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An experimental study on dynamic response for MICP strengthening liquefiable sands

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Abstract: The technology of bio-grouting is a new technique for soft ground improvement. Many researchers have carried out a large number of experiments and study on this topic. However, few studies have been carried out on the dynamic response of solidified sand samples, such reducing liquefaction in sand. To study this characteristic of microbial-strengthened liquefiable sandy foundation, a microorganism formula and grouting scheme is applied. After grouting, the solidified samples are tested via dynamic triaxial testing to examine the cyclic performance of solidified sand samples. The results indicate that the solidified sand samples with various strengths can be obtained to meet different engineering requirements, the use of bacteria solution and nutritive salt is reduced, and solidified time is shortened to 1-2 days. Most importantly, in the study of the dynamic response, it is found that the MICP grouting scheme is effective in improving liquefiable sand characteristic, such as liquefaction resistance.

Keywords: bacteria; bio-grouting; microorganism induced $CaCO_3$ precipitation (MICP); grouting scheme design; dynamic response

1 Introduction

The construction of large infrastructure cannot avoid breaking through the soft soil layer, and the traditional method of strengthening liquefied soil foundations needs improvement. Liquefaction occurs when vibrations of an earthquake cause a soil to lose strength until the effective stress is zero, and then flow in a water environment, which needs to be addressed and solved in civil engineering practice. Physical reinforcement methods generate high construction costs. Meanwhile, chemical grouting methods based on cement, epoxy resin and silicate result in high energy consumption and emissions which lead to environmental pollution, and have been prohibited in many countries (Fkramer, 1996; Karol, 2003).

Microorganism induced $CaCO_3$ precipitation (MICP) is completely different from traditional methods. Comparatively, MICP is an environmental friendly technology (Le *et al*.,1999), and it has become a popular research subject in recent years (De *et al*., 2010; Ivanov and Chu, 2008). MICP technology has been used in waste water treatment, fixation of heavy metal ions in soil and surface repair of limestone (Stocks-Fischer *et al*., 1999; Hammes *et al*., 2003; Li *et al*., 2013). Researchers have already made some important inroads on the practical application of MICP to improve sand strength and stability, and have carried out a number of experiments and studies at the elemental dimension and model level (DeJong *et al*., 2006, 2010; Whiffin *et al*., 2007; Harkes *et al*., 2010; Warren *et al*., 2001; Al-Thawadi, 2008; Van Paassen *et al*., 2010; Nemati and Voordouw, 2003; Cheng and Cord-Ruwisch, 2012; Cheng *et al*., 2013a) and have primarily validated the feasibility of this technology in improvement of liquefiable sands.

Montoya *et al.* (2013) tested the dynamic response of three MICP solidified sand models with different solidified strengths on centrifugal shaking table operation, and compared them with loose sand and dense sand samples. The test results indicate: (1) the dynamic response of MICP solidified sand samples was similar to that of dense sand; i.e., the pore pressure was under effective control, surface subsidence of the foundation was significantly reduced while the acceleration amplitude was increased compared to loose sand; (2) when the MICP solidified sample was destroyed, the surface subsidence of the solidified sand sample will increase suddenly, which exceeds the surface subsidence of dense sand below that of the loose sand models. Although investigation into how to achieve the balance between the liquefaction resistance for soil mass and reduction of acceleration at ground surface is needed, this was a very good example study on sand dynamic

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response, especially with regard to reducing liquefaction.

Cheng *et al.* (2013b) studied the dynamic response of MICP solidified sand samples at the elemental and model level via triaxial and 1g shaking table model test. The results indicated that the solidified samples were better than those of gravel pile reinforcement, but there are also deficiencies in the test as follows. (1) Experimental results showed that the bacteria and nutritive salt solution consumed in the MICP process was much more than required. Thus, the results obtained seemed less dependent on both solutions than previously thought. (2) The samples didn't liquefy, and the strengths of the MICP solidified foundation on the shaking table was so high that it may have adverse effects to the seismic behavior of upper structures.

