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DYNAMIC PROPERTIES OF MICP TREATED SAND BASED ON RESONANT COLUMN TEST

Tzu-Lung Kuo [1], Min-Chien Chu [2], Chi-Chin Tsai [3*], Yu-Syuan Jhuo [4], and Louis Ge [5]

ABSTRACT

Previous studies have shown that the Microbial-induced calcite precipitated (MICP) method can enhance the engineering properties of soil. However, the effect of MICP on dynamic soil properties has been rarely explored. Therefore, this study aims to investigate the dynamic properties of MICP-treated sand with varying densities using a resonant column test. Specifically, we compare the small strain shear modulus, shear modulus reduction curve, and damping curve of untreated samples and those treated for different periods. The results show that MICP treatment results in a slight decrease in small strain shear modulus, more reduction in the modulus reduction curve, and higher damping. Dense sand is found to exhibit more changes in dynamic soil properties than loose sand. Therefore, we suggest a correction factor to obtain the modulus reduction curve of MICP-treated sand from that of untreated sand with different relative densities.

Key words: MICP, resonant column test, small strain shear modulus, shear modulus reduction curve, damping curve.

1. INTRODUCTION

Ground improvement is to enhance the soil mechanical properties (*e.g.* compressibility, stiffness), and also needed to improve the reclaimed land for the intense growth of population around the world. The injection of artificial materials (*e.g.* epoxy, fine cement) in soil is a prevailing way of soil improvement. With the rising awareness of environmental concerns, bio-mediated soil improvement becomes one of the choices which would be more economical and eco-friendlier than other grouting methods (DeJong *et al.* 2010; Jongvivatsakul *et al.* 2019). Specifically, the bio-mediated improvement method is found to be more economic ($0.5-9/m^3) than grouting ($2-72/m^3) in sands by Ivanov and Chu (2008).

The used bacteria in bio-mediated soil improvement comprises Sporosarcina pasteurii, Bacillus sphaericus, and Bacillus megaterium. Researches have adopted these bacteria in improving soil mechanical properties (Whiffin *et al.* 2007; De Muynck *et al.* 2010; DeJong *et al.* 2010; Soon *et al.* 2014). Sporosarcina pasteurii is the most commonly used and has been discovered to have higher urease activity as it decomposes urea (CH_4N_2O) into ammonia (NH_3) and carbon dioxide (CO_2) in a process called urea hydrolysis, and induces calcite precipitates (Ramachandran *et al.* 2001; DeJong *et al.* 2006; Duraisamy 2016). For Urease from microorganisms decompose, they utilize the urea (CH_4N_2O) in the environment into ammonia (NH_3) and carbon dioxide (CO_2). Ammonia could be further dissociated ammonium (NH_4^+), bicarbonate ion (HCO_3^-), and hydroxyl ions (OH^-) with water as follows:

$$CO(NH_2)_2+3H_2O \rightarrow 2NH_4^+ + OH^- + HCO_3^- \quad (1)$$

Calcium ion (Ca^{2+}) in the environment combines with bicarbonate ion, and results in calcite precipitation and pure water (Eq. (2)). These chemical reactions result in calcite called the Microbial-induced calcite precipitated (MICP)

$$Ca^{2+}+ OH^- +HCO_3^- \rightarrow CaCO_3 \downarrow +H_2O \quad (2)$$

The uniformity would be an issue in bio-mediated soil improvement. Van Paassen (2009) applies MICP in sand with 100 m^3 in volume and lets the treatment liquid flow through the specimen. The results showed that MICP do increase the unconfined strength of soil. However, the initial density still has great influence on affecting strength. Through their tests, it was found that microbial growth may lower the permeability for treated liquid flowing through. This may cause nonuniformity in treatment, and further in soil strength. According to the findings of Xiao *et al.* (2020), an improved spatial distribution of calcite in triaxial specimens can be achieved by directly mixing the bacteria solution with soils and layering them in a mold. Additionally, Xiao *et al.* (2021) noted that the distribution of calcite in triaxial specimens is influenced by temperature variations. DeJong *et al.* (2014) proposed a way to induce uniform distribution of microbes (which also means uniform calcite) in field application. They drilled 1 hole in center and 4 holes in the corners of a 3 × 3 m on the ground surface. These holes are the injection points for treatment liquid and have successfully produced a uniform distribution of calcite.

