Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Mitigation of soil liquefaction using microbially induced desaturation*

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Received Mar. 15, 2016; Revision accepted June 16, 2016; Crosschecked June 16, 2016

Abstract: Soil liquefaction can cause disastrous consequences to buildings and human lives. Regular countermeasures against soil liquefaction are often overly expensive for normal buildings and structures. This could be the major reason that liquefaction induced damage is still widely encountered in large- and mid-size earthquakes in recent years. In this paper, a new method for the mitigation of soil liquefaction using the microbially induced soil desaturation is proposed and tested. The desaturation effect in soil is achieved by the generation of nitrogen gas produced from the microbial denitrification process. Some major issues related to this method are experimentally investigated. These include soil desaturation procedures, shapes and distribution of gas bubbles in soil, mechanical responses and liquefaction resistance of desaturated soils, and stability of gas in soils. The desaturation treatment of soils is made simply by introducing denitrifying bacteria and a desaturation solution into soil pores by mixing, flushing, or injection. The degree of saturation can be reduced as the microbial reaction proceeds. Experimental results show that the final degree of saturation is related to the initial nitrate concentration added to the soil: the higher the concentration of nitrate in the desaturation solution, the lower the degree of saturation that can be achieved. The existence of gas bubbles in soil is evidenced by computer tomography (CT) technology. The CT images reveal that gas is in the form of small pockets which has a size a little larger than the mean size of sand grains. It is shown in the shaking table tests that microbially induced desaturation can effectively improve the liquefaction resistance of soil by showing a much lower pore pressure generation, much smaller volumetric strain, and much smaller settlement of the structure in desaturated soil, as compared with those in saturated soil. Triaxial consolidated undrained tests reveal that the desaturation treatment of soil can improve the undrained shear strength of loose sand. The stability of gas is tested under hydrostatic and water flow conditions. The gas phase is stable under the hydrostatic condition, but unstable under water flow conditions. So measures ought to be taken to prevent steady flow in practice.

Key words: Soil liquefaction, Desaturation, Microbial denitrification, Bacteria
http://dx.doi.org/10.1631/jzus.A1600241 **CLC number:** TU472

1 Introduction

Soil liquefaction is a phenomenon where soil loses its shear strength and behaves like a fluid because of the increase in pore water pressure. Liquefaction often accompanies large deformation in soil and can cause disastrous consequences to buildings and human lives. Soil liquefaction is related to much damage in earthquake events, such as slope failure, loss of bearing capacity, and dislocation of retaining walls. 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 Wenchuan earthquake in China.

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* Project supported by the National Natural Science Foundation of China (No. 51578214), the Jiangsu Provincial Natural Science Foundation of China (No. BK20150814), the China Postdoctoral Science Foundation (No. 2015M581714), and the Jiangsu Provincial Postdoctoral Science Foundation of China (No. 1501026C)

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Conventional measures against soil liquefaction, such as soil densification, soil cementation, lowering of groundwater table, and shear strain constraint, are effective in technical performance. However, these methods are usually very expensive. Normal buildings and structures often cannot receive any proper treatment against soil liquefaction. As a result, many existing buildings and structures still face the risk of soil liquefaction. In this situation, the development of cost-effective methods for the prevention or mitigation of soil liquefaction has great practical value.

One of the opportunities to obtain an economical method for the mitigation or prevention of soil liquefaction is to use bacteria. Bacteria are omnipresent 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 harnessed 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. One of the potential applications is to counter soil liquefaction. There are two potential approaches to achieve this goal. One approach is bio-cementation, that 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). The other approach is bio-desaturation, that is, to lower the degree of saturation of originally saturated soil so that the undrained shear strength can be enhanced (Rebata-Landa and Santamarina, 2012; He *et al.*, 2013a; 2014; He and Chu, 2014). These microbial approaches potentially have a larger scope of applications because of their lower cost in materials and implementation, and the applicability to existing buildings and structures, as compared with regular liquefaction countermeasures.

Loose saturated sands are usually susceptible to earthquake liquefaction. However, research has shown that undrained shear strength and liquefaction resistance of loose saturated sand can be improved as the degree of saturation reduces. In cyclic triaxial and cyclic torsional shear tests, if the degree of saturation of initially saturated sand is reduced by merely a few percentage points, the cyclic strength can be much increased (Yang *et al.*, 2004; Okamura and Soga, 2006). Likewise, in shaking table tests, liquefaction susceptibility in desaturated sand can be reduced by showing a much lower excess pore water pressure generation and much smaller volumetric deformation, in contrast to its fully saturated counterpart (Okamura and Teraoka, 2005; Yegian *et al.*, 2007; He *et al.*, 2013a). In monotonic loading conditions, the stress-strain curve of loose sand changes from a strain-softening manner to a strain-hardening manner when the degree of saturation reduces from 100% to lower than 90% (Rad *et al.*, 1994). These experimental results support the idea of using desaturation as a means to mitigate the liquefaction susceptibility of soil.

