Biogeotechnological Methods for Mitigation of Liquefaction

S. Wu[1], B. Li[1], J. He[2] and J. Chu[1*]
[1]*School of Civil and Environmental Engineering, Nanyang Technological University, Singapore*
[2]*College of Civil and Transportation Engineering, Hohai University, Nanjing, China*
E-mail: jchu@ntu.edu.sg

ABSTRACT: Liquefaction of granular soils during earthquake has long been identified as one of the major geohazards. Conventional soil improvement methods for mitigating liquefaction such as dynamic compaction or deep mixing are costly for large-scale applications. Recently some biological processes have shown significant influence on both the physical and chemical performance of geotechnical systems. Two types of biogeotechnological methods, biocementation and biogas desaturation, have been experimentally examined in this study. For the former, a microbial induced carbonate precipitation (MICP) process has turned one cubic meter of loose sand into sandstone-like material. The shear strength of the sand is greatly improved whereas the permeability is reduced at the same time. For the later, tiny inert gas bubbles are generated microbiologically within liquefaction prone ground to increase the resistance of sand to liquefaction. A series of shaking table model tests on biogas treated sand have demonstrated that this biogas desaturation method is effective for reducing pore pressure generation and shaking induced settlement during cyclic loading. When the degree of saturation of the soil is controlled to be around 90%, the generation of pore pressure in sand and the potential for liquefaction could be largely contained.

KEYWORDS: Liquefaction, Biocementation, Biogas, Strength, Pore pressure, Seismic response

1. INTRODUCTION

Liquefaction occurs in granular soils has long been identified as one of the major geohazards that cause disastrous consequences to human society. In recent times soil liquefaction has been encountered in large and mid-size earthquakes, for example, the 2011 Christchurch Earthquake in New Zealand, the 2011 Great East Japan Earthquake, and the 2008 Sichuan Earthquake in China.

Conventional measures against soil liquefaction including soil densification, soil cementation, lowering of groundwater table, deep mixing and so on. Although effective in terms of technical performance, most of these methods are costly for large-scale applications. It is also difficult to apply the conventional methods below existing structures for mitigation of liquefaction. Thus, it is necessary and practically valuable to develop liquefaction mitigation methods that are effective as well as economical for large area applications.

In the past decade, biotechnologies have shown great potential to be applied for mitigation/prevention of soil liquefaction. Bacteria are dominant species in natural subsurface environments and can alter the physical and mechanical behaviour of soil in many ways (Mitchell and Santamarina, 2005). These microbial activities can be employed to modify the soil behaviour in order to solve specific problems for geotechnical engineering. Soil improvement techniques that use bacterial activity have been gaining increasing research interest. As far as for mitigation of liquefaction is concerned, two potential approaches: biocementation and biogas desaturation have been studied. Biocementation is to enhance the shear strength of soils through the formation of microbially-induced cementing materials in soil (Whiffin et al., 2007; Ivanov and Chu, 2008). Biogas desaturation is to lower the degree of saturation of originally saturated soil so that the resistance to liquefaction can be greatly enhanced (He, 2013; He et al., 2013; He and Chu, 2014; Wu, 2015). These methods when fully developed can be more cost-effective and easier to be applied to treat soils below existing buildings or structures as compared with existing liquefaction countermeasures.

Model tests of applying biocementation and biogas desaturation for liquefaction mitigation are presented in this paper. A large scale of 1 m^3 loose sand was successfully transformed into strong sandstone-like block after biocementation. The unconfined compressive strength test results revealed that the shear strength of sand samples obtained from various positions of the sand block were improved accordingly with the calcium carbonate crystals precipitated. At the same time, the permeability of those samples were significantly reduced. Both factors contribute to the sand resistance of liquefaction. A series of shaking table tests were carried out to investigate the biogas desaturation approach for liquefaction mitigation. The results show that the pore pressure generation and settlement in the bio-desaturated sand was largely contained by using the proposed method.

2. BIOGEOTECHNOLOGICAL METHODS

2.1 Biocementation

Biocementation refers to a process in which hardening and welding of porous materials by the precipitation of mineral matter through microbial activities. Many types of microbes are capable of producing biocementation, for examples, urease producing bacteria (UPB), iron reducing bacteria (IRB), nitrifying bacteria, oligotrophic microaerophilic bacteria, sulphate reducing bacteria (SRB), and dimorphic phytase-active yeast which could produce calcium-phosphate precipitation (Dejong *et al*., 2006; Ivanov and Chu, 2008; Roeselers and van Loosdrecht, 2010). The most well accepted and widely applied method so far is to produce microbial carbonate precipitation by urease producing bacteria.