The main objective of this paper is to present an experimental study on MICP strengthening liquefiable sands by dynamic triaxial tests. They were employed to study detailed characterization of solidified sand samples' liquefaction resistance. The results were compared with MICP grouting technology at home and abroad, i.e., colloidal silica chemical grouting technology.

2 Materials and methods

2.1 Sand for test and sample preparation

The tested sand is commercial fine sand and its main parameters are shown in Table 1. It can be observed that the sample is poor graded ($C_u < 5$, $C_c < 1$) sand made up of sub-angular and sub-rounded particles. Its particle grading curve is shown in Fig.1 (Gallagher and Mitchell, 2002). It shows that the particle size distribution of the soil used is comparable to other soils that have been found to liquefy.

To ensure the repeatability of test results, the original saturated loose sand column is prepared with the sand rain method with 30% relative density and the initial degree of saturation is 100%.The column is 50 mm in diameter and 120 mm in height. The grouting system is shown in Fig. 2.

Table 1 Index properties for test sand

USCS classification symbol	SP
D_{60} (mm)	0.240
D_{50} (mm)	0.212
D_{30} (mm)	0.175
D_{10} (mm)	0.145
Coefficient of uniformity, C_u	1.655
Coefficient of curvature, C_c	0.88
Specific gravity, G_s	2.61
Minimum density (g/cm^3)	1.362
Maximum density (g/cm^3)	1.593
Maximum void ratio, e_{max}	0.916
Minimum void ratio, e_{min}	0.638

2.2 Bacteria cultivation and nutritive salt

The *Sporosarcinapasteurii* used in this experiment was from the American Type Culture Collection (ATCC, NO. 11859). The experiments were performed in a controlled environment where the humidity was 50% and the temperature was 26 degrees. A ventilation system was applied to keep the air clean in the lab. The OD_{600} and enzymatic activity of the solution needs to be tested before use. For this bacteria solution, the initial OD_{600} was 1.2–3.2 and enzymatic activity was 0.8–1.5 mS/(cm·min). The formula of nutritive salt was a mixed solution of 0.5 mol/L urea and 0.5 mol/L $CaCl_2$.

3 Grouting schemes

To learn about grouting schemes in detail based on MICP (Montoya *et al*., 2013; Cheng *et al*., 2013b; Burbank *et al*., 2011) and colloidal silica technologies (Gallagher and Mitchell, 2002) worldwide, the main grouting parameters of each scheme are listed in Table 2. It can be seen that there are large differences in microorganism types, fixation liquid formulas, nutritive salt formulas and grouting methods of each scheme. However, for easy preparation of samples and test control, the amount of bacteria solution and nutritive salt, solidification time and other aspects have already been quantified. The main grouting procedures of each scheme are also analyzed in detail as shown in Table 3.

According to the procedure, the total experiment time can be simply added by bacterial, nutritive salt grouting time and reposing time. (The injection rate and total amount of both bacteria and nutritive salt solution is shown in Table 2.The grouting volume of each batch bacteria or nutritive salt was all 1.2 pore volume in literature from both Scheme 1 and 2, as well as Scheme 3.)

In this study, the MICP formula and grouting scheme was adjusted in Scheme 3 (with 30% relative density) for saturated loose sand samples. The specific adjustments were: First, 25 mM/L fixation liquid as mixed with an equal volume of bacterial solution and 1.2 pore volumes