The bio-mediated soil improvement is basically contributed by biomineralization which includes the production of greigite, magnetite, and calcite (Kohnhauser 2007). MICP could be used to address the inadequate soil properties (Whiffin *et al.* 2007; De Muynck *et al.* 2008; DeJong *et al.* 2010; DeJong *et al.* 2011; Soon *et al.* 2014; Montoya and Dejong 2015; Nafisi and Montoya 2018). Numerous of researches have shown the effects of MICP on increasing monotonic stiffness (DeJong *et al.* 2006; Mortensen *et al.* 2011; Montoya and DeJong 2015), increasing peak strength

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[1] Master Student, Department of Civil Engineering, National Chung Hsing University, Taiwan.
[2] Postdoctoral Research Fellow, Department of Civil Engineering, National Chung Hsing University, Taiwan.
[3*] Distinguished Professor (corresponding author), Department of Civil Engineering, National Chung Hsing University, Taiwan (e-mail: tsaicc@nchu.edu.tw).
[4] Postdoctoral Research Fellow, Department of Civil Engineering, National Taiwan University, Taiwan.
[5] Professor, Department of Civil Engineering, National Taiwan University, Taiwan.

(DeJong *et al.* 2006; Mortensen *et al.* 2011; Rong *et al.* 2012; Montoya and DeJong 2015), increasing liquefaction resistance (Darby *et al.* 2019; Zamani and Montoya 2019), reducing permeability (Gollapudi *et al.* 1995; Chu *et al.* 2012; Kang *et al.* 2015), and reducing compressibility (Dennis and Turner 1998; Seki *et al.* 1998; DeJong *et al.* 2010).

Compared to the static soil properties, less studies focus on the effect of MICP on dynamic soil properties. Recently, Zhou and Chen (2022) adopted bender element and unconfined triaxial test to evaluate the improvement of strength and enhancement of wave velocity (stiffness) with treatment of soil by MICP, respectively. In their study, the concentration of urea and adding times of calcium chloride are the varying factors. It showed that the 0.75M and 5-time treating would result in highest strength and stiffness, indicating that too many treating may not lead to a higher strength. Na *et al.* (2023) utilized resonant column test to evaluate the change of small-strain stiffness and modulus reduction and damping curves of MICP-treated soils. The result show that soil treated by injection do increase cementation level and the stiffness. Moreover, the modulus reduction and damping curves is also a function of cementation level as indicated by the increment of small-strain stiffness.

As reviewed previously the results of treated soil behaviors might be affected by the treating method and the uniformity of cementation within specimens. Besides, limited researches study on dynamic properties of MICP treated soil, especially for uniformly treated specimens. Hence, there is a need to conduct more research on dynamic properties of the MICP treated soil. In this study, dynamic stiffness of samples with different relative densities after treatments in a small to medium strain level is evaluated by resonant column tests as compared to Na *et al.* (2023) that only considered one specific relative density. Therefore, the modulus reduction and damping of MICP treated soil can be assessed for a wide range of conditions. Moreover, the porewater generation behavior that has not yet been reported previously will be discussed as well. Lastly, unlike prior studies that injected solution into bottom pore lines of triaxial system (Mortensen *et al.* 2011; Martinez *et al.* 2013; Montoya and DeJong 2015), this study used paper molds to soak specimens, which may eliminate concerns about uniform calcium carbonate distribution in soil specimens.

2. LABORATORY TEST PROGRAM

2.1 Materials

The characteristics of adopted Malaysia sand is listed in Table 1, and grain size distribution curve is shown as Fig. 1. The coefficient of uniformity is 1.35 and median grain size (D_{50}) is 0.31 mm. *Sporosarcina pasteurii* is the adopted bacteria in this study due to its wide usage in improving soil properties (Ramachandran *et al.* 2001; DeJong *et al.* 2006) and its highly active urease enzyme (Ferris *et al.* 1996) that is efficient in producing calcite precipitation. The bacteria solution is shown in Fig. 2(a). The growth medium (Fig. 2(b)) provides nutrients for growing *Sporosarcina pasteurii*. The source of urea is reagent grade urea of which contains are over 99%. The source of calcium ion is calcium nitrate.

Table 1 Properties of Malaysia sand

Properties	Value
Specific gravity of solids	2.65
Median size D_{50} (mm)	0.310
Effective size D_{10} (mm)	0.230
Coefficient of uniformity C_u	1.35
Soil type (USCS)	SP
e_{max}	0.940
e_{min}	0.440