The formation of biocement occurs where urease producing bacteria (UPB) induce calcite precipitation through the hydrolysis of urea in the presence of dissolved calcium salt solution (DeJong *et al*. 2006; Whiffin *et al*. 2007; Ivanov and Chu, 2008; Harkes *et al*. 2010). UPB produce enzyme urease that hydrolyzes urea and generates ammonium and carbonate. The overall process can be described as the following reaction

$$(NH_2)_2CO + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^- \quad (1)$$

The use of MICP to alter or improve mechanical properties of porous media has been extensively investigated. The calcium carbonate crystals formed between the grains in porous media can bridge sand grains together and fill in porous voids as well. The precipitates increase the stiffness and strength of the cemented soil and reduce the porosity and permeability at the same time.

Several studies have been conducted to apply biocementation to liquefiable soils. Burbank *et al*. (2011) studied field-scale ureolysis-driven MICP to strengthen liquefiable soils. Different ranges of calcite precipitation were observed in soil samples after the treatment. Montoya *et al*. (2013) carried out centrifuge model test to investigate the dynamic response of liquefiable sand improved by

MICP. They found increased resistance to liquefaction and decreased excess pore pressure ratios in the MICP-treated models.

2.2 Biogas desaturation

Biogas is typically produced by the breakdown of organic or inorganic matters through microbial processes, for example, anaerobic digestion with anaerobic bacteria or fermentation with biodegradable materials. Due to numerous microbial processes, biogas or biogenic gas universally existed in soil. The most common biogenic gases found in subsurface soils are methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2) and nitrogen (N_2).

A number of studies (Rad and Lunne 1994; Grozic *et al*. 2000; Fourie *et al*. 2001; Amaratunga and Grozic 2009; He and Chu 2014) have shown that the mechanical behaviour of soil is significantly affected by the presence of gas in either dissolved or free form. A certain amount of gas bubbles present in sand has been found to lead to an increase in cyclic shear strength in triaxial tests (Martin *et al.* 1975, Sherif *et al.* 1977; Yoshimi *et al.* 1989; Xia and Hu 1991). Use of gas injection or gas generated chemically for desaturation to increase the resistance to liquefaction has been attempted before (Yang *et al.* 2004; Okamura and Soga 2006; Yegian *et al.* 2007).

However, there are technical deficiencies in the existing desaturation methods. One is stability of the gas bubbles and another is the uniformity of gas distribution. There is no effective way yet to inject gas bubbles uniformly into soil and keep the bubbles in soil for a long time. To overcome these difficulties, the biogas desaturation method to use microbial processes to produce gas bubbles in-situ has been proposed (He et al. 2013). Biogas bubbles produced by microbial activities are very tiny and thus much more stable. Furthermore, as the bubbles are produced in-situ by bacteria, the bubbles are much smaller and the distribution of the bubbles can be more uniform compared to the injection methods.

In this study, nitrogen gas through a denitrifying process was used. As an inert gas, the nitrogen is neither explosive nor corrosive. It does not react with soils or other elements in the field and remains undissolved for a prolonged period.

Denitrification is a microbially facilitated process of nitrate reduction that ultimately produce nitrogen through a series of intermediate steps. The complete denitrification process can be expressed as a redox reaction as Eq (2).

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \quad (2)$$

As many other biological activities, denitrification is a highly environment-interactive process. Environmental factors ineluctably affect the occurrence and effectiveness of the process. In general, complete denitrification is promoted by high soil moisture content, neutral to slightly soil pH, high soil temperature, low rates of O_2 diffusion and the presence of labile carbon source (Saggar *et al.* 2012).