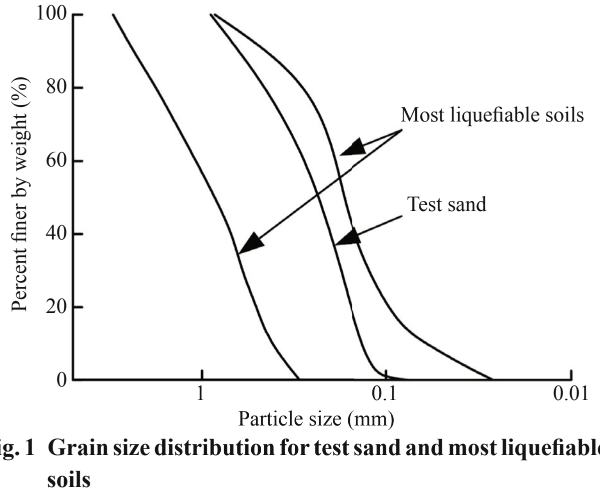


Fig. 1 Grain size distribution for test sand and most liquefiable soils

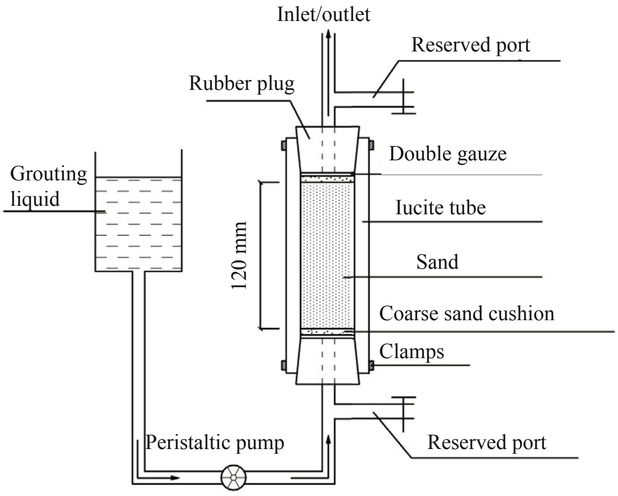


Fig. 2 Schematic plan of grouting test setup

of solution was applied to the sand column at a flow rate of 1.0 mL/min. It was then allowed to stand for 12 hours. Then, 1.2 pore volumes of nutritive salt mixture of 0.5 mol/L urea and 0.5 mol/L $CaCl_2$ solution) was dumped at the same speed, and then allowed to stand for 12 hours again.

4 Mechanical test schemes and results

4.1 Mechanical test scheme

The dynamic triaxial test was employed for the evaluation of solidification. In the process of loading, the input waveform was a sine wave and the vibration frequency was 2 Hz; samples were back pressured for

Table 2 MICP technology and colloidal silica grouting scheme contrast in reinforcing liquefiable sands

	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Author	Montoya *et al*.	Cheng *et al*.	Han *et al*.	Gallagher *et al*.
Test type	Centrifuge shaking table test, Cyclic direct shear test	Uniaxial compression test, Dynamic triaxial test, Shaking table test	Dynamic triaxial test	Uniaxial compression test, Dynamic triaxial test
Relative density D_r (%)	40	30	30	22
Microorganism type	S.P.	S.P.	S.P.	5%–20% different concentrations silica solution
Fixed liquid	1Lbacteria and 7L 0.5mol/L urea mixed liquid	Equal volume of bacteria and 50 mM $CaCl_2$ mixed liquid	Equal volume of bacteria and 25 mM $CaCl_2$ mixed liquid	--
Microorganism injection rate (mL/min)	Surface percolation	2.26	1.0	--
Microorganism repose time (h)	6	6–24	12	--
Nutritive salt concentration (mol/L)	1 mol/L urea 0.5 mol/L $CaCl_2$	0.5 mol/L urea and 0.5 mol/L $CaCl_2$ mixed liquid	0.5 mol/L urea and 0.5 mol/L $CaCl_2$ mixed liquid	
Nutritive salt injection rate (mL/min)	Surface percolation	0.29	1.0	--
Microorganism grouting batch	1	2	1–2	10-132
Nutritive salt grouting batch	According to the sample shear wave velocity	Continuous grouting 36 h, 2 batch	2–4	

