Journal of GeoEngineering, Vol. 16, No. 1, pp. 035-046, March 2021
http://dx.doi.org/10.6310/jog.202103_16(1).4

SOIL IMPROVEMENT BY MICROBIAL INDUCED CALCITE PRECIPITATION AND A CHEMICAL METHOD FOR LIQUEFACTION MITIGATION

Jun-Xue Huang [1], Yi-Hsiu Wang [2*], Thien-An Nguyen [3], Chia-Sheng Hsu [4], and Wen-Yi Hung [5]

ABSTRACT

Microbial induced calcite precipitation (MICP) is a geochemical process for ground improvement by enhancing the mechanical properties of the soil stratum. A bacteria and nutrient containing liquid are injected into the sand to precipitate the formation of calcium carbonate crystals through the metabolism of microorganisms. The calcium carbonate crystals precipitate in pores between the grains of sand, effectively cementing the particles of sand together and filling the pore volume, consequently, increasing the shear strength and reducing the permeability. However, the functioning of the MICP method is quite sensitive to environmental conditions such as temperature and humidity. Another way to cement the soil layers is to use a chemical process where a Na_2CO_3-$CaCl_2$ liquid mixture is added to produce $CaCO_3$ which helps to harden the soil. However, this method has significant undesirable side effects in the ground environment. In this study, a series of experiments is carried out comparing samples that have been improved by MICP and a chemical method under different conditions with the original non-improved samples. The experiments include direct shear testing, constant head testing and centrifuge testing. The results show that the treated sand layer has better resistance to liquefaction, decreased excess pore water pressure, and improved settlement which also shortens the excess pore water pressure dissipation time. In addition, it is also demonstrated that the temperature, humidity and nutritional liquid have a critical effect on the effectiveness of the MICP and chemical methods.

Key words: Soil improvement, MICP, soil liquefaction, centrifuge modelling, chemical improvement.

1. INTRODUCTION

Recent studies reported, thanks to advancements in biotechnology, a novel technique has been developed that can be used for improvement called microbial-induced calcite precipitation (MICP). The bacteria used have the highest biological reproduction rate and a large specific surface area, allowing more energy to be absorbed and enhance the speed of metabolic reaction and reproduction if an environment containing the correct nutrient sources, including nitrogen, phosphorus, sulfur, potassium, and magnesium (Chawla *et al.* 2009; Jhuo 2011). With the addition of certain types of nutrients, some kinds of bacteria can produce urease in metabolic reactions. Urease can catalyze urea to become ammonium ions (NH_4) and carbonate ions (CO_3^{2-}) after hydrolysis (Eq. (1)), after which the calcium carbonate will combine with calcium ions (Eq. (2)) in the soil to produce calcite precipitates (DeJong *et al.* 2006).

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4 + CO_3^{2-} \tag{1}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow \tag{2}$$

The primary functions of MICP are bio-cementation and bio-clogging, where microorganisms will produce extracellular polysaccharides during the metabolic reaction. This substance can increase the degree of contact bonding between sand particles and increase the shear strength and stiffness of the soil layer, a phenomenon called bio-cementation. Calcite will precipitate at the particle pores to decrease the porosity after clogging. The permeability is reduced as well; this is called bio-clogging (Ivanov and Chu 2008). These two major processes not only can effectively improve the engineering properties of the soil but also offer some directions for the development of strategies for disaster reduction, like ground improvement and mitigation of soil liquefaction.

This study aims to study the effect of MICP as a countermeasure for liquefaction hazards. Liquefaction occurs when a loose sandy layer is subjected to seismic loading so that the pore water pressure (pwp) increases and the effective stress decreases. If the effective stress in the stratum is reduced to zero (excess pwp ratio is equal to 1), then soil liquefaction occurs, which can lead to the significant settlement of structural foundations. Underground structures can also be affected by the uplift force (Ishihara 1983). Some of the conventional methods for mitigating the effects of liquefaction are the use of pile foundations, replacement methods, and dynamic compaction, which can enhance the shear strength within a short construction time. However, these methods have the disadvantages of high construction

---

Manuscript received January 18, 2021; revised February 21, 2021; accepted February 20, 2021.

[1] Ph.D. Candidate, Department of Civil Engineering, National Central University, Taoyuan City 32001, Taiwan, R.O.C.

[2*] Ph.D. Student (corresponding author), Department of Civil Engineering, National Central University, Taoyuan City, Taiwan, R.O.C. (e-mail: wang841215@gmail.com).

[3] Research Assistant, Department of Civil Engineering, National Central University, Taoyuan City, Taiwan, R.O.C.

[4] Assistant Engineer, Taiwan International Ports Corp., Ltd (Port of Keelung), Keelung City, Taiwan, R.O.C.

[5] Associate Professor, Department of Civil Engineering, National Central University, Taoyuan City, Taiwan, R.O.C.

costs and may also a negative effect on the soil ecosystem. Thus MICP was considered as an environment-friendly approach.

Although the MICP method might be an option for a green approach that we can apply in the future, its functioning is dependent on factors such as the growth and metabolic reaction of the microorganisms, and the environmental conditions (*e.g.*, temperature and humidity). The higher the temperature, the faster the precipitation rate of calcite, and the higher the amount of calcium carbonate the bacteria can produce, and vice versa (Peng *et al*. 2016). Therefore, a possible solution to reducing the effect of unfavorable environmental conditions is to directly mix the urease enzyme with the specimen cultured by the urea-calcium chloride liquid (Yasuhara *et al*. 2012). It has been proven that this method can significantly increase the shear strength of sand. The significant factors affecting the process are the concentration of the urea-calcium chloride liquid and the content of the urease enzyme. However, to simulate practical in-situ construction, the enzyme should be mixed with the urea-calcium chloride liquid prior to being injected into the specimen rather than mixed with the sand before specimen preparation (Neupane *et al*. 2013). Another problem is that of cost because the urease enzyme is quite expensive, so it might not be economical for industrial-scale application. Therefore, in this work, the samples were prepared by a less sophisticated method than in other studies. To better understand the feasibility of the MICP method for the in-situ application, we also take into consideration the uncontrollable conditions, so all of the sandy specimens are placed in an outdoor environment. In addition, this study also investigates the effects of the bacteria content, culturing methods, and nutritional concentration on the treatment sand. However, quite a long time is needed to achieve the target stiffness with the MICP method, so in the experiments a mixed sodium bicarbonate (Na_2CO_3) and calcium chloride ($CaCl_2$) solution are used to produce $CaCO_3$ precipitation, to mimic improvement of the specimens by the MICP method. Based on the results of the chemical imitation, a centrifuge model was built to investigate the effects of soil improvement on liquefaction mitigation.

Recently, the Microbial-induced calcite precipitation (MICP) is considered as a novel soil-improvement technique that can improve the behavior of sands under cyclic loading (Feng and Montoya 2017). Some recent previous studies applied the MICP method on sandy soil to investigate the effect of MICP on the strength of sand. Xiao *et al*. (2018) conducted a series of undrained cyclic triaxial tests to observe the effect of MICP for liquefaction resistance on bio-cemented calcareous sand. The test results indicated that the liquefaction resistance might increase treated by MICP. Riveros and Sadrekarimi (2020) used MICP to improve the cyclic resistance of Fraser River sand specimens. The results show that the specimen's shear wave velocity increases when calcium solution is introduced into the specimen. A series of cyclic direct and simple shear tests were conducted to measure the specimens' liquefaction resistance. The cyclic resistances of the MICP-treated specimens are higher than those of the untreated sand. Darby *et al*. (2019) performed centrifuge tests for untreated and treated ground subjected to several shaking events at the UC Davis Center for Geotechnical Modeling. The saturated loose Ottawa sand was treated lightly, moderately, and heavily with MICP. The in-flight cone penetration test was applied during the centrifuge test to observe the effect of the MICP for cone penetration resistance and shear wave velocity of the sand deposit. The test results indicated that the resistance of the sand, which was treated lightly, moderately, and heavily with MICP, increase from 2 to 5, 10, and 18 MPa, respectively. The results of shaking table tests conducted by Zhang *et al*. (2020) show the cementation by MICP method could increase the strength, stiffness, and liquefaction resistance of the soil.