To implement the desaturation method in engineering practice, reliable techniques to achieve the desaturation effect in soil are required. Several techniques have been proposed and tested. The use of a chemical, sodium perborate, was adopted by Eseller-Bayat *et al.* (2013) to achieve a controlled desaturation effect. The degree of saturation is reduced through the generation of oxygen gas from the hydrolysis of sodium perborate in soil pores. The desaturation effect of soil can also be attained by water electrolysis, that is, to apply an electric current through soil so that pore water can be decomposed to oxygen and hydrogen gases (Yegian *et al.*, 2007). Direct air injection is a straightforward method and has been tested by Okamura *et al.* (2011) in a field experiment. The degree of saturation of sandy ground was successfully reduced to 68%–98% within a 4-m range from the injecting point. Microbial methods is another option. In this study, we choose a denitrification process to produce nitrogen gas for soil desaturation.

2 Soil desaturation through the microbial denitrification

The microbial denitrification process is a reduction reaction of nitrogen intermediated by denitrifying bacteria. The complete reaction of denitrification involves stepwise reductions from nitrate to nitrogen gas, with each step catalyzed by specific enzymatic activities, as shown below:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2. \quad (1)$$

Many organic compounds can be used as electron donors in the reaction. If ethanol is used, the reaction equation is

$$\begin{aligned}&5C_2H_5OH+12KNO_3 \rightarrow \\ &\qquad 6N_2\uparrow+10KHCO_3+9H_2O+2KOH.\end{aligned} \quad (2)$$

In the equation above, nitrogen gas (N_2) is the effective product for soil desaturation. N_2 gas has very low solubility in water and its chemical properties are inert. So the stability of N_2 gas bubbles in soil is better than other gases. There are also some limiting factors affecting the process of denitrification. High concentration of nitrate in the substrate solution can cause the accumulation of nitrite (NO_2^-) and further reaction will be impeded (Blaszczyk *et al.*, 1985; Glass and Silverstein, 1998; van Paassen *et al.*, 2010a). The upper limit at which the nitrate-N concentration (the mass concentration of nitrogen element in nitrate) does not cause serious nitrite accumulation is around 100 mmol/L (van Paassen *et al.*, 2010a). This value is far higher than the requirement for soil desaturation. It is reported that neutral and moderately alkaline pH is preferable for high enzymatic activity and the complete reaction of denitrification (Saleh-Lakha *et al.*, 2009). An anaerobic environment with the absence of oxygen gas can help produce more N_2 than some intermediates such as N_2O (Saleh-Lakha *et al.*, 2009). A temperature range from 15 to 35 °C is optimal for denitrification (Stanford *et al.*, 1975). From these studies, we can see that these limiting factors are unlikely to adversely affect the progress of denitrification in subsurface environments below the ground water table. After all, the denitrification is a widespread microbial process in the soil ecosystem. Conditions for it to take place in subsurface conditions are not difficult to satisfy.

Knowing the principles and limiting factors of microbial denitrification process, we have then cultivated denitrifying bacteria and use the bacteria in the soil desaturation experiment. The denitrifying bacteria in this study were cultivated from anaerobic sludge in a wastewater treatment plant. Anaerobic sludge often contains various kinds of bacteria and is commonly used as a source to obtain any desired kind of bacteria. The cultivation of denitrifying bacteria was made through two steps, that is, cultivation using an enrichment culture and a pure culture. In the enrichment culture of denitrifying bacteria, certain amounts of anaerobic sludge and cultivation medium were mixed and favorable growing conditions were provided. The medium of the enrichment culture contains nutrients that support the growth of desired bacteria (here denitrifying bacteria), while inhibiting the growth of others. As a result, denitrifying bacteria gradually dominate. A pure culture of denitrifying bacteria was obtained by diluting and spreading a bacterial suspension of enrichment culture on a solidified agar plate. A single strain on the agar plate (growing from one single bacterium) can be isolated and cultivated in an aseptic condition. The cultivation medium of the enrichment culture comprised the following contents: C_2H_5OH, 0.5 g; KNO_3, 1.01 g; NH_4Cl, 0.12 g; KH_2PO_4, 0.75 g; K_2HPO_4, 2.5 g; $MgSO_4\cdot7H_2O$, 0.1 g; $FeSO_4\cdot7H_2O$, 0.01 g; $CaCl_2\cdot2H_2O$, 0.015 g; addition of tap water to 1 L. The composition of the medium of the pure culture was the same as the enrichment culture and solidified with the addition of 12 g/L agar. A nearly full length 16S ribosomal ribonucleic acid (rRNA) gene sequencing analysis was made on the dominant type of colonies on the solid medium. The result shows that the dominant species in the enrichment culture belongs to Acodovorax species, which is a common species of denitrifying bacteria in wastewater treatment facilities.