Note: Grouting volume of each batch bacteria or nutritive salt is all 1.2 pore volume

Table 3 Grouting process schematic diagram of every grouting scheme

Scheme	Grouting process				Note
	①The mixed liquid of bacteria and fixed liquid	② Repose time	③ Nutritive salt	④Silica	
Scheme 1	①+②+③+②……, The repeated times of step ③ is determined by the reinforced sand shear wave velocity				Grouting method is surface percolation.
Scheme 2	①+②+③+②+①+②+③+②				
Scheme 3	①+②+③+②+③+② or ①+②+③+②+①+②+③+②				
Scheme 4	④+②……, The step ④ is repeated 10 times				

saturation (in the test, the back pressure can reach up to 900 kPa.); the samples were ensured to reach over 95% saturation; and the effective confining pressure of all tests was 100 kPa and remained the same in the dynamic loading process. The test process was controlled according to standard test methods specified by ASTM D5311.

To observe the liquefaction resistance of the solidified sand sample in a straightforward way, dynamic triaxial tests were conducted for five loose saturated sand samples, four dense sand samples, and 13 MICP solidified samples. The test arrangements are shown in Table 4.

4.2 Dynamic triaxial test

The performance of the MICP grouting technology for liquefaction sand foundation improvement was assessed by comparing the liquefaction resistance of the MICP solidified samples with saturated loose and dense sand samples. The liquefaction resistance of the solidified samples was subjected to double-index control. The pore pressure ratio (ratio of pore pressure to confining pressure) of the samples was 100% and the accumulated axial strain was 1%, 2% and 5%. The cyclic vibration times are shown in Table 5 (CSR: cyclic shear ratio).

Generally, as the batches of bacteria solution and nutritive salt grouting increase, the liquefaction resistance of the solidified samples will also increase. The liquefaction resistance of MP10 and MP11 were basically the same, both were higher than saturated loose sand samples, and lower than dense sand samples (D_r = 85%) (Fig. 3). The resistance of MP12 was higher than dense sand samples while the average density of this group of solidified samples was 1,485 kg/m^3, which was lower than dense sand density (1,553 kg/m^3, see Table 5 for details). These data indicated that the improvement of liquefaction resistance of the solidified samples was not only due to $CaCO_3$ precipitation filling, but also the increase in inter-grain bonding strength caused by MICP cementation.

For MP13-1 sample, there was no significant change in pore pressure (Table 5). It can be preliminarily determined that with the MP13-1 grouting scheme, no liquefaction occurred when the confining pressure of the solidified samples was at the initial condition (100 kPa).

During dynamic loading, the dynamic response of solidified sand samples, loose sand samples and dense sand samples was quite different (Fig. 4). For sample LS2, the effective CSR was 0.37 and it reached tensile failure after cyclic loading for eight times when the pore water pressure reached 100%. Comparatively, for the solidified samples, the pore pressure and accumulated axial strain were more effectively restrained than loose sand samples. The MP10-1 sample was first elongated and then compressed so that the development of axial strain was similar to the loose sand samples. However, for MP12-1, as the solidification strength increased, it could not elongate any more so that the development of axial strain was similar to the dense sand samples. Fig. 4 (c) and 4 (d) presents the hysteresis loop of deviatoric stress q and mean effective stress p' as well as q and axial strain, respectively. The MP10-1 sample's hysteresis loop characteristics were similar to the loose sand samples, while that of the MP12-1 sample resembled dense sand samples.

From the test results above, it was found that subjecting solidified sand samples to 1–2 batches of bacteria solution and nutritive salt grouting can effectively slow down the development of pore pressure and axial strain in dynamic loading. According to the post-disaster survey, a dense sand sample with D_r = 85% was basically not liquefied at MS8 seismic intensity (Seed, 1982; Idriss and Boulanger, 2008). Yet, the liquefaction resistance of the MP12 solidified samples was higher than the dense sand samples. As a result, the grouting formula and scheme of this group of samples can be considered as a liquefaction resistance reference for MS8 seismic intensity. To meet different requirements for seismic resistance, bacteria solution and nutritive salt grouting batches can be adjusted according to the MP10 formula.