Therefore, this study will conduct a series of laboratory tests (such as direct shear test, unconfined compression test, and constant head test) to understand the performance of $CaCO_3$ precipitation in MICP and chemistry methods before and after treatment. In addition, the centrifuge modeling test will be performed to understand the MICP method's effectiveness of clogging and cementation on the settlement behavior and seismic responses of a liquefiable soil deposit. Because the MICP method needed a long culturing time, a chemical method was also used to generate the calcium carbonate and increase the bond strength between the sand particles in the same manner as in MICP but at a much higher speed.

2. MATERIALS AND SAMPLE PREPARATION

2.1 Silica Sand and *Pseudomonas sp bacteria*

The material used was silica sand with the following properties: specific gravity (G_s) of 2.65, D_{50} = 0.19 mm, D_{10} = 0.15 mm, maximum and minimum dry unit weight of 16.3 kN/m³ and 14.1 kN/m³, respectively. The particle size distribution of the silica sand is plotted in Fig. 1. The silica sand was classified as poor grade sand (SP) according to the Unified Soil Classification System (USCS). Based on the particle size distribution curve, the distribution curve of the silica sand is located at the high potential liquefaction zone. The frictional angle of the sand was 35°, with a relative density (RD) of 50% (Table 1). The samples were placed in a transparent plastic mold adapted to have the direct shear test apparatus dimensions.

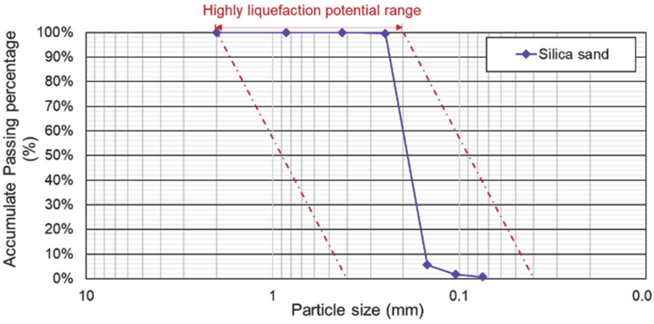


Fig. 1 Particle size distribution of the silica sand used in the experiments

Table 1 The properties of silica sand

Specific gravity	2.65
Mean grain size	0.19 mm
Effective grain size	0.15 mm
Maximum dry unit weight	16.3 kN/m³
Minimum dry unit weight	14.1 kN/m³
Friction angle ψ (D_r = 50 %)	35°
Soil classification (USCS)	SP

The *Pseudomonas sp bacteria* were employed to perform MICP. This is a genus of motile, polar-flagellate, non-spore forming, strictly aerobic bacteria containing straight or curved, not helical, gram-negative rods that occur singly. It can enhance the recreation of metabolism during ureolysis to produce $CaCO_3$, thus improving the mechanical properties of sand.

Direct shear tests, unconfined compression tests, and constant head permeability tests were employed to observe changes in the mechanical properties after the application of the MICP and chemical methods. These tests were performed with respect to the ASTM testing standard.

First, in preparation for the direct shear tests and constant head tests, the filter paper was placed in the bottom of the plastic molds and placed on the porous stone. The quart sand was pluviated into the plastic mold layer by layer. The relative density of the specimen was about 50%. After sample preparation, the nutrient was injected into the specimens and they were then allowed to stand for a while. The purpose of this step was to let the nutrient diffuse uniformly throughout the voids in the sample; it also can provide a suitable environment for the *Pseudomonas sp* to advance. When the nutrient liquid was evenly diffused, a needle was used to inject the bacteria liquid (the OD value is controlled at 0.622) into the specimens to allow the *Pseudomonas sp* to be well distributed and fully produce the metabolic reactions. The unconfined compression and constant head samples were prepared in the same manner but in different molds.

In addition, a physical modeling test with treated and untreated zones was also conducted to understand further the effects of the clogging and cementation for liquefaction mitigation on the geotechnical centrifuge of the Experimental Center of Civil Engineering (ECCE) at the National Central University (NCU), shown in Fig. 2. The nominal radius of the NCU Centrifuge is 3 m with a capacity of 100 g-ton (Table 2) and a 1-D servo-hydraulic shaker (Fig. 3) integrated into the swing basket. The dimensions of the shaking table are 1,000 mm (length) × 550 mm (width), and it has a maximum payload of 400 kg with a maximum gravity level of up to 80 g. The working frequency range of the shaker is from 0 Hz to 250 Hz and the maximum shaking force is 53.4 kN (Table 3). A rigid container (Fig. 4) was made of an aluminum alloy and had a payload of 400 kg. The interior dimensions (L × W × H) are 767 mm × 355 mm × 400 mm.

After injecting *Pseudomonas sp* into the specimen, adding nutrient liquid promotes the growth and reaction of metabolism of *Pseudomonas sp* continuously and strengthens the effectiveness of cementation and clogging. However, the realistic environment, the types of nutrients, and the injection rate may affect the improvement effects. Therefore, this research not only focuses on the effect of the MICP method but also adopts the chemistry method Na_2CO_3 and $CaCl_2$ mixed liquid to produce the calcium carbonate precipitation. It can reduce the outside environment's factors to affect the reaction of calcium carbonate precipitation and simulate the characteristics of the sand layer improved by calcium carbonate precipitation. So, this research will conduct a variety of test arrangements to know the difference about the mechanical properties of sand and choose the better improvement ways to be the mitigation method.

Fig. 2 NCU geotechnical centrifuge

Table 2 The specification of the NCU geotechnical centrifuge

Capacity	100 g-ton
Nominal radius	3 m
RPM	25 ~ 265 RPM

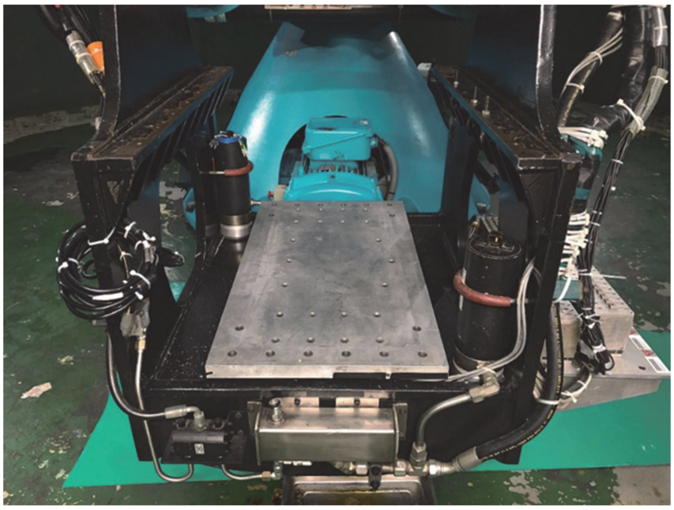
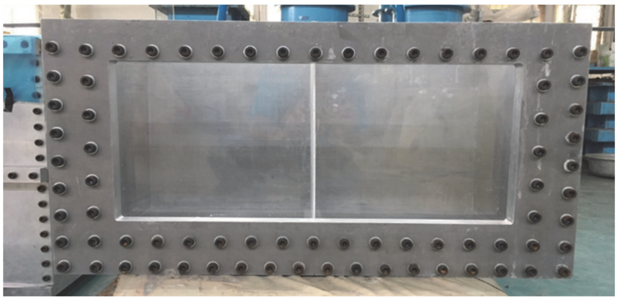


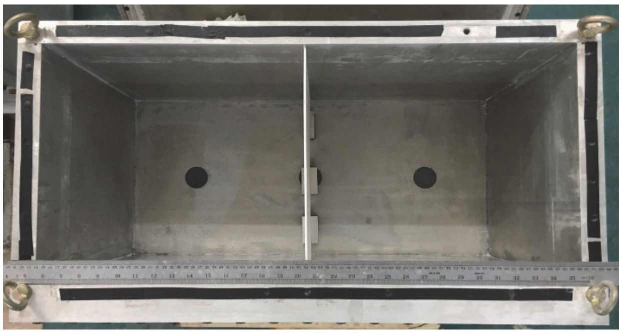
Fig. 3 NCU shaking table

Table 3 The specification of the shaking table

Payload dimension ($L \times W$)	1,000 × 550 mm
Maximum payload	400 kg
Nominal shaking force	± 53.4 kN
Maximum shaking velocity	1 m/sec
Maximum displacement	± 6.4 mm
The range of frequency	0 ~ 250 Hz
Maximum centrifugal acceleration	80 g



(a) Side view



(b) Top view

Fig. 4 Rigid container

2.2 Preparation of Soil Samples by the MICP and Chemical Methods

2.2.1 MICP Method: Culture Bacteria by Nutrient Type 1

The relative density of dry sand specimens is 50% and injects different bacteria content (5%, 15%, and 25%) into the specimens. After injection, the specimens will be placed at the culture containers and add the nutrients. The nutrient liquid surface keeps attach to the bottom of specimens, and the culture time is seven days. Previous researches (Zhao *et al.* 2014; Liu and Gao 2020) shows the effect of temperature and humidity on MICP. However, controlling the temperature and humidity in the real site is not feasible due to the cost. In this study, the uncontrolled environment is also simulated in the tests. The temperature and humidity during culturing of samples are in a natural condition (Fig. 5).