Soil desaturation tests were conducted to explore the feasibility and effectiveness of the microbial soil desaturation method. A simple set-up as shown in Fig. 1 was adopted to evaluate the soil desaturation process. The soil desaturation solution and bacteria were mixed with a certain amount of sand and poured

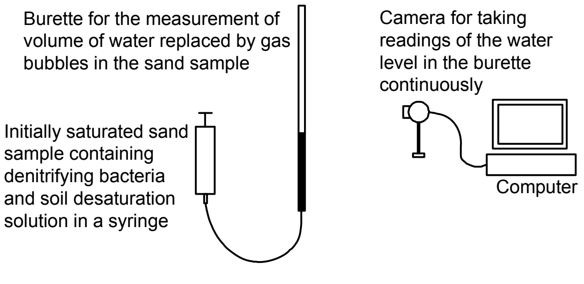

Fig. 1 Set-up of soil desaturation test

into a 60 mL syringe to form an initially saturated soil sample. The syringe was connected to a burette. When gas bubbles were produced in the soil, some volume of pore water would be replaced and pushed into the burette. The volume of water replaced can be recorded by a computer-controlled camera. The amount and rate of gas generation, as reflected by the water level in the burette, can thus be measured. Soil used in this test and the other tests presented in this study is Ottawa sand (ASTM graded type). It is a poorly-graded quartz sand with a mean size of 0.4 mm. The particle size distribution curve is presented in Fig. 2.

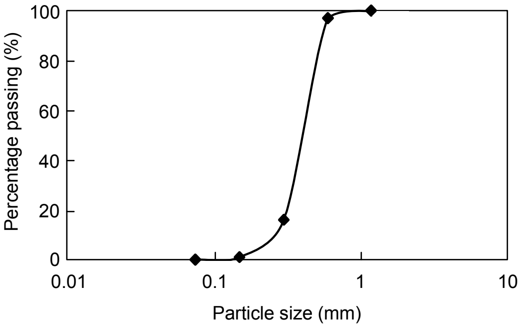

Fig. 2 Particle size distribution curve of Ottawa sand (ASTM graded type)

The soil desaturation solution contains the same chemicals used in the cultivation medium but with different concentrations. The concentration of KNO_3 in the desaturation solution is determined based on the required volume of gas according to the chemical balance in Reaction (2). The molar ratio of KNO_3 to C_2H_5OH is 1:1.1. The concentrations of the other chemicals used in the soil desaturation solution are one-tenth of those used in the cultivation medium. Bacterial suspension's 1% volume with an optical density-based concentration of 0.51 was added into 99% volume of desaturation solution before applying to the soils.

The results of three tests with different initial nitrate concentrations are presented. As can be seen from Fig. 3, when the initial nitrate concentration is in the range of 125–374 mg/L, the degree of saturation can be reduced to a range of 76.5%–91.6%. The higher the nitration concentration used, the lower the final degree of saturation that can be obtained. The degree of saturation starts to decrease around 2 d after soil sample preparation and completes within 4 d. All three tests show similar rates of the reduction in the degree of saturation, irrespective of nitrate concentrations. Some testing parameters and results are provided in Table 1. In tests 1 and 2, residual nitrate and nitrite are minor. But in test 3 with relatively high nitrate concentration, there are about 10% residual nitrate and 7% residual nitrite accumulation. The reason could be that, in a stagnant treatment condition, the nutrients cannot be completely consumed by bacteria. In all three tests, pH increases in the process. This is consistent with the chemical equation (Reaction (2)) in which hydroxides are produced.