3. MATERIALS AND METHODOLOGY

3.1 Microorganism

The strain of urease producing bacteria used in this study (namely strain VS1**)**, was obtained from beach sand in Singapore and soil polluted by urea. The probable identity of the bacterial strain was determined most likely to be *Bacillus* sp. (Chu et al., 2012). Medium for the cultivation of urease producing bacteria (UPB) contains following components: Trypic Soy Broth DIFCO^{TM}, 20 g; Yeast Extract 10 g; Urea 20 g; NaCl 10 g; $MgSO_4 \cdot H_2O$ 12 mg, $NiCl_2 \cdot 6H_2O$ 24 mg and 1 L distilled water. Adjust pH to 7.3. All components of the medium, except urea, were sterilized at 121°C for 30 minutes. Urea solution with a concentration of 20 g/L was sterilized through a 0.2 μm Whatman^{TM} nitrocellulose membrane because heating would decompose the urea. On completion of cultivation, the bacteria culture was stored in 4°C.

Denitrifying bacteria can be isolated from various sources, for example, waste water, soils and meadows. Most of them are heterotrophic bacteria, such as *Paracoccus denitrificans*, *Pseudomonas denitrificans etc*. The source for extracting denitrifying bacteria used in this study was a mixture of soil samples collected from various locations of campus. Batch experiments were performed to cultivate the enrichment culture. An enrichment growth medium (He and Chu, 2014) favoured by denitrifying bacteria was prepared for the batch test. Fifty grams of soil excavated from campus was first mixed with the denitrifying growth medium in a 1L glass bottle and put on a shaker for 15 minutes. Then the liquid culture was purged with nitrogen gas to eliminate the dissolved oxygen and transferred to a light-proof environment for cultivation over 48 hours. After the first batch, 200 mL of the culture was kept to mix with another 800 mL growth medium for a second batch cultivation. The same process was repeated until the fourth batch was complete. Gas bubbles were found at the surface of the culture during the second and third batch. After three batches of cultivation in anaerobic and lightproof condition, the obtained enrichment culture was kept in the fridge for up to two weeks for further application.

3.2 Sand properties

Two types of sand were used in this study: standard Ottawa sand from the U.S. Silica Company for the biogas desaturation model tests and filtration sand imported from Riversand^{TM}, Australia (grade W9) for the biocementation model tests. Both were poorly graded fine sand. Table 1 summarizes the basic properties of the two sands.

Table 1 Sand characteristics

Sand Type	D_{50} (mm)	G_s	e_{max}	e_{min}	Grain Shape	Bulk Density (kg/m^3)
Ottawa sand	0.3	2.65	0.87	0.52	Round	1600
River sand	0.25	2.63	0.85	0.50	Round	1500

3.3 *1 m^3 model test for biocementation in sand*

To simulate the progress of MICP in situ, a 1 m^3 up-scaled model test was performed under a controlled environment using conditions and injection techniques anticipated in practice. A total of 1440 kg of dry sand was packed at a loose state into a plastic box with dimensions of 112 cm in length, 96 cm in width and 95 cm in depth (see Figure 1). The volume of sand in box was 1.02 m^3. Two plastic cylindrical drains with a diameter of 50 mm were used for the model test. One was for injection and another for the extraction purpose. A layer of geotextile was wrapped outside the drain to prevent sand clogging effect on the wall of drain.

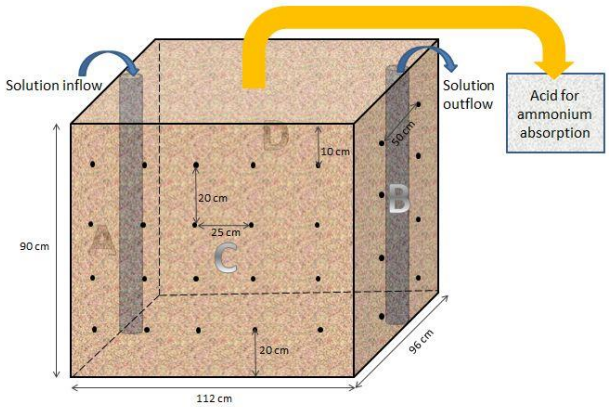


Figure 1 Experimental setup for the 1 m^3 model test

After the sand surface was flattened and smoothed, tap water was directly sprayed on the sand until the sand surface was fully submerged under the water. A reservoir of water above the sand surface is formed with a depth of around 5 cm. Afterwards, the box was left still for 24 hours for sand settlement and fine content removal. This procedure was repeated for three times until no further settlement of the sand structure could be observed visually.