2.2.2 MICP Method: Use Immersion Method to Culture Bacteria by Nutrient Type 1

The 5% of bacteria liquid is injected into the specimen, and the relative density is 50%. After injection, the specimens are placed in the culture containers and add the nutrients. The nutrient liquid surfaces will over the top of specimens to culture for seven days.

2.2.3 MICP Method: Use Pump System to Culture Bacteria by Nutrient Type 1

The relative density of dry sand specimens is 50% and injects bacteria content 5% into the specimens. After injection, the specimens will be placed at the culture containers, add the nutrients, and motor with other equipment connected with the tube to put into the nutrient liquid. It can let the nutrient be injected into the specimens and flow out from the bottom to become a circulatory system, and the culture time is seven days.

2.2.4 MICP Method: Use Pump System to Culture Bacteria by Nutrient Type 2

The relative density of dry sand specimens is 50% and injects bacteria content 5% into the specimens. After injection, the specimens will be placed in the culture containers and add different Urea-$CaCl_2$ mixed liquid (1, 0.5, and 0.25 mol). The motor will be connected with the tube to put into the nutrient liquid. It can let the nutrient be injected into the specimens and flow out from the bottom to become a circulatory system, and the culture time is seven days. After finishing the culture, one specimen will be placed into the oven to dry for 24 hours, and another keep at a moisture state.

2.2.5. Chemical Methods

According to the MICP test results at the different concentration of Urea-$CaCl_2$ mixed liquid (1, 0.5, and 0.25 mol), we can know the change of dry unit weight of sand as compared with the initial condition and calculate that how many calcium carbonate precipitate inside the void volume of the specimen. After that, using the Na_2CO_3-$CaCl_2$ mixed liquid inject into the specimens to let the specimen have the same specimen condition after improving by MICP method. The dry sand specimen's relative density is 50%; uses the motor to inject the Na_2CO_3 and $CaCl_2$ solutions, respectively, and the specimen is at the near saturation state after injection. When the chemical liquid is injected, we will stand the specimen for a few minutes to let the Na_2CO_3 and $CaCl_2$ react entirely to produce the calcium carbonate precipitation. After improvement, one specimen will be placed into the oven to dry for 24 hours and another keep at a moisture state.

3. EXPERIMENT PROCESS AND RESULTS

3.1 Effect of the Initial Bacteria Content

The mass ratio of the *Pseudomonas sp bacteria* diluent liquid to dry sand of the sample defines the bacteria content. Several different samples with three different bacterial contents (5%, 15%, and 25%) were prepared in plastic molds using the same conditions of humidity and temperature (Fig. 5) over seven days. Montoya and DeJong's recipe (2015) was used for the type 1 nutritional liquid. After the culturing process had finished, the mechanical properties of the samples were measured by a direct shear test. Figure 6(a) shows the summarized results of the direct shear tests for different bacteria content. Depending on the concentration of the bacteria, the friction angle could be increased around 5° to 10°, and the cohesion is risen around 4 to 9 kPa in comparison to the original pure sand sample. The sample with the lowest percentage exhibited the highest friction angle among the different bacteria contents, but it was only slightly higher than the others. The main effect of the initial bacteria content in relation to the cohesion of the samples. There is a strong relationship between the bacteria content and the cohesion for 50% relative density of SP sand with a mean size of 0.19 mm by using *Pseudomonas sp* bacteria. Under the cyclic changes of temperature and humidity of nature culturing environment, 5% of the initial bacteria content has a cohesion of about 4 kPa. And every 10% increment from 5% leads to about a 2.3 kPa increase in sample cohesion. It has to be noted that this trend of incremental only extends up to a certain bacteria content. This is because environmental conditions limit bacterial growth. For conservative MICP effectiveness testing, an initial bacteria content of 5% was chosen for the following experiments.

3.2 Effects of Culturing Method

Similar to the procedures used to study the effects of the bacteria content, direct shear testing was employed to study the impact of two different culturing methods, namely the immersion and cyclic pumping methods (Fig. 7), designed to simulate two different in-situ conditions: with and without water flow. Samples with the same bacteria content (5%) were cultured by the two aforementioned methods with nutritional liquid type 1. The results in Fig. 6(b) show that there is an insignificant difference between the samples cultured by these two methods. Thus, in further tests, the cyclic pumping method was used to simulate in-situ conditions with dynamic water flow due to hydrological features or rainfall.

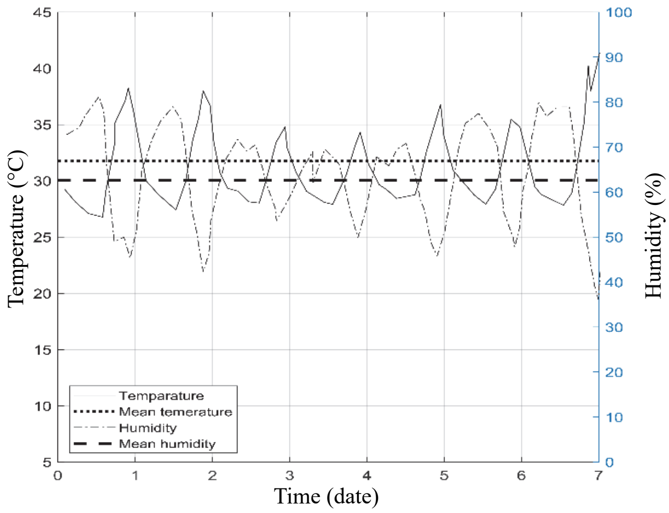
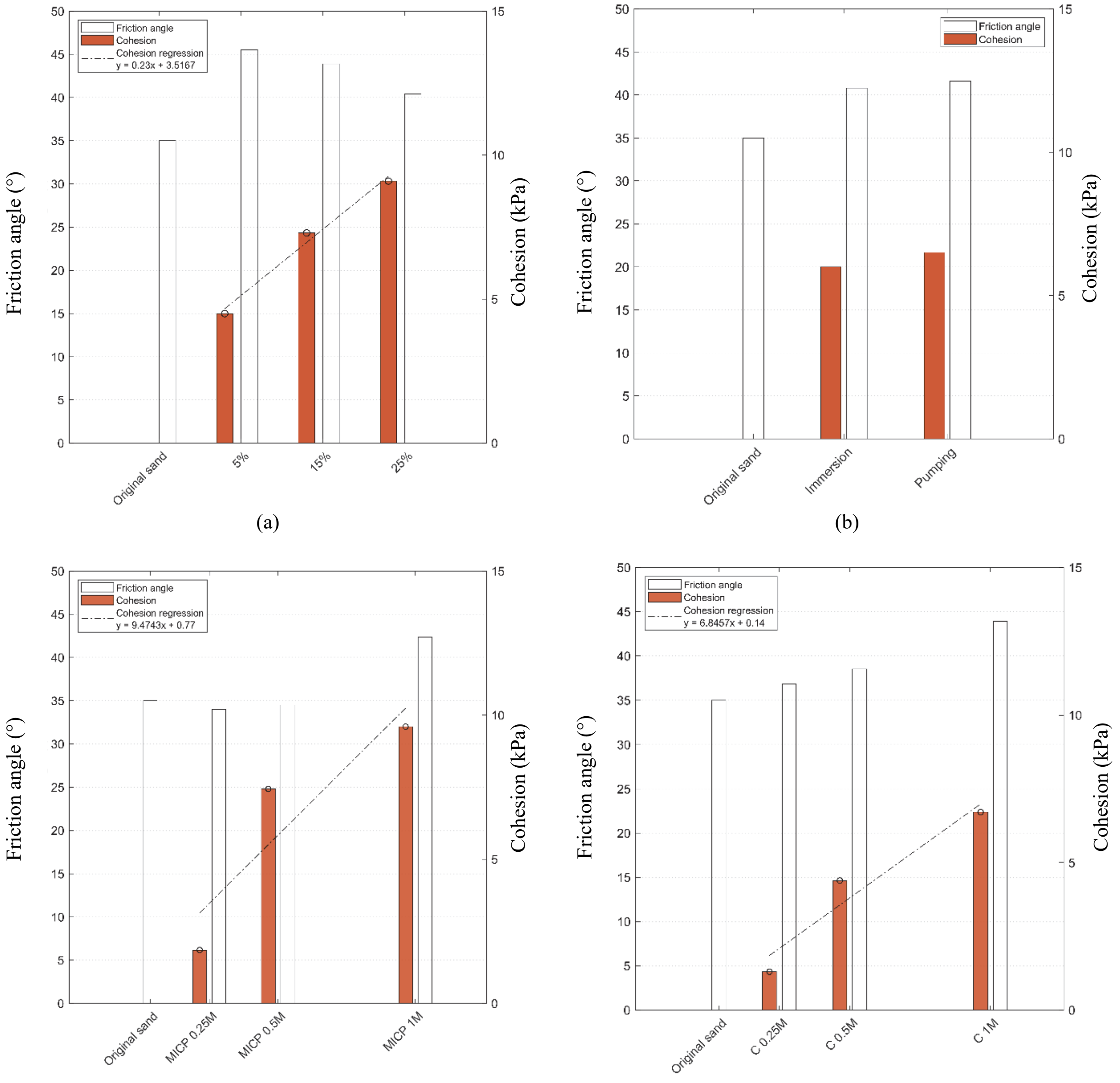