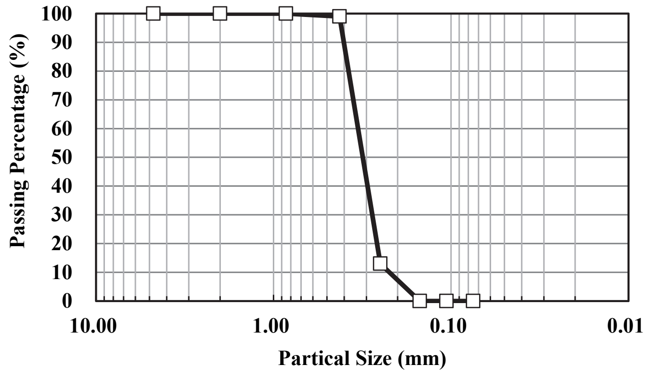


Fig. 1 Grain size distribution curve of Malaysia sand

(a) 50 ml bacterial solution in centrifuge tube

(b) 800 ml medium

Fig. 2 Materials adopted for the MICP improvement

2.2 Preparation of MICP Treated Soil

200 ml bacterial solution, 800 ml medium, and 60.6 g urea are mixed to produce soil improvement solution (total volume is 1000 ml) that has 1 M of urea in concentration. 24-hours air-pumping (Fig. 3) is provided to soil improvement solution to produce proper aerobic cultures for bacteria. Paper molds with dimension of 66 mm and 140 mm in height (shown in Fig. 4(a)) were used for specimens remolding with soil improvement solution. Based on the measured height and diameter of paper molds, the amount of sands for desired densities was determined. Molds were installed with membrane at the bottom (Fig. 4(b)) so that specimens with membrane can be placed at the pedestal of resonant column directly after the microbial induced calcite precipitation. The bottom of molds is placed with filter paper, plastic wrap (Fig. 4(c)) and oversized acrylic plate (Fig. 4(d)). Filter paper could prevent sand loss and make a flat specimen surface. Plastic wrap is used to avoid the leakage of soil improvement solution. The acrylic plate strengthens the stability of plastic wrap. The designated weight of sand for specimens is blended uniformly with 150 ml soil improvement solution and 150 ml calcium nitrate (with 0.21 M in concentration). Then, the mixture is divided into five portions and filled into the paper mold to reach the target density and cured the treated specimen until designated curing period.

Fig. 3 24-hours air pumping for soil improvement solution

2.3 Test Program

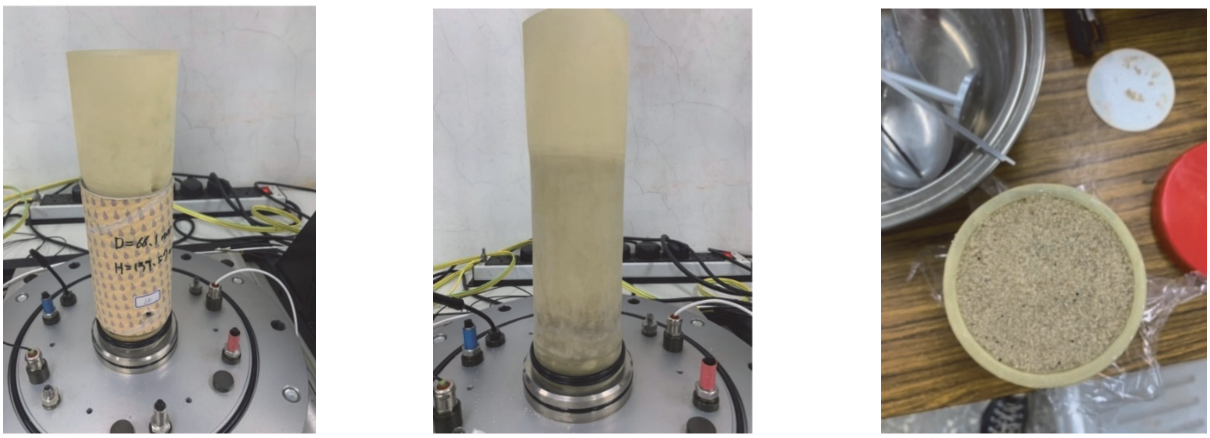
The curing periods of 0, 7, 15, and 30 days were adopted for the specimens with relative densities of 40, 60, and 80. The 0 day mean untreated specimen. The test program is shown in Table 2. After the desired curing period, the paper mold and specimen were placed on the pedestal of the resonant column system (Fig. 5(a)). The paper mold was pulled out, and specimen (Fig. 5(b)) was ready for the resonant column test.