The MICP treatment for this 1 m^3 sand block was divided into two major steps: preliminary and secondary treatments, each involved five batches of treatment. During the preliminary treatment, 20 L of bacteria suspension was poured into the box through the inlet tube with flow rate at 20 L/hr, followed by 50 mM $CaCl_2$, recirculating for two hours, and left overnight for maximizing the attachment to the sand surface. Sequentially 50 L cementation solution (containing 0.75 M $CaCl_2$ plus 1.5 M urea) was injected through the injection well, transporting along the length of sand box (110 cm) towards the extraction well, and then recirculating for one week. This process was considered as one round of preliminary treatment.

Similar to the preliminary treatment, during the secondary treatment, 20 litres of bacteria suspension was poured into the box through the injection well with flow rate at 20 L/hr, recirculating for one hour, and left overnight for maximizing the attachment to the sand surface. A certain amount of $CaCl_2$ (50 mM) was added in during recirculation of UPB. 200L of cementation solution was then added at rate of 30 L/hr through the injection well, until a reservoir about 5 cm in height was formed on top of sand surface. The fluid was then removed from the extraction well at roughly the same rate as injection. Noted minor adjustment of flow rate was made during injection/extraction, to prevent the reservoir from overflowing and avoid the mixing of fluid for injection/extraction.

One round of the cementation process lasted for about 7 ~ 8 hours. New batch of bacteria was then added in the evening, and another round of cementation process began in the following morning. Five rounds of this secondary step of treatment lasted for five days, which was considered to be fast and might be practical for industrial usage. Total cementation solution supply was 1250 L in the two steps of biocementation. The ultimate mean calcite content (g/g dry sand) that could be achieved in the cubic meter box after MICP was calculated to be 4.92%, by assuming 100% cementation efficiency. Figure 2 shows the sand block after biotreatment.

Figure 2 Photo of 1 m^3 sand block after treatment

3.4 Shaking table tests for biogas desaturated sand

The design of a shaking table system and arrangements of measuring instruments is given in Figure 3. It consists of a manual shaking table and a laminar box sitting on top. The laminar box consists of a stack of 10 rectangular laminate rings separated by linear ball bearings. The rings are 457.2 mm (18 inch) in length, 304.8 mm (12 inch) in width and 25.4 mm (1 inch) in height. They are all made of high strength aluminum alloy. Linear ball bearings created a 1 mm gap between adjacent two rings. Those ball bearings are arranged to allow free lateral movement with minimal friction and prevent vertical displacement or tilt of the rings during the cyclic motion.

In this study, a manual shaking table was designed and fabricated to simulate dynamic loading. Two big pieces of plane wood plates with a dimension of 1219 x 812 x 25.4 mm were connected by two mild steel plates through steel bolts and angle bars. The top plate functioned as a shaker and the bottom plate mounted on the concrete floor served as a base. A force can be applied to the top plate to create a cyclic motion along the horizontal direction. There was an accelerometer installed on the plate to monitor the amplitude of the acceleration. Thus a specific shaking acceleration can be maintained manually.

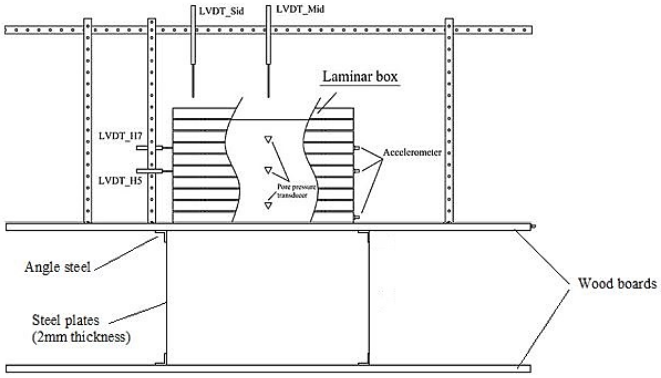


Figure 3 Instrumented shaking table system

The shaking table used in this study was designed to provide harmonic sinusoidal motion along the horizontal direction and can be treated as a single degree of freedom system in the analysis. Similar one degree of freedom testing device has been used before and was proofed to be reliable (Prasad *et al*. 2004; He *et al*., 2013). By applying a small magnitude of force, it is able to create an acceleration of a = 1.5 m/s^2 as recorded in Figure 4. The acceleration, settlement and pore water pressure were monitored during the shaking. Three pieces of Kulite XCL-11-250 miniature pore pressure transducers (PPTs) were employed to measure the pore pressure change during the dynamic loading. Three pieces PPTs were buried at the bottom, 2/3 depth, and 1/3 depth of the sand specimen along the central line, respectively. The pressure change were recorded in a frequency of 2 readings per second. To ensure high quality of measurement, all PPTs were immersed in vacuum applied de-aired water prior to each test for 24 hours. The settlement was measured by high range LVDTs (DCTH3000A, ±75mm) from the RDP Group.