The soil desaturation solution used above is a water solution of low viscosity. This feature enables the microbial desaturation to be implemented in the field simply by injecting or circulating denitrifying bacteria and the soil desaturation solution in the soil

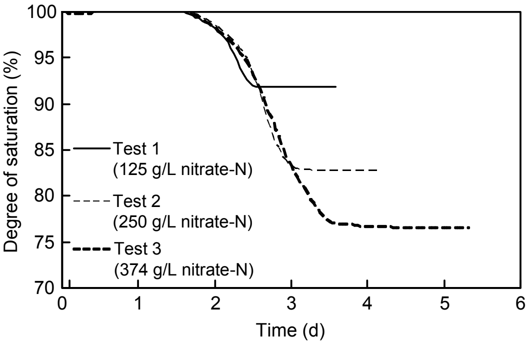

Fig. 3 Variation of saturation degree with time in the soil desaturation test

Table 1 Results of soil desaturation test

Test No.	Void ratio	Relative density (%)	Nitrate (-N) concentration (mg/L)	Final degree of saturation (%)	Residual nitrate (-N) (%)	Residual nitrite (-N) (%)	Initial pH	Final pH
1	0.678	40.7	125	91.9	0.4	Trace	7.2	7.7
2	0.678	40.7	250	82.7	0.4	0.1	7.2	8.2
3	0.678	40.7	374	76.5	9.5	6.8	7.2	8.5

ground. Similar techniques have been adopted in the large-scale experiments of bio-cementation of soil grounds, as reported by van Paassen *et al.* (2010b). In comparison, conventional cement-based ground improvement methods, such as cement mixing and jet grouting, require heavy machinery and relatively high costs.

3 Observational analysis of microbially desaturated soil using computer tomography

Computer tomography (CT) was used to carry out the observational analysis on the microbially desaturated soil samples. The CT apparatus used was a high-resolution digital radiography and computed tomography system. The CT image is a map of density distribution. Denser materials have brighter pixels and lighter materials have darker pixels. Plastic test tubes with an inner diameter of 1.46 cm were used for the preparation of sand samples. The samples were prepared in the same way as that in the soil desaturation tests. For each sample, a 2 cm length in the mid range of the tube was scanned.

CT images of two samples are shown in Fig. 4. The first sample is saturated and the distributions of sand grains and pore voids are uniform (Figs. 4a and 4b). The second sample is desaturated to a saturation degree of 94%. Compared with the saturated sand, the desaturated sand sample contains a few pockets of pores as shown in Figs. 4c and 4d. The same pockets can be seen from both the vertical and horizontal slides as circled in Figs. 4c and 4d. The pockets of pores, shown as the dark patches in the images, are a little larger than the size of a sand grain (the mean size of the sand grains is 0.4 mm). The dark colour of the pockets indicates that the pockets consist of gases or a combination of gases and water.

4 Liquefaction resistance and mechanical responses of microbially desaturated soil

To evaluate the liquefaction resistance and mechanical responses of microbially desaturated sand, 1-*g* shaking table tests and triaxial consolidated undrained tests were conducted. Results presented in this section have been published in several previous