Table 2 Test settings of specimens

No.	Diameter (mm)	Height (mm)	Relative density (%)	Curing time (days)
G01	67.5	138.6	60	7
G02	66.4	139.1	60	15
G03	67.5	138.6	60	30
G04	67.3	140.3	60	7
G06	67.5	138.6	60	30
G07	67	137.8	40	7
G08	67.2	138.3	40	15
G09	67.0	137.8	40	30
G10	67.0	137.8	40	7
G11	66.8	137.6	40	15
G12	66.1	139.6	40	30
G13	67.4	138.8	80	7
G15	67.2	138.3	80	30
G16	67.0	139.0	80	7
G17	66.8	137.7	80	15
G18	67.2	138.3	80	30
G19	66.9	138.8	80	7
G20	67.2	138.3	80	15
N05	70.0	140.0	40	0 (untreated)
N06	70.0	140.0	60	0 (untreated)
N07	70.0	140.0	80	0 (untreated)

(a) Top view of mold (b) Membrane and mold (c) Plastic wrap, membrane and mold (d) Acrylic plate on the bottom of mold

Fig. 4 Paper mold for Malaysia sand



(a) Treated specimen with paper mold (b) Specimen on the testing system (c) Specimen after 15 days curing period

Fig. 5 Specimen preparation

The specimens were applied back pressure (600 kPa) to increase the saturation degree until reaching 0.95 in B value, and the consolidation stress is 100 kPa for all specimens. The Stoke-type resonant column system was used in this study to measure the dynamic responses of soils at small strain level. By propagating waves in a range of frequencies, the resonant frequency could be obtained. The frequency could be used in evaluating the wave velocity and stiffness of soils. The damping could be obtained from the shape of free vibration decay curve. The pore water pressure generation would also be measured during the undrained tests by the pore pressure transducers.

3. TEST RESULTS

Figure 6 shows shear modulus versus strain under with different relative density (Dr) of untreated samples and treated sample for different days. The small strain shear modulus is defined as G_{max}. For the untreated specimen, an increase in Dr results in an increase in G_{max}, which is consistent with findings from prior research. G_{max} can be estimated empirically by using the following equation (Hardin and Drenevich 1972):

$$G_{max} = A \cdot \frac{(2.17 - e)^2}{1 + e} \cdot \left(\frac{\sigma'_v}{100} \right)^{0.5} \tag{1}$$

Here, σ'_v represents the vertical effective stress, e denotes the void ratio, and A is a calibrated model constant with a value and is found as 67 (MPa) for untreated samples. The obtained value falls within a similar range as suggested by Hardin and Drenevich (1972) (typically 100 MPa), which indicates the accuracy and reliability of the test results. In comparison to untreated samples, the shear modulus reduction changes with different curing times. Specifically, the G_{max} (maximum shear modulus) and the shape of the curve both show alterations. It seems that as the curing time increases, the shear modulus experiences a more pronounced drop in strain level of 0.01% to 0.02%. Further details regarding the differences between the treated and untreated samples will be discussed later.

Figure 7 shows maximum shear modulus versus days of treatment with different Drs. G_{max} of some treated soil is higher than that of untreated one and some are lower. Generally, the G_{max} of treated soil samples is mostly lower than that of untreated ones. Even in the case of the sample treated for 15 days, which exhibited a relatively higher G_{max} than other treated samples, the value was still lower than that of the untreated sample. This trend was observed for all Drs. The decreased G_{max} of the treated soil is opposite to the general observation of increased static stiffness (DeJong *et al.* 2006; Mortensen *et al.* 2011; Montoya and DeJong 2015). The possible reason for the discrepancy is discussed in detail later.

Figure 8 shows the comparison of modulus reduction treated with different days given a Dr. The treated soil exhibits a higher degree of degradation compared to the untreated soil. Nevertheless, there is no apparent correlation between the extent of degradation and the duration of treatment. Consequently, a mean curve of all treatment days and its corresponding standard deviation (represented by the dashed line) were plotted and compared with the untreated curve in Fig. 9. Generally, the more degradation of