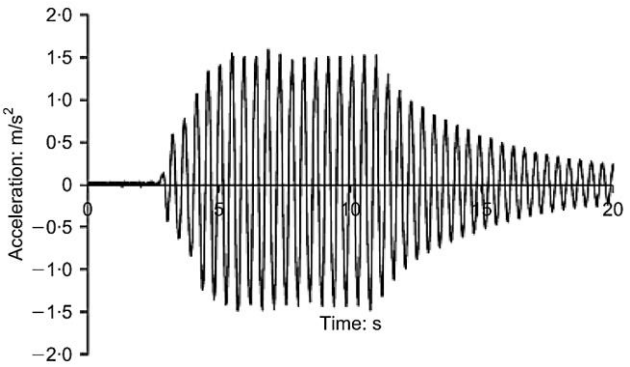
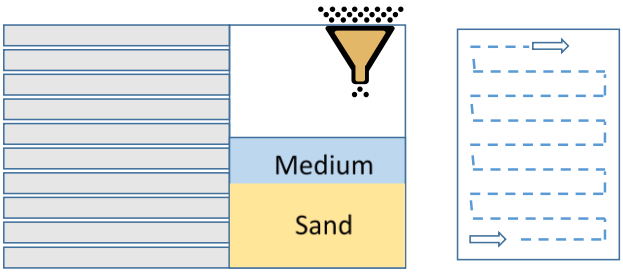


Figure 4 Typical input acceleration (a=1.5m/s^2)

Before spraying sand into the laminar box, two liters of inoculated enrichment denitrifying bacterial medium (for desaturated samples) or distilled water (for fully saturated samples) was poured into the box first. The volume of the nutrient solution was pre-determined based on the desired degree of saturation through phase calculation. The same wet sedimentation method used for sand column test was adopted for the sand specimen preparation. As shown in Figure 5, dry sand was rained down slowly into the laminar box through a funnel until the sand level almost reached the water surface. The samples prepared in this way gave a relative density about 25-30 percent. The denitrification process usually took 3 to 4 days to generate enough gas bubbles to reduce the degree of saturation to a desired value. The progress of denitrification process was indicated via the measurement of surface water level change. At the beginning, all pore voids among sand grains were filled with denitrifying nutrient solution. When the denitrification process took place, nitrogen gas was generated gradually. Because the nitrogen gas has a poor solubility in the atmospheric pressure condition. It would occupy space and exclude the solution in sand. In this case, measuring the risen height of water surface can be a reasonable approach to estimate the volume of nitrogen gas generated within the sand specimen.



(a) Wet sedimentation (b) Sand spray

Figure 5 Schematic of sand preparation method

4. RESULTS AND DISCUSSION

4.1 Engineering properties of biocemented sand

The 1m^3 biocemented sand block was cut into 27 pieces for testing of its engineering properties. The block was divided into three layers by height (A, B and C, counting from the sand surface) and 9 pieces per layer, as shown in Figure 6. Legend of sampling position referring in later sections would be based on this figure.