Fig. 5 Temperature and humidity during culturing of samples with different bacteria contents



(a) (b)

(c) (d)

Fig. 6 Direct shear result of (a) different bacteria content, (b) different cultural method, (c) different nutrition concentration, (d) different chemical concentration

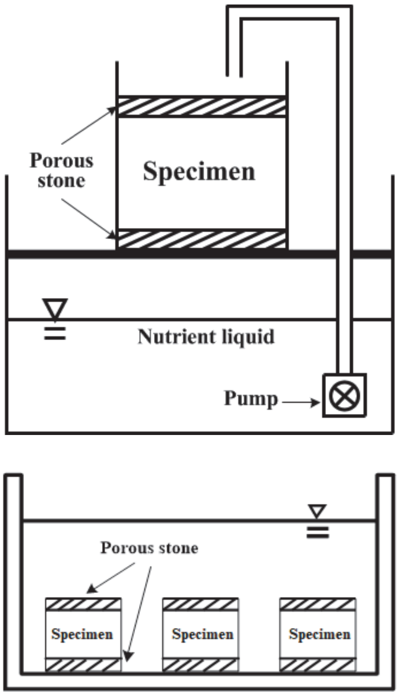


Fig. 7 Culturing methods for cyclic pumping (upper) and immersion (lower)

3.3 Effects of Nutritional Concentration

The nutritional concentration has a critical impact on the results of MICP because the amount of $CaCO_3$ generated is closely related to the quantity of bacterial growth, which can occur very quickly in ideal conditions. The cyclic pumping culturing system was used in these experiments. The prepared samples had a 5% bacterial content in a liquid mixture of urea and calcium chloride (molar ratio of 1:1). The three molar concentrations studied were 0.25, 0.5, and 1.0 M (Table 4). These three values were also tested in the laboratory experiments of Yasuhara *et al.* (2012). As mentioned above, the culturing method was cyclic pumping with the bacteria content was 5%. After seven days of curing, direct shear tests were performed and the results are plotted in Fig. 6(d); the environmental conditions are shown in Fig. 5. The cohesion increased significantly with the higher molarity of the nutrition liquid. The regression slope indicates that the cohesion increased by about 9.5 kPa with an increase in the molarity of the nutrition liquid of 1 M. However, once again, this increment is only valid until a certain nutritional concentration is reached due to the limits of the bio cementation process. The optimal density of the nutrition liquid may need to be determined by further study.

The mass of calcite precipitate was observed by measuring the dry mass of the sample after being washed by an acid (HCl). The amount of calcite precipitate was estimated based on the change in dry unit weight of the samples to be used as the benchmark for determining the chemical concentration required for simulating the MICP results through the chemical method. The void ratio and dry unit weight change are shown in Table 5.

3.4 Chemical Method

In order to mimic the process of the clogging of sand particles by calcium carbonate, Na_2CO_3 and $CaCl_2$ liquid were added to the soil. The resultant chemical reaction produced calcium carbonate ($CaCO_3$) and sodium chloride (NaCl or salt). By generating calcium carbonate through the chemical method, we can increase the bond strength between the sand particles in the same manner as in MICP but at a much higher speed, in a matter of hours rather than weeks.

This method also offers more consistent results because it is less dependent on the temperature and humidity of the environment. However, there is an environmental trade-off because the side product of the chemical reaction is NaCl, which in large concentrations may have adverse effects on the ground environments. Three different chemical liquid concentrations are investigated in this work: C 0.25, C 0.5, and C 1 M. These three values were obtained by a trial and error process based on the benchmark values in Section 3.3. The component ingredients of the liquids are shown in Table 4.

Table 4 Ingredients of nutritional liquid type 2 and chemical method

Category	Sample notation(a)	Ingredients	Mass concentration (g/L)	Molarity (M)
MICP Nutrient liquid type 1	–	Urea	20.0	0.33
		$CaCl_2$	2.8	0.03
		NH_4Cl	10.0	0.19
		$NaHCO_3$	2.2	0.03
		LB broth	3.0	–
MICP Nutrient liquid type 2	MICP 1M	Urea (CH_4N_2O)	60.0	1
		$CaCl_2$	110.0	1
	MICP 0.5M	Urea (CH_4N_2O)	30.0	0.50
		$CaCl_2$	55.0	0.50
	MICP 0.25M	Urea (CH_4N_2O)	15.0	0.25
		$CaCl_2$	27.5	0.25
Chemical method	C 1M	Na_2CO_3	105	1
		$CaCl_2$	110	1
	C 0.5M	Na_2CO_3	52.5	0.50
		$CaCl_2$	55.0	0.50
	C 0.225M	Na_2CO_3	26.3	0.25
		$CaCl_2$	27.5	0.25

(a) All the MICP nutrient type 2 samples cultured by cyclic pumping method with 5% bacteria content.

Table 5 Changes in samples unit weight before and after the curing process

	Method	MICP 1M	MICP 0.5M	MICP 0.25M	C 1M	C 0.5M	C 0.25M
Direct shear	Initial void ratio	0.72					
	Final void ratio	0.65	0.68	0.71	0.66	0.69	0.70
	Initial dry unit weight (g/cm³)	1.51					
	Final dry unit weight (g/cm³)	1.57	1.55	1.52	1.56	1.54	1.52
UCS	Initial void ratio	0.72					
	Final void ratio	0.64	0.69	0.71	0.65	0.69	0.71
	Initial dry unit weight (g/cm³)	1.51					
	Final dry unit weight (g/cm³)	1.59	1.54	1.52	1.58	1.54	0.52

The molds used for the MICP tests were reused in this step to ensure the process similarity. The molded sand was firstly partially saturated with sodium carbonate, and the cyclic pumping system was employed to inject calcium chloride into the samples until saturation. The samples were left at room temperature for one day before performing the direct shear tests. Figure 6(d) shows the results of the direct shear tests for these samples. Clearly, a higher concentration leads to higher shear strength. The regression results indicate an increase in the cohesion of 6.8 kPa with an increase in the chemical molarity of 1 M. The friction angle also increases if higher molarity is used.