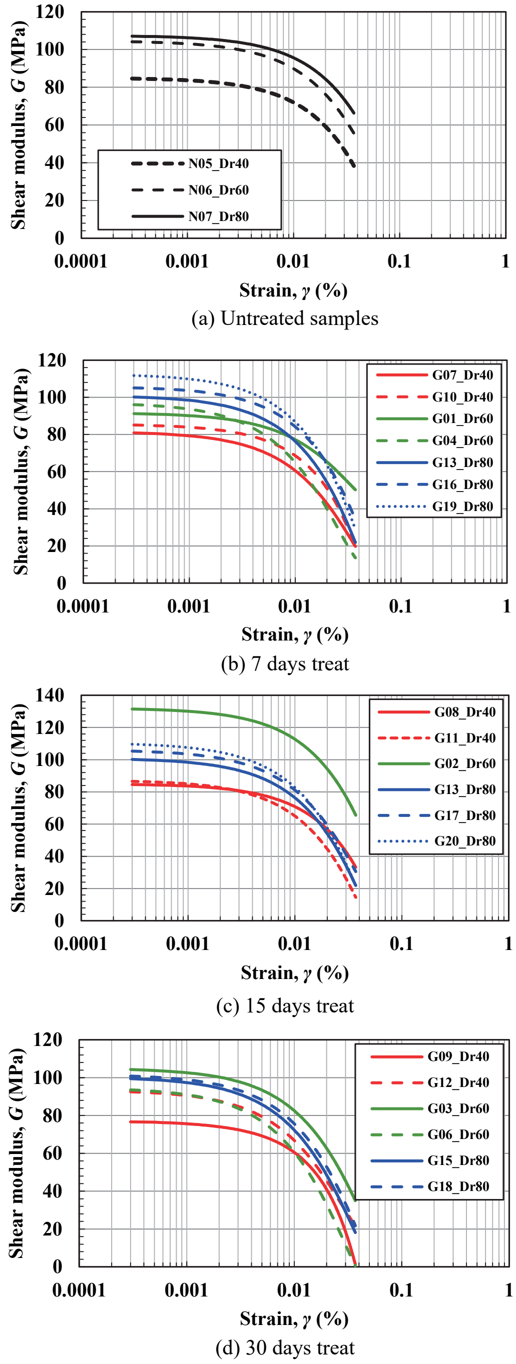


Fig. 6 Shear modulus versus strain with different Drs

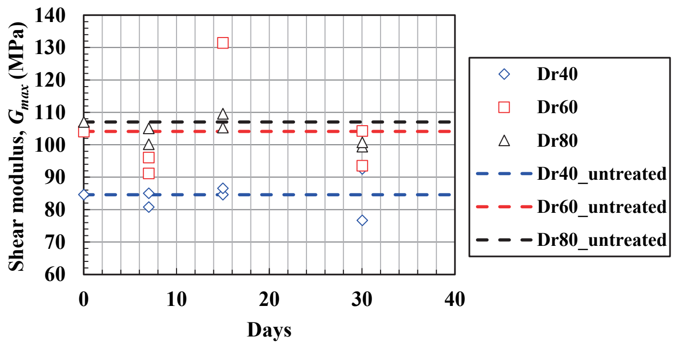
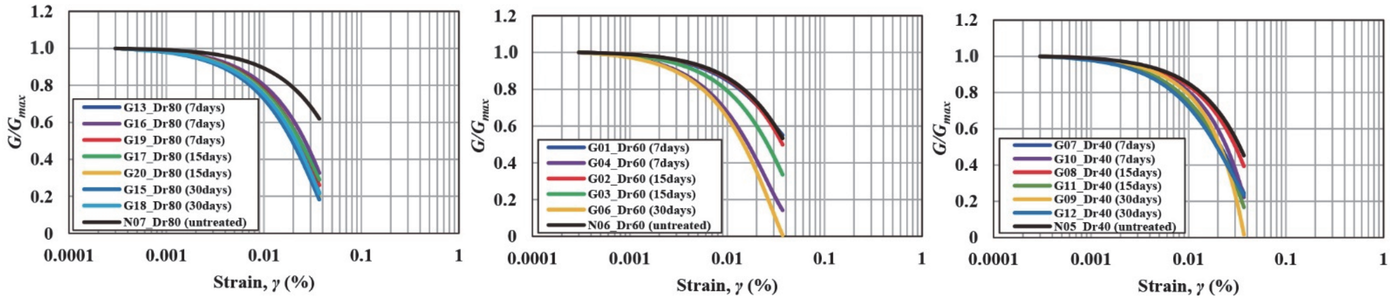
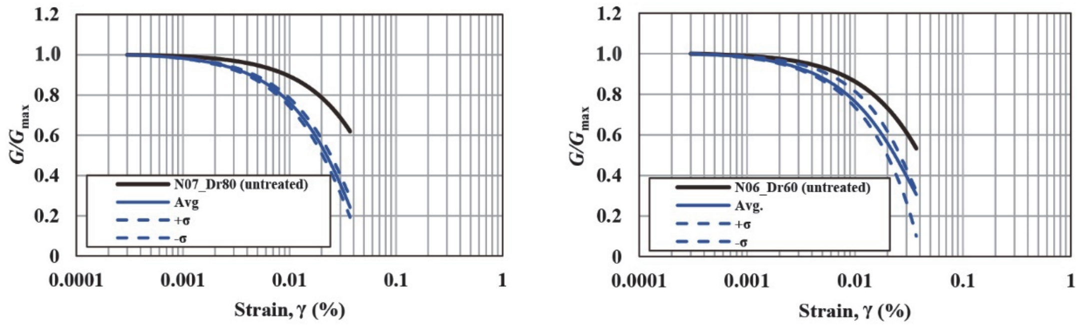