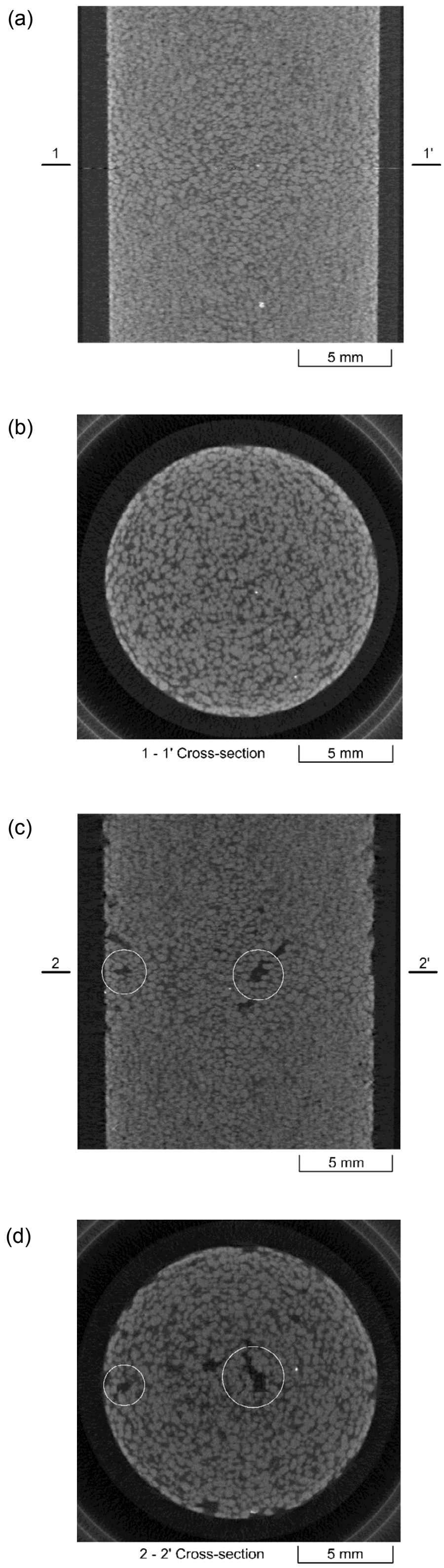

Fig. 4 CT images of saturated and desaturated soils
(a) and (b): saturated soil; (c) and (d): desaturated soil with 94% saturation degree

papers by the authors (He *et al.*, 2013a; 2013b; 2014; He and Chu, 2014) and are summarized and discussed here.

4.1 Shaking table tests

The tests were conducted using a laminar box model fixed on a shaking table. This laminar box consists of ten layers of frames stacked together as shown in Fig. 5. Ball bearings were placed between the frames to allow free movement in the horizontal shaking direction. An impervious plastic sheet was used to line the laminar box to hold the soil and water inside. This sheet was place in a loose manner in order not to impede the free movement of laminar frames. The laminar box has an inner size of 45 cm×30 cm×29.7 cm (length×width×height). The soil desaturation solution was prepared and poured into the laminar box first. Dry sand was then carefully deposited into the water through a funnel. Soil samples made in this way can achieve an initial relative density of around 20%. Four samples with 80%–100% saturation degree were prepared and tested. On each sample, seismic loading was applied at several steps. Settlement can be measured after each step of loading using a linear variable displacement transducer (LVDT), and thus the average relative densities at the start and end of each loading can be calculated. The frequency of the seismic loading was 2 Hz. The instrumentation includes those for pore water pressure, surface settlement, settlement of structure resting on the soil surface, input and surface accelerations, and horizontal displacement of laminar frames at different heights. Based on this testing scheme, we can obtain the seismic performance and liquefaction resistance of soils with various degrees of saturation and relative densities.

Two examples of test results are provided to explain the effect of degree of saturation on liquefaction resistance. Fig. 6 gives comparative test results on two relatively loose soil samples with 100% and 90% saturation degrees (S_r), and 21% and 17% relative densities, respectively. Both tests were subject to a horizontal sinusoidal acceleration of a_{max}=0.5 m/s^2. Fig. 7 provides the comparative test results on two relatively dense samples with 100% and 90% saturation degrees, and 73% and 42% relative densities, respectively. These two tests were subject to an acceleration of a_{max}=1.5 m/s^2. In the test results, pore

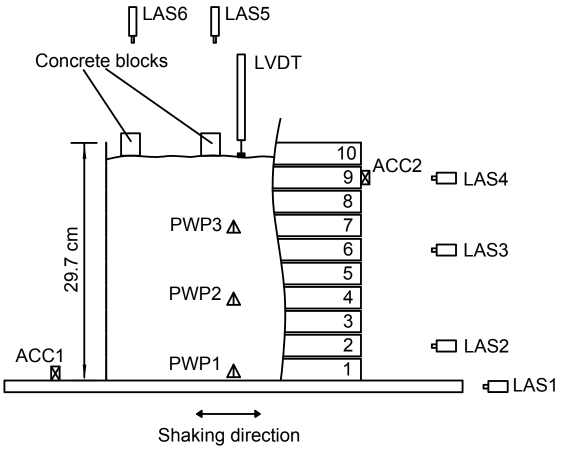

Fig. 5 Set-up and instrumentation of shaking table test
PWP: pore water pressure sensor; LAS: laser displacement sensor; ACC: accelerometer