3.5 Element Tests for the Specimens Prepared by the MICP and Chemical Methods

The results of direct shear tests for samples prepared using the MICP and chemical methods are plotted in Fig. 8. It can be seen that the results for both ways have the same trend, namely improvement of the mechanical properties whenever the concentration of nutritional liquid or chemical increases. With the same molarity, the cohesion and friction angle close together; however, MICP produces a more considerable value. It is stated that different nutrition types have different effects on the properties of the treated sand. The type-1 cured samples have a higher friction angle, while the type-2 samples seem to have increased cohesion. The trend appears to be similar for the chemical method MICP with similar nutritional concentrations. However, the chemical method offers slightly greater cohesion, and the MICP method offers lower cohesion. With both methods, increasing the nutritional molarity or increasing the bacteria content had a certain effect on the increase of cohesion of the samples.

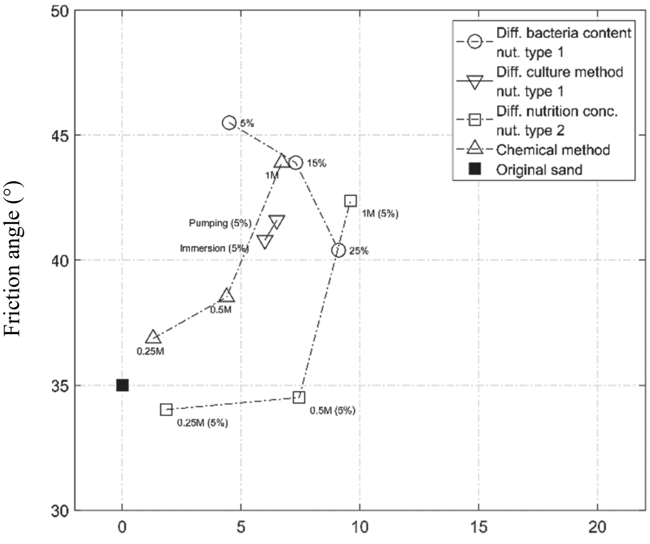
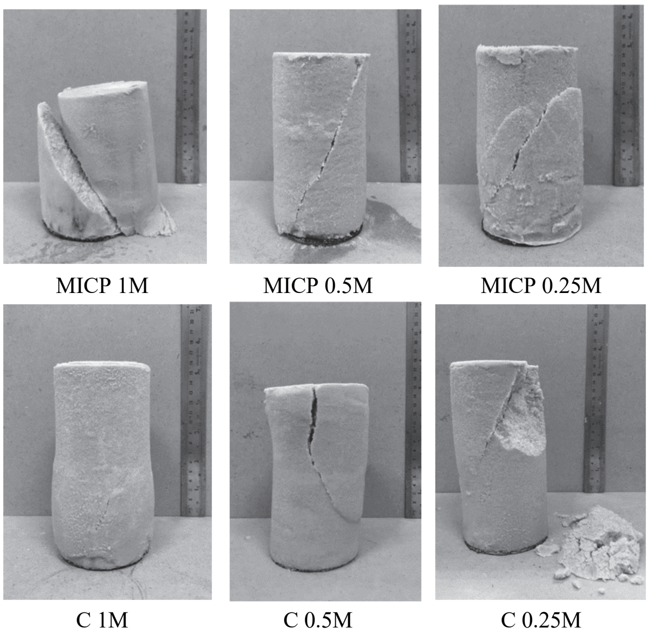


Fig. 8 Scatter plot of friction angle and cohesion

In order to further investigate the differences between the MICP and chemical methods, samples were prepared for unconfined compression tests using a process similar to that used to make the direct shear samples, but with a mold that would meet the requirements for UCS testing. The mold was 72.2 mm of diameter and 150 mm of height. Once again, three values of nutrient concentrations and chemical solutions with three different molarities were employed to improve the mechanical properties of the sand.

Table 6 shows the results of the UCS tests. The average values of UCS for the MICP method and chemical methods are 9.7 and 11.3 kPa, respectively. The standard variation is negligible, less than 1 kPa for both sample groups. Therefore, although showing a clear relationship in the direct shear tests the samples with different nutritional and chemical concentrations exhibited different behavior in the UCS test. This may have contributed to the different failure modes presented by the samples (Fig. 9). The MICP samples showed an ideal failure plane compared to the chemically treated samples. This phenomenon may have been due to the better calcite precipitation distribution with MICP than with the chemical method.


MICP 1M MICP 0.5M MICP 0.25M

C 1M C 0.5M C 0.25M

Fig. 9 Failure modes of MICP and chemically treated samples in UCS tests

In addition, it should be noted that in this work, simpler methods were used for the preparation of samples and different types of bacteria were applied to obtain the UCS results than the more sophisticated techniques used in other studies such as those by Yasuhara *et al.* (2012) and Montoya and DeJong (2015). Therefore, the MICP method may provide different results corresponding to the idealness of the media. Thus, it necessary to understand the various mechanics of MICP for field applications.

Constant head tests were performed to evaluate the hydraulic conductivity of the samples. The samples were cultured directly in the constant head test molds and then saturated and tested. The results of the tests are shown in Table 6. The average hydraulic conductivity of several samples is 0.08 mm/sec. Clearly, the clogging effect of calcium carbonate, which infills the space between the sand particles decreases the velocity of the water flow through the sand samples compared to the original sand without treatment, but the difference is negligible.

Table 6 Hydraulic conductivity and unconfined compression strength

Sample code	Hydraulic conductivity (mm/sec)	Unconfined compression strength (kPa)
Original sand	0.0931	–
MICP 1M	0.0795	10.7
MICP 0.5M	0.0879	11.8
MICP 0.25M	0.0866	11.5
C 1M	0.0754	8.5
C 0.5M	0.0819	10.4
C 0.25M	0.0866	10.1

4. CENTRIFUGE MODELING OF IMPROVED SOIL LIQUEFACTION RESISTANCE

Sasaki and Kuwano (2016) carried out a series of cyclic loading tests on MICP treated sand, Simatupang and Okamura (2017) also studied the cyclic loading behavior of enzymatically induced calcite precipitation (EICP), a similar method to MICP, but using an enzyme instead of bacteria. Both found the treated sand to have higher liquefaction resistance than the original sand. In this current research, a centrifuge model was made to study the effects of soil improvement processes in terms of increasing the soil's resistance to liquefaction. The model was made by the pluviation method with the same material employed in the previous experiments for this study. Several blue-colored sand layers were added to the model to make it easy to observe the movement of the soil layers. The centrifuge modeling scaling law based on stress-strain conservation at different stages of artificial gravity is considered in the tests using the scaling factors for several quantities proposed by Kutter (1992), which are listed in Table 7.

Table 7 Scale factors for centrifuge model tests adopted by Kutter (1992)

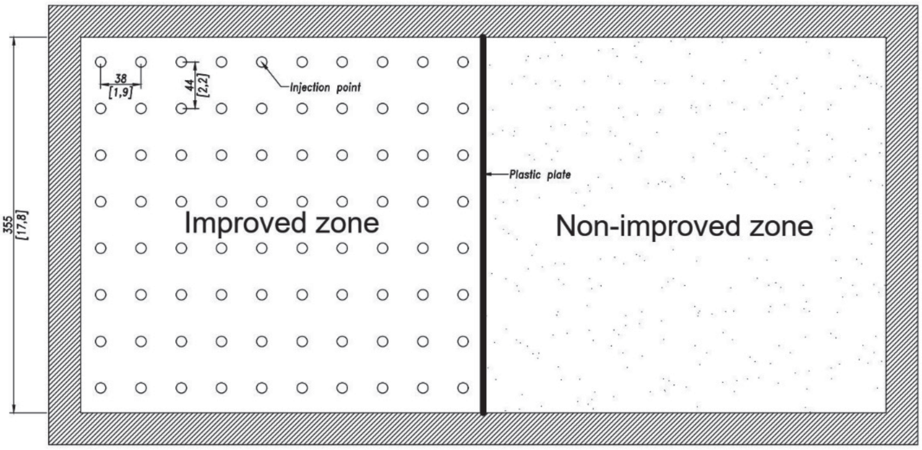
Quantity	Symbol	Units	Scale factor
Length	L	L	N^{-1}
Volume	V	L^3	N^{-3}
Mass	M	M	N^{-3}
Gravity	g	LT^{-2}	N
Force	F	MLT^{-2}	N^{-2}
Stress	σ	$ML^{-1}T^{-2}$	1
Moduli	E	$ML^{-1}T^{-2}$	1
Strength	s	$ML^{-1}T^{-2}$	1
Acceleration	a	LT^{-2}	N
Time (dynamic)	t_{dyn}	T	N^{-1}
Frequency	f	T^{-1}	N
Time (diffusion)	t_{dif}	T	N^{-1} or N^{-2}