Fig. 7 Maximum shear modulus versus days of treatment with different Drs

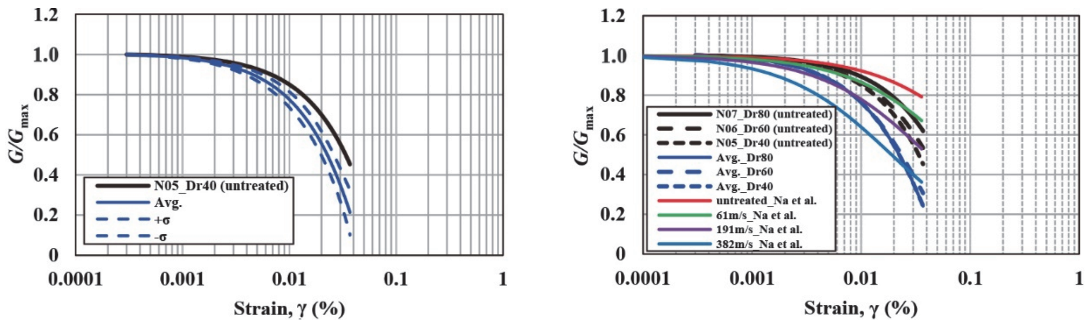


(a) Dr = 80% (b) Dr = 60% (c) Dr = 40%

Fig. 8 Shear stiffness versus shear strain of treated and untreated specimens



(a) Dr = 80% (b) Dr = 60%



(c) Dr = 40% (d) Comparison with previous study

Fig. 9 Normalized shear stiffness versus shear strain

treated soil is consistent with the previous study (Na *et al.* 2023a, 2023b) (Fig. 9(d)). Besides, as Dr increases, the treated soil displays more degradation compared to the untreated soil. The reason could be that the samples after treatment exhibit more obvious tendency toward brittle-like behavior than untreated sample. Consequently, the stiffness reduction would be more severe in the range of 0.01%-0.02% strain level.

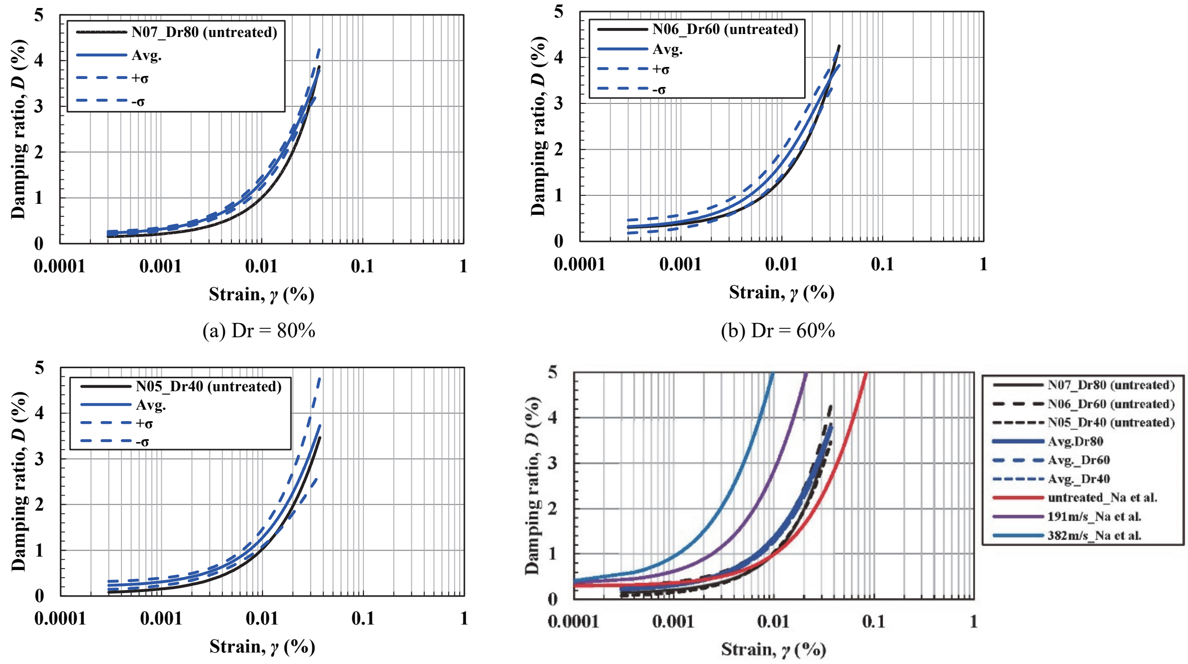
Figure 10 compares the damping curve with and without treatment. Overall, the damping ratio of the treated soil is higher than that of the untreated soil, which is consistent with the previous study (Fig. 10(d)) (Na *et al.* 2023a, 2023b). The results tagged with 61 m/s, 191 m/s, and 382 m/s are from Na *et al.*(2023a, 2023b) which expressed the cementation level indicated by the increment of shear wave velocity. Nevertheless, this difference is not as significant as the disparity observed in the modulus reduction curve. The increase in damping ratio can be attributed to the greater modulus reduction (*i.e.,* nonlinearity) observed in the treated soil, in accordance with Masing's rule (Masing 1926; Krammer 1996).