It was found that the dynamic triaxial test results

Table 4 Test arrangement

Sample No.	10^8/mL	Bacteria batches	Nutritive salt batches	Number of samples prepared	Test type
MP10 group	0.55	1	1	4	Dynamic triaxial test
MP11 group	1.10	1	1	4	
MP12 group	0.55	2	2	4	
MP13-1	0.55	4	4	1	

Note: 1. Sample relative density D_r is 30 %;
2. Injection rate is 1 mL/min;
3. Fixation liquid is 25mM $CaCl_2$;
4. Different concentration bacteria are diluted by culture medium

Table 5 Dynamic triaxial test results

Sample	Effective CSR	Vibration times, *N*				Initial density (kg/m^3)	After cured density (kg/m^3)
		Pore pressure rate 100%	Strain 1%	Strain 2%	Strain 5%		
LS-1	0.36	10	74	94	106	1424	--
LS-2	0.37	8	3	15	110	1424	--
LS-3	0.34	11	13	16	30	1424	--
LS-4	0.24	29	15	22	46	1424	--
LS-5	0.14	163	79	96	148	1424	--
DS-1	0.40	72	25	39	86	1553	--
DS-2	0.29	180	167	220	580	1553	--
DS-3	0.20	504	116	144	278	1553	--
MP10-1	0.34	22	14	40	247	1424	1451.6
MP10-2	0.28	82	131	195	614	1424	1454.8
MP10-3	0.20	198	291	362	746	1424	
MP10-4	0.20	543	401	527	1165	1424	1469.3
MP11-1	0.42	47	35	53	97	1424	1448
MP11-2	0.31	52	936	>1000		1424	1445.6
MP11-3	0.20	483	324	336	408	1424	1453.5
MP11-4	0.16	646	455	561	760	1424	1447.2
MP12-1	0.36	272	20	46	121	1424	1460.9
MP12-2	0.28	167	71	210	270	1424	1457.8
MP12-3	0.25	332	180	290	558	1424	1465.4
MP12-4	0.20	1080	1150	1160	1320	1424	1459.1
MP13-1	0.50		>3000			1424	1494.9