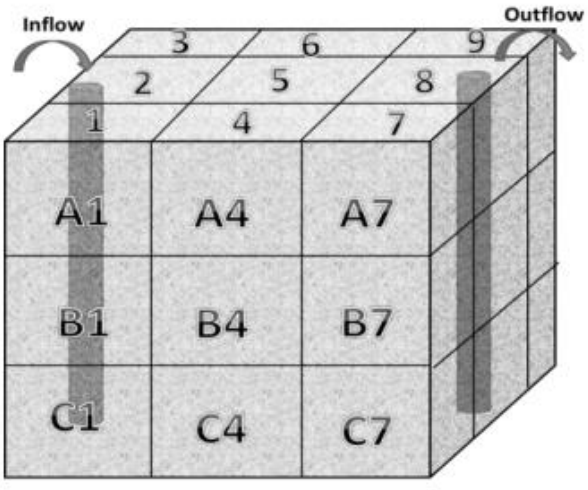


Figure 6 Sketch of sampling positions in the 1 m^3 sand block

The Unconfined Compressive (UC) strength versus calcite content is summarized in Figure 7. The UC strength is the maximum axial compressive stress that a cylindrical sample of material can withstand under unconfined conditions. Calcite contents in sand samples were determined by ICP test. Overall mean calcite content in the sand box was 4.55%, which was 5.5, 3.3 and 4.8% in layer A, B and C respectively. Cementation efficiency is calculated to be 93% in terms of calcite precipitation, which is comparable with data reported in the literature, varying from 50% to 92% (DeJong et al., 2006; Whiffin et al., 2007; Al Qabany et al., 2012).

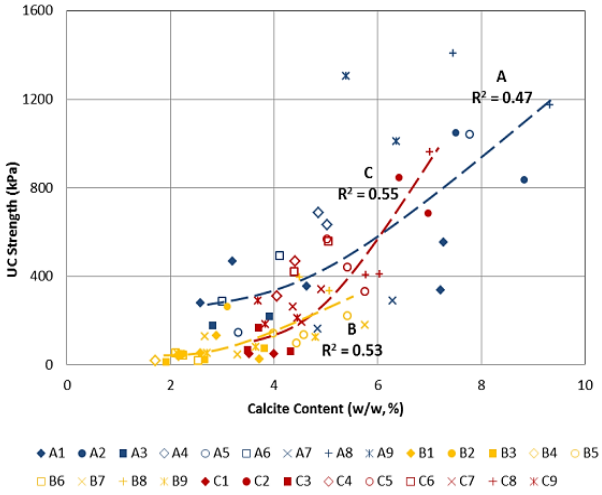


Figure 7 UC strength versus calcite content in the 1 m^3 sand block

As shown in Figure 7, the UC strength varied in the range of 10 to 1400 kPa while having 2 to 9% calcite by weight in the whole block. The UC strength is highly dependent on the calcite content. In all, specimens in the top layer A are found to have relatively higher calcite content and the UC strength, followed by the bottom layer C. The middle layer B gained the lowest calcite content as well as the UC strength. This observation is similar to the data perceived from the small scale model test in previous researches (Al Qabany and Soga, 2013; DeJong et al., 2006; Whiffin et al., 2007; van Paassen, 2009). Sand near the inlet area gained greater calcite content and also correspondingly higher UC strength as expected, as $CaCO_3$ precipitation was thermodynamically favoured near the inlet part (Phillips *et al*, 2013). In addition, as the rate of crystal growth is directly related to the available crystalline surface, more calcite may intend to precipitate at where calcite crystal had already existed.

The permeability test was performed in a triaxial cell by using the flexible wall method, following the ASTM D5048-10 standard. The test method is to establish a steady flow condition in a cylindrical specimen by maintaining a constant pressure difference of 5kPa at the two ends. A radial confining pressure of 50 kPa was applied using a GDS pressure/volume controller. The volume of effluent was measured directly by another GDS controller connected to the end of the specimen. Once a steady flow condition was obtained, the permeability can be calculated. The permeability of clean untreated sand was 9 x 10^{-5} m/s. Figure 8 shows the relationship between the coefficient of permeability and calcite content in the 1m^3 biocemented sand block. The trend of permeability coefficient k was generally lower at higher calcite content level, despite of the scatter of data pattern. However, it could be observed that the fitting line of layer A lies above it of layer B and C, which means specimens in layer A resulted in higher coefficient of permeability at the same calcite level comparing to layer B and C. Such a phenomenon could be due to the greatest of the saturation states of calcium and carbonate ion near the surface because of the immersion of whole sand block, thus created an area where calcite precipitation was thermodynamically favoured. And as the rate of crystal growth is directly related to the available

crystalline surface, more calcite may intend to precipitate at where calcite crystal had already existed.