4. DISCUSSION

4.1 Change of G_{max}

Previous studies (*e.g.* DeJong *et al.* 2006; Mortensen *et al.* 2011; Montoya and DeJong 2015; Na *et al.* 2023a, 2023b**)** have shown that stiffness of treated soil is mostly higher than the untreated soil. However, some studies also reported the opposite trend as observed in this study. For example, Fig. 11 shows the stress-strain curve obtained from the static loading (CD test) (Jhuo *et al.* 2023). Despite the fact that the treated soil exhibited greater strength due to the cohesion induced by MICP, its stiffness remained lower than that of untreated soil, particularly at small strain ranges. Both the dynamic and static test results indicate that MICP treatment may reduce the stiffness of soil, particularly at small strain levels.

As pointed by Na *et al.* (2023a), the possible reason of inconsistent observation could be due to slippage occurs between the loading platen and the specimen during the resonant column (RC) test, which may lead to a misinterpretation of results. The potential



(a) Dr = 80%

(b) Dr = 60%

(c) Dr = 40%

(d) Comparison with previous study

Fig. 10 Damping ratio versus shear strain

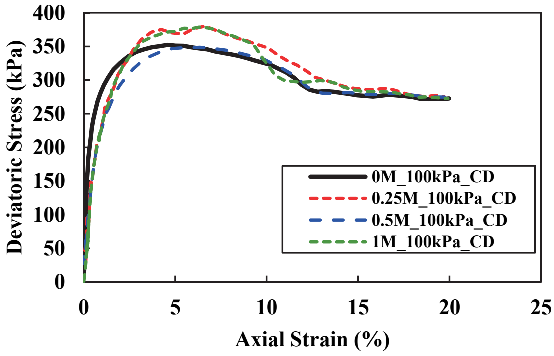
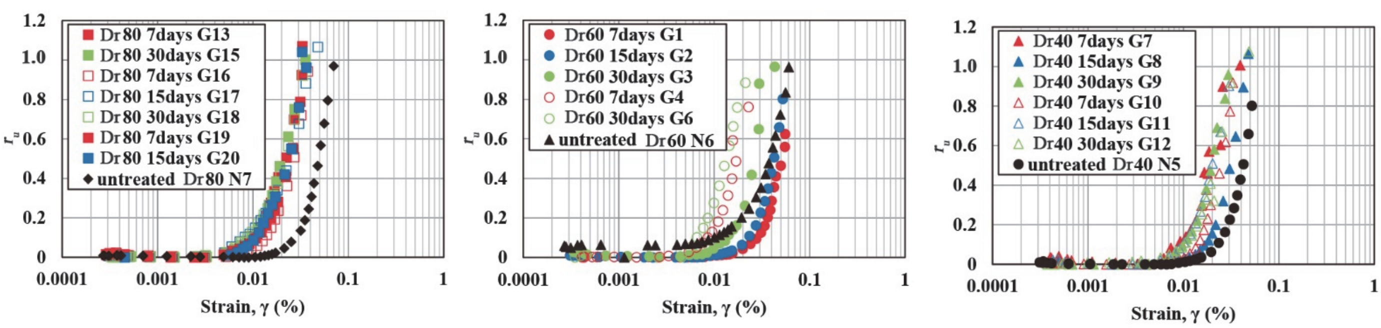


Fig. 11 Stress-strain curves for different calcium ion concentrations (from Jhuo *et al.* 2023)

for slippage increases as the treated soil become more bounded and stiffer and thus cannot be embed into the groove of loading plate. The researcher may follow the method suggested by Na *et al.* (2023a) to overcome the issue of slippage during the specimen preparation.