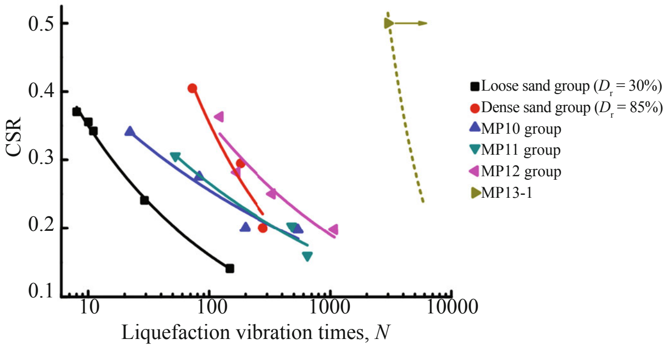
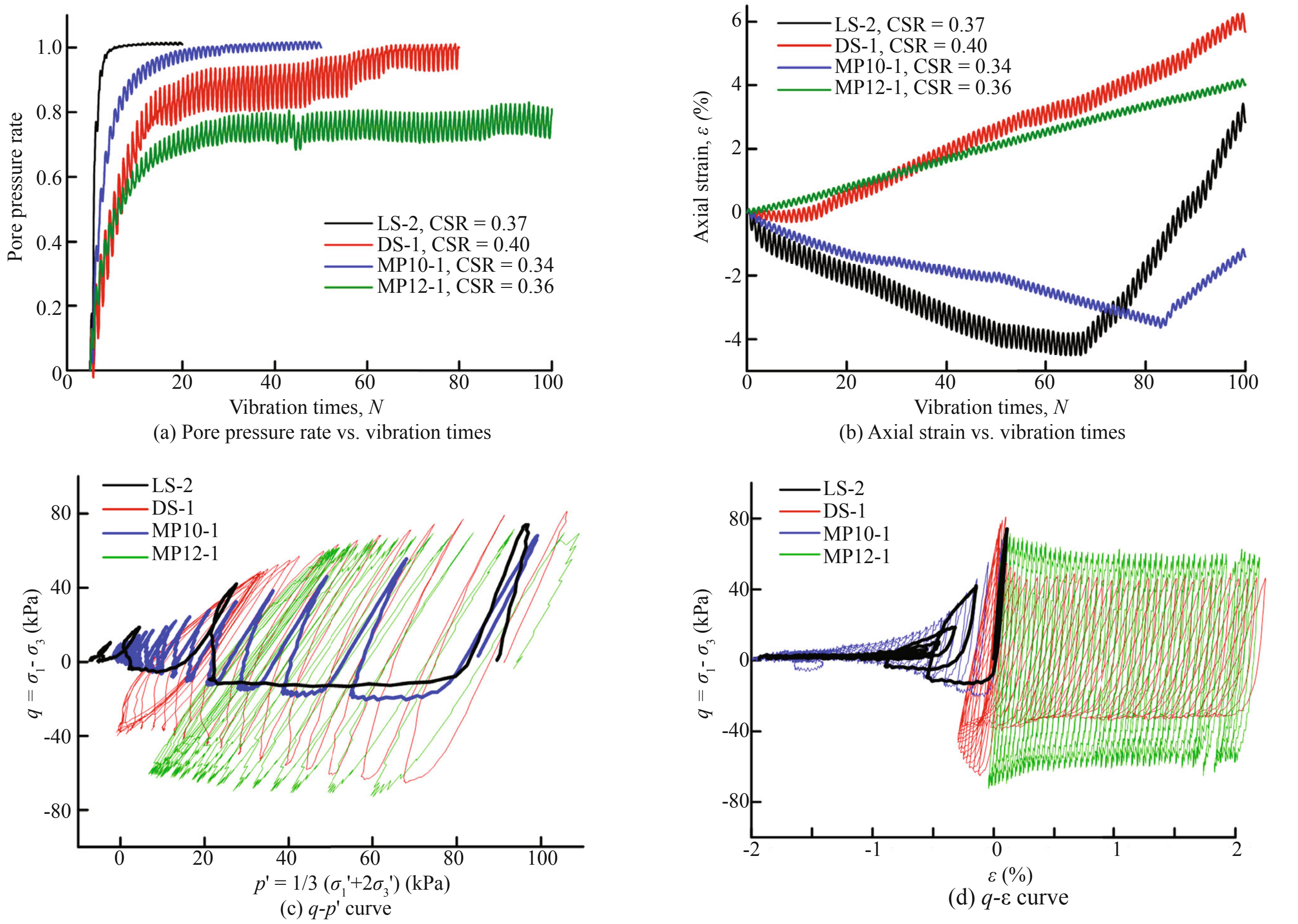


Fig. 3 Different samples CSR vs. Liquefaction vibration times

of the MICP solidified samples in reference (Montoya *et al*., 2013) were similar to those in reference (Cheng *et al*., 2013b). When the CSR was about 0.37, samples liquefied only after 8–72 cycles of loading; and when the CSR was about 0.2 (For MP10 and MP 12), samples can experience more than 1,000 loading cycles before starting to liquefy. Thus, the liquefaction resistance of the samples in reference (Montoya *et al*., 2013) and (Cheng *et al*., 2013) was higher than MP10 and MP12, but lower than MP13-1. For the MP13-1 sample, when CSR was 0.5, it failed to liquefy after 3,000 loading cycles and the axial strain was only 0.1%. However, its bacteria solution volume was only 1/2 of that in reference (Cheng *et al*., 2013), and its nutritive salt solution volume only 1/3. Thus, it is clear that the liquefaction strength increased significantly while the volume of the bacterial solution and nutritive salt reduced.