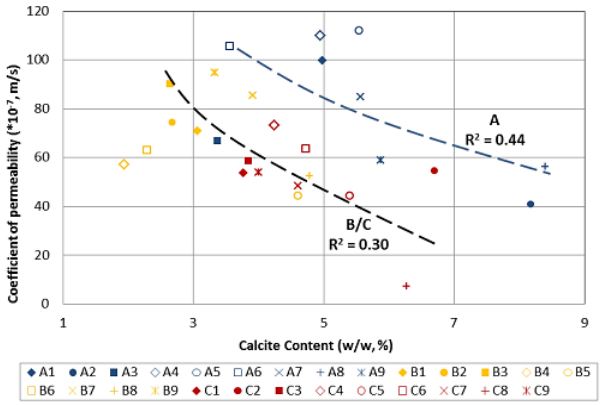


Figure 8 Permeability versus calcite content in the 1 m^3 sand block

The success of turning loose sand into sandstone-like material in a $1m^3$ scale by using biogrouting technique strongly suggests that the MICP can be used to improve large amount of liquefiable soils. The combination effect of increased shear strength and reduced permeability of the biotreated sand will substantially benefit the resistance to liquefaction.

However, it needs also to be pointed out that the use of biocementation for liquefaction suffers from the following shortcomings: 1) this method required the use of a large amount of biomass and chemicals and thus is still expensive; 2) as biocementation needs to be carried out in a number of rounds, the construction process can be even longer than the conventional process; and 3) the treatment can be highly non-uniform as shown by this model tests.

4.2 Seismic response of biogas desaturated sand

A series of shaking table test were conducted to investigate seismic response of biogas desaturated sand. Figure 9 shows the development of pore pressure ratio in sand with different degrees of saturation under the same input acceleration of a = 1.5 m/s^2. R_u is defined as the ratio of maximum excess pore pressure generated by the cyclic load to the initial effective overburden stress. The pore pressure increased during the cyclic loading and dissipated afterwards. For fully saturated sand, there was a considerable amount of increase in excess pore pressure as the shaking took place. The pore pressure ratio exceeded 0.9 which indicates that the liquefaction occurred (He *et al*. 2013). The pore pressure generated in biogas desaturated sand were substantially lower than that in fully saturated sand. When the degree of saturation S_r dropped slightly to 90%, the increase in pore pressure becomes insignificant. The maximum R_u ratio in the biogas desaturated sample (S_r = 90%) was less than 0.2 which is far less than a trigging value of R_u = 0.5 when liquefaction could occur (He *et al*. 2013).

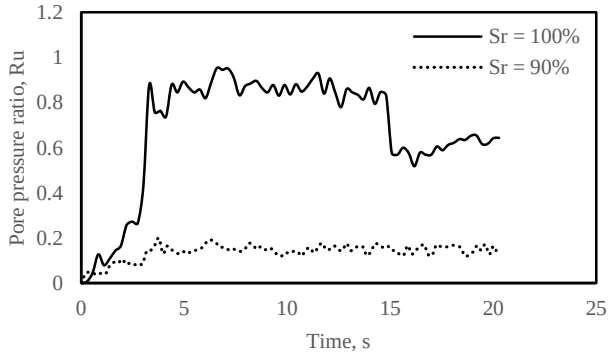


Figure 9 Change of pore water pressure

There is a significant difference in the vertical strain between the saturated and the biogas desaturated sand specimen as shown in Figure 10. When the sample was fully saturated, a considerable settlement occurred which indicated that the sand sample liquefied. When the degrees of saturation dropped to 90 percent, the volumetric strain caused by the ground shaking were mostly confined within only 1%. This is evident that the biogas desaturated sand had strong resistance to liquefaction. This finding corroborates the description of Tokimatsu and Seed (1987), who reported that volumetric strains observed in non-liquefiable soils were usually less than 1%.