For the centrifuge modeling test, a schematic representation of the model is shown in Figs. 10(a) and 10(b). The left part of the model contains the original sand without any improvement, while the upper layer on the right-hand side is improved by the chemical method. The silica sand was pluviated into the rigid container until the model height of 300 mm. The accelerometers and pore water pressure transducers were embedded to monitor the acceleration time history and the generation and dissipation of excess pore water pressure. Also, the linear variable differential transformers (LVDT) are used to monitor the surface settlement of the sand layer after the seismic response. After pluviation, the relative density of the sandy model is about 50.12%. In order to simulate the prototype fluid flow rate in a dynamic test, the model was saturated with Na_2CO_3 (1 M) *via* a vacuum system, then $CaCl_2$ with a molarity of 1 M was injected into the sand layer using a needle (maximum depth of injection was 5 m or 100 mm on the model scale) and have about 0.675 kg of $CaCO_3$ precipitate inside the void volume of the sand stratum. During model saturation, the air inside the container was simultaneously and continuously vacuumed out until the fluid level rose to the predetermined elevation. The injection was performed in a square pattern, as shown in Fig. 10(c). The two parts were separated by a plastic plate to minimize the effect on each other. There are several reasons for choosing the chemical method over the MICP method for centrifuge testing. First, the chemical process requires less model preparation time than the MICP, which could take over one week. Second, the MICP method is more sensitive to environmental conditions, especially the temperature of the soil. However, as mentioned previously, the chemical method seems to be less effective than the MICP method in some circumstances. Thus, the results of the effects of soil improvement to counter liquefaction are conservative.

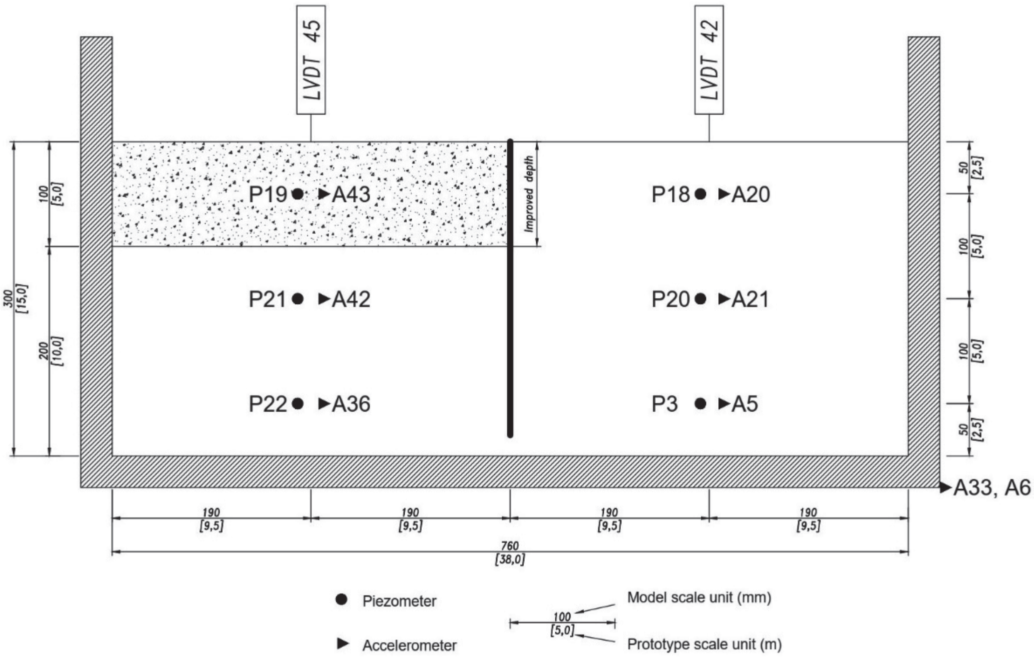
The centrifuge model was equipped with several transducers to measure pwp, acceleration, and the settlement on each side. A schematic of the transducer arrangement is plotted in Fig. 10(a) and 10(b). The artificial acceleration was increased stepwise to 50 times the earth's gravity or 50 g for short. The model was then subjected to shaking generated by a servo-hydraulic shaking table which was mounted at the base of the centrifuge bucket. The shaking had a magnitude of 0.2 g, a frequency of 1 Hz and lasted for 15 seconds. The shaking generated excess pwp that liquefied the soil at a shallow depth.

The acceleration histories along the model are shown in Fig. 11. The accelerometer responses were similar on both sides of the model. At a depth of 12.5 m, the acceleration had a consistent shape corresponding to the input shaking; the magnitude of the shaking did not significantly decrease until the last 4 cycles. Indicated that at this depth, there was no significant liquefaction. The decreased acceleration over the last few cycles was caused by a decrease in the shear strength of the soil subjected to cyclic loading.

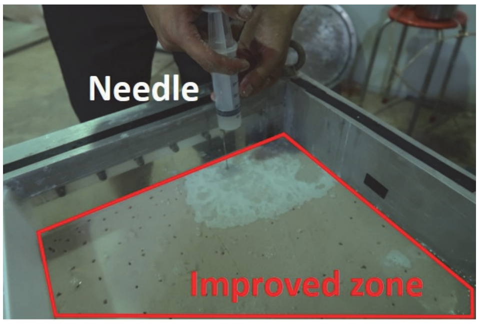
In contrast, at depths of 2.5 m and 7.5 m, the magnitude of acceleration significantly decreased after the first few cycles. This reduction contributed to the phenomenon of liquefaction observed by the pwp transducers and will be discussed further later. However, there were some differences between the improved layer and



(a) Top view



(b) Side view



(c) Chemical injection

Fig. 10 Centrifuge model schematic and chemical injection process

the non-improved layer. The maxima acceleration at the center of the improved sand layer (Acc. 43) during the first 3 cycles was about 0.3 g with a significant decrease to 0.1 g on average near the end of the shaking event; the corresponding values for the non-improved layer (Acc. 20) were 0.12 g and 0.05 g, respectively. Thus, the magnitude of the acceleration in the improved sand layer was almost double the value in the non-improved layer. This means that the shear strength of the enhanced layer remains higher even after being subjected to the shaking. As shown by the basic test results in previous reports, the improved sand layer has a higher shear strength than the untreated one; thus, a higher acceleration response can be expected. The shear wave velocity can be estimated based on the acceleration histories (Lee *et al*. 2012). The shear wave velocities of the improved and unimproved layers are 133 and 90 m/s, respectively.