The liquefaction strength of the MP10 solidified samples was higher than the 5% silica solidified samples, and the MP12 solidified samples was close to the 10% silica solidified samples (Fig. 5). Thus, it is clear that MICP solidified samples can obtain a liquefaction resistance similar to silica chemical grouting solidified samples. However, the solidified time of silica chemical grouting was 4–56 d, and the grouting batches were up to 10–132 times, while the MICP solidified samples in the present study only needed 1–2 d of solidified reaction time and 2–6 batches of grouting. These features fully justify the better economic benefits and broad prospects of modified MICP techniques in liquefied sand foundation improvement.



(a) Pore pressure rate vs. vibration times

(b) Axial strain vs. vibration times

(c) q-p' curve

(d) q-ε curve

Fig. 4 Dynamic responses of samples during loading process

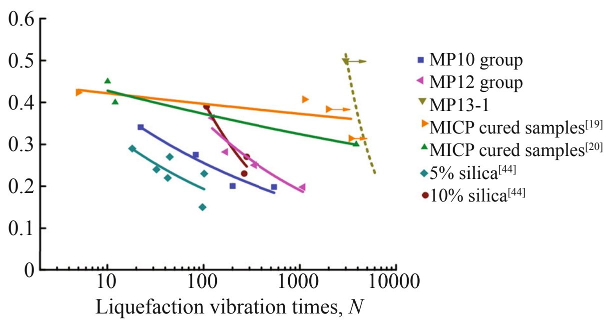


Fig. 5 Liquefaction reduction characteristics of MICP cured samples compared with treated samples in literature

5 Conclusions

The MICP formula and grouting schemes were applied through by the MICP grouting process, and detailed tests were conducted to determine the mechanical performance of the MICP solidified samples by dynamic triaxial tests. Thus, the general conclusions can be summarized as follows:

(1) From Fig. 4 (b), 4 (c) and 4 (d), the hysteretic loop characteristics of the MP10-1 sample (light cementation) were similar to the loose sand samples, while that of the MP12-1 sample (moderate cementation) resembled dense sand samples, because the MP12 samples were solidified by multiple treatment, which is more effective.

(2) MP10 and MP11 were very similar. The only difference was the OD_{600} value. It is thought that the bacteria solution for two tests was enough. All the Ca^{2+} in the nutritive salt solution was converted into $CaCO_3$. As a result, the dynamic triaxial test results were similar. MP13 is much better. However, in the dynamic triaxial test, it did not liquefy. It then becomes meaningless to continue the study, since once the samples reach a certain strength, it is no longer economically or environmentally relevant. Meanwhile, if the loose sand is strengthened to a “dense sand like” behavior like MP12, it is already enough and the solidified sand will not easily liquefy under an earthquake. Thus, further strengthening is not necessary.

(3) The grouting formula and scheme of this group of samples can be considered as a liquefaction resistance reference for MS8 seismic intensity. To meet different requirements for seismic resistance, the bacteria solution and nutritive salt grouting batches can be adjusted according to the MP10 formula.

(4) Compared with the MICP solidified samples in the references, a bacteria solution in the same amount of the MP13-1 sample is only 1/2 of that in reference (Cheng *et al*., 2013) , and the nutritive salt solution amount is

only 1/3. Compared with the solidified samples of silica chemical grouting in reference (Gallagher and Mitchell, 2002), the new MICP formula and grouting scheme is also more efficient.

(5) In dynamic tests, it is found that this grouting formula and scheme is effective in improving sand characteristics and reducing liquefaction.

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