4.2 Threshold Strain

During the undrained test, monitoring of the pore water pressure is conducted. Figure 12 illustrates the ratio of the accumulated pore water pressure to the initial effective confining stress (100 kPa), known as r_u. In the case of untreated soil, the pore water pressure begins to accumulate at 0.01%-0.02%, which is consistent with the threshold strain observed in other studies on sandy soil (Hsu and Vucetic 2006). On the other hand, the treated soil shows pore water pressure accumulation at 0.005%-0.01%, indicating a lower threshold strain than untreated soil. This observation suggests that the treated soil is more susceptible to volume change and pore water pressure accumulation, and may explain the higher level of modulus reduction observed in the treated soil. The observation is consistent with that threshold strain decreases as cementation levels increase (Na *et al.* 2023a, 2023b). The observed threshold strain of treated soil is corresponding to that of low cementation level (1.25%). According to Na *et al.* (2023a), the decrease in the threshold strain is likely related to an increase in the brittle nature of the MICP-cemented sands. As the cemented bonds break due to the applied loading, the microstructure of the soil



(a) Dr = 80%

(b) Dr = 60%

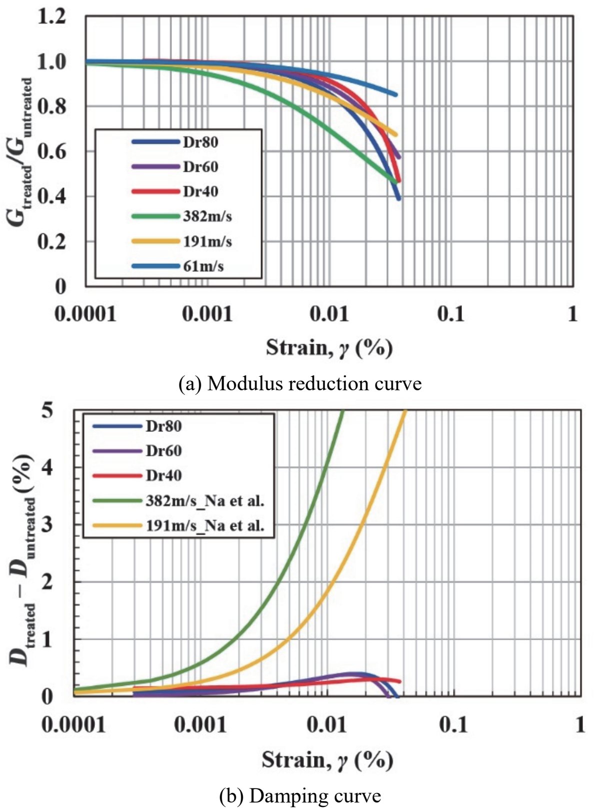
(c) Dr = 40%

Fig. 12 Excess pore water pressure ratio versus shear strain

evolves, and the soil experience volume change. Consequently, the strain level at which the breakage of cementation occurs is approximately 0.005%-0.01%. This finding is consistent with the observations by DeJong *et al.* (2006), which also suggest that the breakage of cement bonds may take place between large and small strains, closer to the small strain levels due to its brittle nature.

4.3 Quantifying the Influence of Treatment on Dynamic Properties

Figure 13 shows the correction factor ($G_{treated}/G_{untreated}$ and $D_{treated} - D_{untreated}$) to modify the modulus reduction curve and damping curve of original (untreated) soil to those of lightly treated soil, respectively. For the modulus reduction, the correction is depending on the relative density. As Dr increase, a lower correction factor is needed to adjust the original modulus reduction curve. The amount of correction is consistent with those of light to medium treated soil found in Na *et al.* (2023b). On the other hand, adding damping (~0.2%) is required to represent the condition of treated soil. However, the amount of increase is independent of Dr.



(a) Modulus reduction curve

(b) Damping curve

Fig. 13 Correction factor for dynamic curve

5. CONCLUSIONS

This study investigated the dynamic properties of MICP-treated sand with varying densities using a resonant column test. In summary, the results has demonstrated the effects of MICP treatment on the dynamic properties of soil, and has highlighted the need for further research to fully understand and optimize the treatment. Specifically, the results indicate that while MICP treatment has noticeable influence on the engineering properties of soil, such as by inducing cohesion, it can also have negative effects on the stiffness of soil, particularly at small strain levels. In addition, the treated soil exhibited a higher degree of degradation, increased damping ratio, and greater susceptibility to pore water pressure accumulation and volume change.

These findings suggest that MICP treatment should be optimized for various soil types and conditions. Moreover, the results of this study highlight the need for further research to fully understand the effects of MICP treatment on soil behavior and to develop strategies for mitigating any negative effects.

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DATA AVAILABILITY

The data generated 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.

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