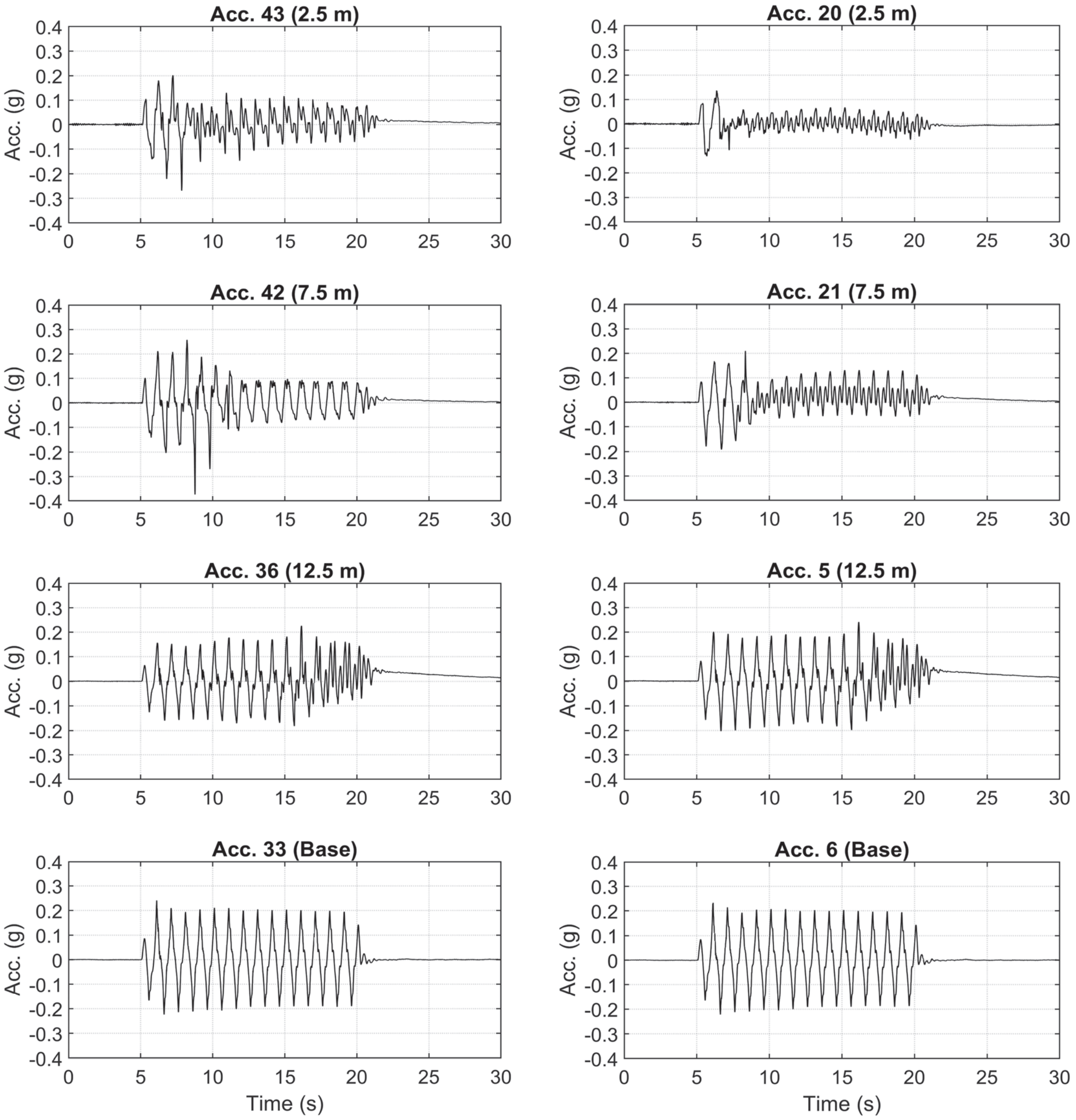


Fig. 11 Acceleration history of centrifuge model during shaking

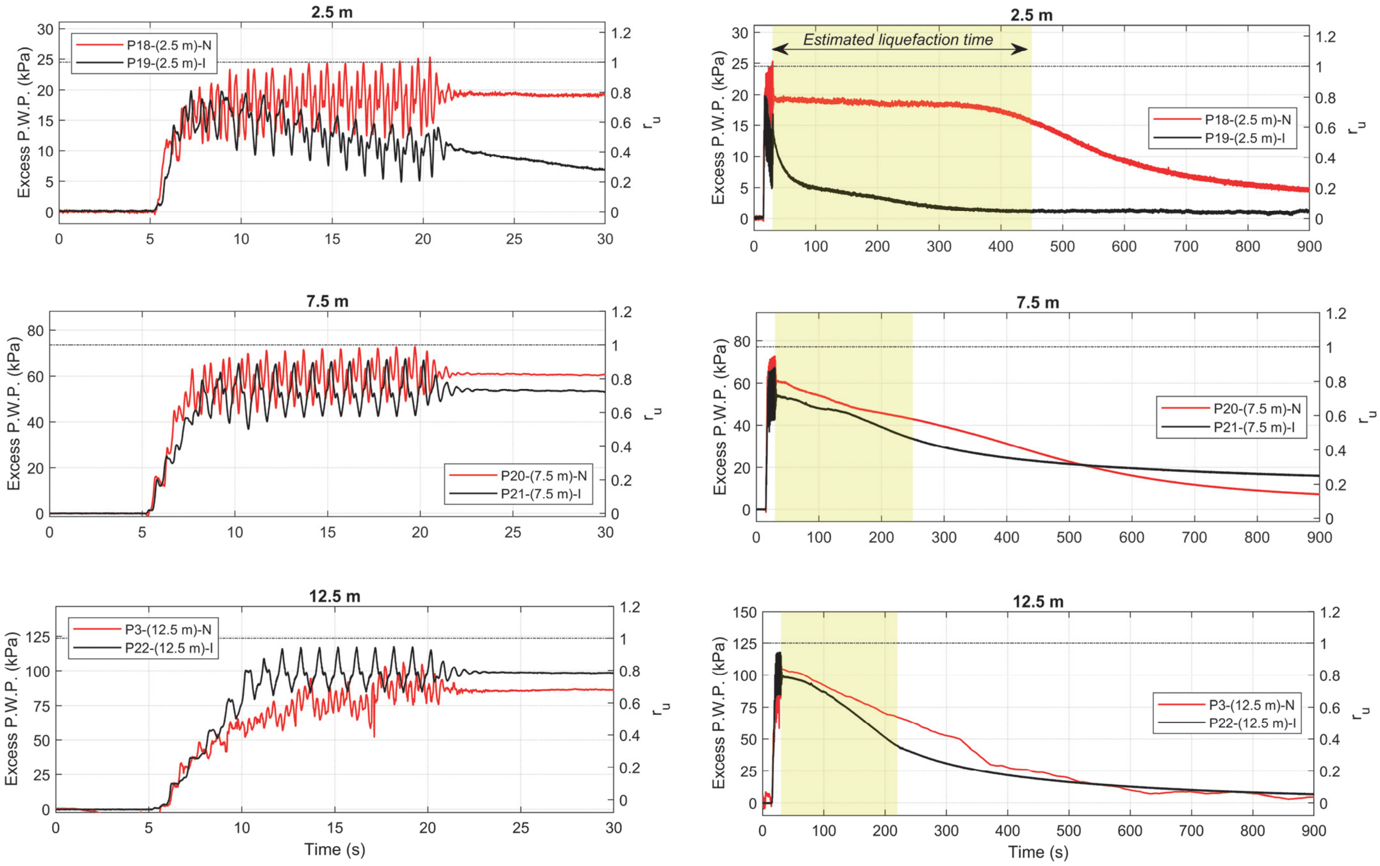
Figure 12(a) shows the excess pwp and the excess pwp ratio (r_u), which was computed by taking the ratio between the excess pwp and the initial effective stress. At a shallow depth (2.5 m) in the treatment zone, the excess pwp decreases much faster than in the non-improved area, but in the deeper layer where the chemical substance may not have much of an effect, the excess pwp history of both sides is almost identical. On the other hand, the dissipation time of the excess pwp is much faster in the improved zone than in other places. Figure 12(b) shows the dissipation time throughout the model. Dissipation of excess pwp took about 400 seconds in the improvement zone took about 400 seconds but at least 800 seconds in the other zones.

The enhancement of the strength of the improved zone leads to the resultant improvement in the acceleration and pwp, thus decreasing the settlement of the sand layer. Figure 13 plotted the settlement of each side in the model measured by two LVDTs on the surface. The total settlements of the improved and non-improved zones were 0.39 m and 0.42 m, respectively.

5. CONCLUSIONS

Laboratory tests and centrifuge modeling tests help users to evaluate the feasibility of the calcite precipitation method for in-situ construction applications. The following conclusions can be drawn:

- After improvement by $CaCO_3$ precipitation, the sand layer exhibited a greater shear strength and therefore increased its resistance against the hazard of liquefaction. Due to the enhancement of the strength, the improved zone has a higher amplitude of acceleration and shorter excess pwp dissipation time. During seismic loading, the initial liquefaction state did not occur at the improved zone; the r_u only increased to 0.8 during the initial period (in 10 seconds) and quickly dissipated to a steady-state.
- The results of the surface settlement and shear wave velocity show a reduction in the void volume in the improved zone compared to the unimproved area for the same main shaking event.