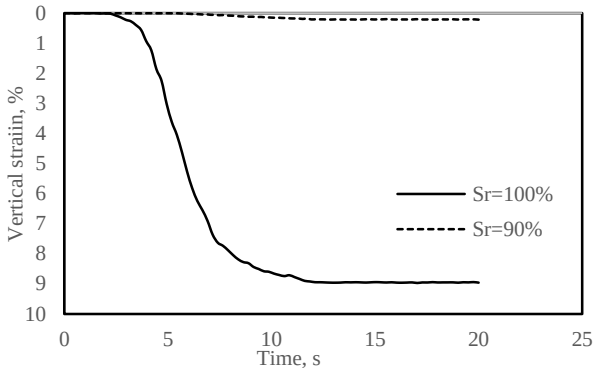


Figure 10 Vertical strain development in sand under shaking

Figure 11 shows the response of volumetric strain and relative density to the seismic loading. Compared with the fully saturated sand, biogas desaturated sand developed a much smaller volumetric change during the cyclic loading. The volumetric strain was calculated using the surface settlement compared with the total thickness of sand deposit by assuming the soil deformed one-dimensionally. The sand deposit turned from medium loose to dense with the application of cyclic loading. For fully saturated sand, even under high relative density condition, the volumetric strain still much bigger than ones developed in slightly desaturated sand. Tokimatsu and Seed (1987) pointed out that pore water pressure generation and volumetric strain also occurred in a non-liquefiable soil; however, the magnitude was often much smaller and the volumetric strains observed in non-liquefiable cases were usually less than 1%. The levels of volumetric strains for partially saturated soil were mostly within 1% strain, indicating that the partially saturated soil had strong resistance to liquefaction and volumetric change. The volumetric strain in saturated sand as observed in the model tests was about 3 to 4%. To achieve a non-liquefaction response, we can either densify the soil to 90% relative density, or desaturate the soil to 95% saturation degree or lower. However, the cost involved in the two methods are considerably different. Biogas desaturation is much cheaper, non-destructive, much easier to be applied and requires much less heavy machineries.

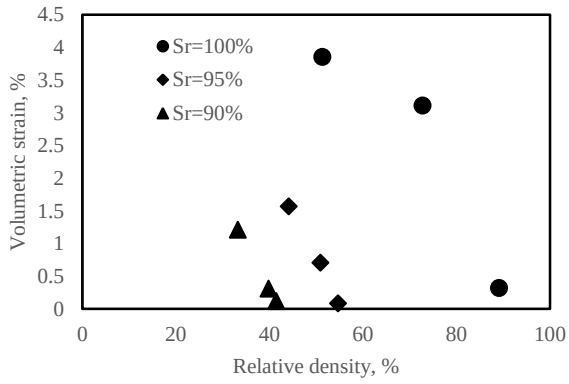


Figure 11 Volumetric strain against relative density

When there is no or very small seepage flow in the soil, the biogas desaturation method is sufficient for mitigation of liquefaction hazards. However, when there is a relatively big seepage in soil, the stability of the gas bubbles may become a concern. In this case, a combined biogas desaturation and bioclogging or the so-called "combined biodesaturation and bioclogging" method could be used instead (Wu, 2015). In this combined approach, the purpose of bioclogging is to "block" the passage for small gas bubbles to aggregate into bigger bubbles so as to pre-empt the conditions for gas bubbles to escape from the ground. The amount of biogrout required for bioclogging in this case is much less than that for biocementation for the purpose to increase the shear strength of sand. In terms of cost-effectiveness, the construction cost involved in the combined biodesaturation and bioclogging method for liquefaction mitigation will still be significantly lower than the cost in the solo biocementation method. The detail of the combined biodesaturation and bioclogging method will be presented in a separate paper.

5. CONCLUSIONS

The application of biogeotechnological methods for mitigation of liquefaction hazard is discussed in this paper. Two methods, biocementation and biogas desaturation, were studied using large scale model tests.

For the biocementation method, a model test with 1 m^3 sand block was carried out. Through treatment using the MICP process, a UC strength of up to 1400 kPa was achieved after 5 rounds of treatment or when the calcite content reached 6%. The permeability of the biotreated sand was also reduced substantially. Thus, the biocementation method can possibly turn soil behaviour from 'soil-like' to 'rock-like' and thus reduce the liquefaction susceptibility. However, this method suffers from the following shortcomings: 1) it requires the use of a large amount of biomass and chemicals and thus is still expensive; 2) as biocementation needs to be carried out using several rounds of treatment, the construction process can be even longer than the conventional process; and 3) the treatment can be highly non-uniform in soil as shown by this model tests.

For the biogas desaturation method, a series of model tests using a shake table were carried out. The results of the shaking table tests illustrate that reducing the degree of saturation of the soil slightly can improve the soil behaviour under dynamic loading by reducing the generated pore pressures and shaking-induced settlements. The shaking table test results showed that the liquefaction occurred in fully saturated loose sand under an acceleration of a = 1.5 m/s^2. However, after the degree of saturation is reduced to 90% using biogas desaturation, liquefaction was prevented. The pore pressure ratio in biogas desaturated sand is only tenth of that in fully saturated sand.

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