment results. In the studies of (Simatupang and Okamura, 2017), 1% calcite precipitation under low degree of saturation (30%) doubled the liquefaction resistance. They explained that when lowering the saturation degree, pore water concentrated at particle contacts, which helped the CaCO<sub>3</sub> to precipitate at effective places. In our tests, the sample T1 with 3.15% CaCO<sub>3</sub> liquefied quite rapidly and no improvement in cyclic resistance was seen. This could be attributed to an ineffective precipitation on grain surface. The larger the grain size, the smaller the number of contact points, and the chances to precipitate at contact points also decrease. It might also be due to insufficient CaCO<sub>3</sub> content with respect to the size of the grains. The problem might also arise from the fact that the structure of the treated-soil was delicate, and transferring this kind of treated sample from the mold to the apparatus might have damaged the structure.

For the treated T2 sample, 8.6% of CaCO<sub>3</sub> seem to be the minimum content to make a well-structured bio-

cemented soil, and to observe a big difference between untreated and treated samples. With another additional 3% of CaCO<sub>3</sub>, like in T3, the soil behaved like concrete.

## 4 CONCLUSIONS

In this study, a soil with relatively large grain size was used. For the results of undrained cyclic tests, untreated loose sand liquefied after 42 cycles at CSR 0.25 and 18 cycles at CSR 0.3. Pore pressure increased quickly and axial strain achieved  $\pm 5\%$  in several following cycles once the 0.5% strain was obtained. For treated sand with 3.15% CaCO<sub>3</sub>, no improvement showed in cyclic resistance due to insufficient precipitation at particle points or delicate soil structure. Treated sample with 8.6% CaCO<sub>3</sub> showed transitional state between untreated and well-treated samples, with lower excess pore pressure increment and lower axial deformation increment. Well-cemented test sample with 11.5% of CaCO<sub>3</sub> helped the soil behave like cement.

## ACKNOWLEDGEMENTS

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