(a) Excess pwp (b) Excess pwp ratio

Notation P3 – (12.5 m) – N stand for [transducer no.] – [depth] – [Non-improvement side]

Fig. 12 Pore water pressure (PWP) and pore water pressure ratio (r_u) during shaking

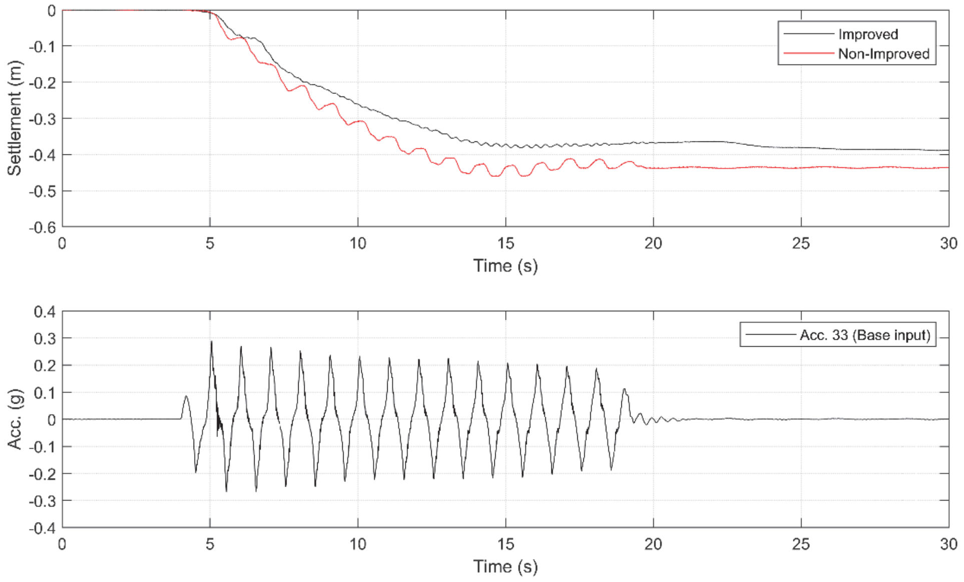


Fig. 13 Surface displacement of model

- The MICP method may be affected by the curing environment, such as temperature and humidity. The two different culturing methods used in this study (immersion and cyclic pumping) did not have a significant effect on the mechanical properties of the soil. The bacterial content also had some impact on the shear strength of the improved sample. The nutritional concentration seems to have a critical effect on the improvement in the mechanical properties.
- As mentioned above, MICP may be affected by the culturing environment so it takes more time to produce the desired results but with the chemical method, the reaction needed to produce similar mechanical properties can be completed

more rapidly time, with less dependence on the environment. However, the chemical method has a negative effect on the soil environment and thus more investigation is needed before using it on an industrial scale.

- By using a less sophisticated culturing method than which was used in previous research, we were able to produce samples that could be subjected to an environment that is closer to an in-situ one. Therefore, the archived shear strength is lower than has been found in previous studies. So the differences between the laboratory and field conditions should be taken into account when employing MICP.

ACKNOWLEDGMENTS

The authors would like to thank the Laboratory of Geotechnical Centrifuge and Shaking Table, National Central University, Taiwan for their technical support. These supports made this study and further research possible.

FUNDING

The authors received no funding for this work.

DATA AVAILABILITY

The data presented in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

REFERENCES

Chang, D.H., Rhee, M.S., Kim, J.S., Lee, Y., Park, M.Y., Kim, H., Lee, S.G., and Kim, B.C. (2016). "Pseudomonas kribbensis sp. nov., isolated from garden soils in Daejeon, Korea." *Antonie van Leeuwenhoek Journal of Microbiology*, **109**, 1433-1446. https://doi.org/10.1007/s10482-016-0743-0

Darby, K.M., Hernandez, G.L., Dejong, J.T., Boulanger, R.W., Gomez, M. G., and Wilson, D. W. (2019) "Centrifuge Model Testing of Liquefaction Mitigation via Microbially Induced Calcite Precipitation." *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, **145**, 04019084. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002122

Feng, K. and Montoya, B. M. (2017) "Quantifying Level of Microbial-Induced Cementation for Cyclically Loaded Sand." *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, **143**, 06017005. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001682

Ishihara, K. (1985). "Stability of natural deposits during earthquake." *Proceedings of 11th International Conference on Soil Mechanics and Foundation Engineering,* San Francisco, **1**, 321-376.

Ivanov, V. and Chu, J. (2008). "Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ." *Environmental Science and BioTechnology*, **7**, 139-153. https://doi.org/10.1007/s11157-007-9126-3

Kutter, B.L. (1992). "Dynamic centrifuge modeling of geotechnical structures." *Transportation Research Record*, 1336, 24-30.

Lee, C.J., Wang, C.R., Wei, Y.C., and Hung, W.Y. (2012). "Evolution of the shear wave velocity during shaking modeled in centrifuge shaking table tests." *Bulletin of Earthquake Engineering*, **10**, pp. 401-420. https://doi.org/10.1007/s10518-011-9314-y

Liu, S. and Gao, X. (2020) "Evaluation of the Anti-Erosion Characteristics of an MICP Coating on the Surface of Tabia." *Journal of Materials in Civil Engineering,* ASCE, **32**, 04020304. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003408

Montoya, B.M. and DeJong, J.T. (2015). "Stress-Strain Behavior of Sands Cemented by Microbially Induced Calcite Precipitation." *Journal of Geotechnical and Geoenvironmental Engineering,* ASCE, **141**, 191-210. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001302

Montoya, B.M., Dejong, J.T., and Boulanger, R.W. (2013). "Dynamic response of liquefiable sand improved by microbial-induced calcite precipitation." *Géotechnique*, **63**, 302-312. https://doi.org/10.1680/geot.SIP13.P.019

Peng, J., He, X., Liu, Z.M., Feng, Q.P., and He, J. (2016). "Experimental research on influence of low temperature on MICP-treated soil." *Chinese Journal of Geotechnical Engineering*, **38**, 1769-1774. https://doi.org/10.11779/CJGE201610004

Riveros, G.A. and Sadrekarimi, A. (2020) "Liquefaction resistance of Fraser River sand improved by a microbially-induced cementation." *Soil Dynamics and Earthquake Engineering*, **131**, 106034. https://doi.org/10.1016/j.soildyn.2020.106034

Sasaki, T. and Kuwano, R. (2016). "Undrained cyclic triaxial testing on sand with non-plastic fines content cemented with microbially induced $CaCO_3$." *Soils and Foundations*, **3**, 485-495. https://doi.org/10.1016/j.sandf.2016.04.014

Simatupang, M. and Okamura, M. (2017). "Liquefaction resistance of sand remediated with carbonate precipitation at different degrees of saturation during curing." *Soils and Foundations*, **57**, 619-631. https://doi.org/10.1016/j.sandf.2017.04.003

Whiffin, V.S., van Paassen, L.A., and Harkes, M.P. (2007). "Microbial Carbonate Precipitation as a Soil Improvement Technique." *Geomicrobiology Journal*, **24**, 417-423. https://doi.org/10.1080/01490450701436505

Xiao, P., Liu, H., Stuedlein, A.W., and Evans, T.M. (2018) "Liquefaction resistance of bio-cemented calcareous sand." *Soil Dynamics and Earthquake Engineering*, **107**, 9-19. https://doi.org/10.1016/j.soildyn.2018.01.008

Yasuhara, H., Neupane, D., Hayashi, K., and Okamura, M. (2012). "Experiments and predictions of physical properties of sand cemented by enzymatically-induced carbonate precipitation." *Soils and Foundations*, **52**, 539-549. https://doi.org/10.1016/j.sandf.2012.05.011

Zhang, X., Chen, Y., Liu, H., Zhang, Z., and Ding, X. (2020) "Performance evaluation of a MICP-treated calcareous sandy foundation using shake table tests." *Soil Dynamics and Earthquake Engineering*, **129**. https://doi.org/10.1016/j.soildyn.2019.105959

Zhao, Q., Li, L., Li, C., Li, M., Amini, F., and Zhang, H. (2014) "Factors Affecting Improvement of Engineering Properties of MICP-Treated Soil Catalyzed by Bacteria and Urease." *Journal of Materials in Civil Engineering,* ASCE, **26**, 04014094. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001013