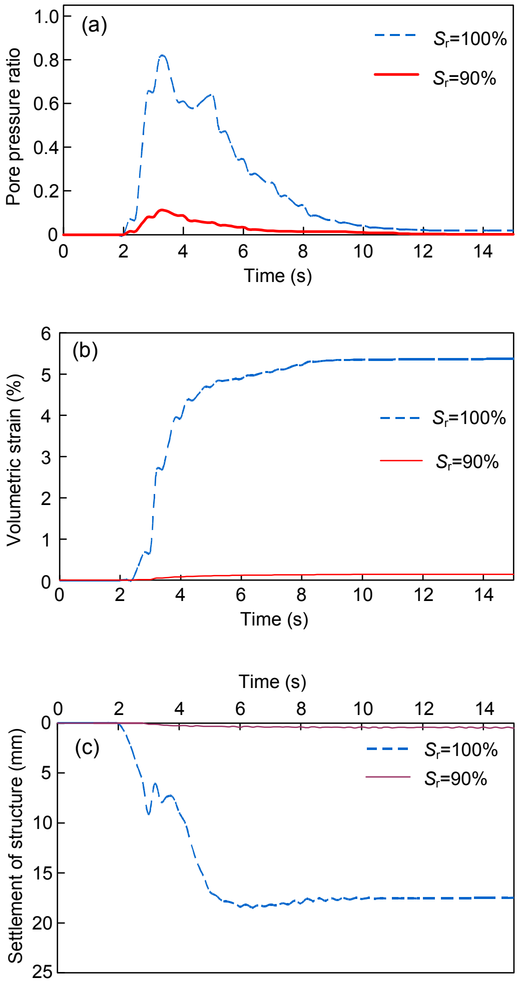

Fig. 6 Seismic responses for relatively loose soils under a_{max}=0.5 m/s^2: (a) pore pressure ratio; (b) volumetric strain; (c) settlement of structure

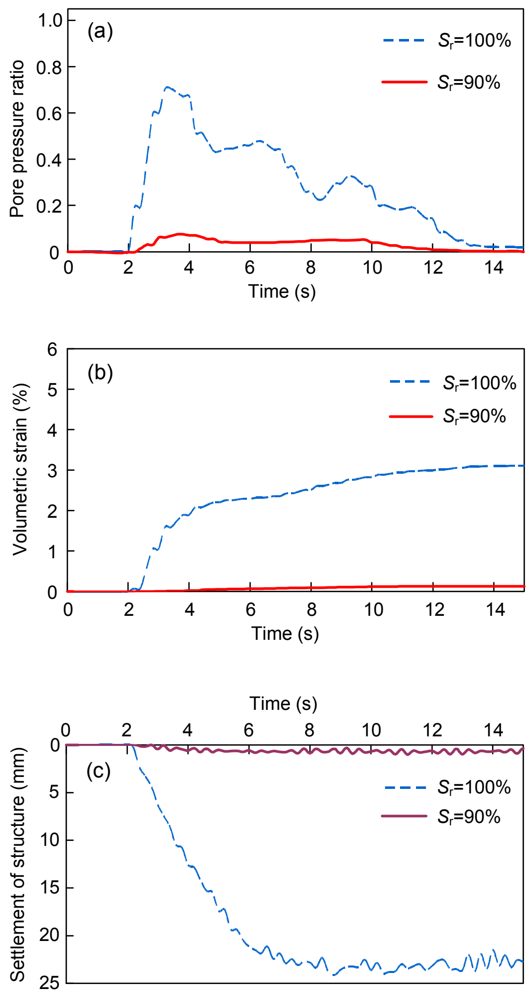

Fig. 7 Seismic responses for relatively dense soils under a_{max}=1.5 m/s^2: (a) pore pressure ratio; (b) volumetric strain; (c) settlement of structure

pressure ratio, volumetric strain, and settlement of the structure are presented. Pore pressure ratio is defined as the ratio of maximum excess pore water pressure to the initial effective overburden pressure. If soil completely liquefies, the pore pressure ratio becomes unity. Data used for the determination of pore pressure ratio is collected by pore water pressure sensor PWP2, which is installed at around 2/3 depth of the soil samples (Fig. 5). In Fig. 6, clear contrasts can be seen between the two tests. In saturated samples, soil manifests a liquefaction manner by showing a high pore pressure ratio, large volumetric strain, and large settlement of structure. In comparison, microbially desaturated soil with 90% saturation degree displays a complete non-liquefaction manner. Pore pressure ratio, volumetric strain, and the settlement of structure are all by far smaller than those in saturated sands. In relatively dense samples as shown in Fig. 7, the results are similar to those in Fig. 6. That is, the desaturated sample shows a non-liquefaction manner, but its saturated counterpart manifests otherwise. Such comparative results clearly demonstrate that microbial desaturation can effectively enhance the liquefaction resistance under seismic loading.

Results of the shaking table tests are summarized and discussed. The data of pore pressure ratio in relation to saturation degree and relative density are presented in Fig. 8. Pore pressure ratio reduces with the decrease in saturation degree and increase in relative density. Saturated sand liquefies at 52% relative density by displaying a pore pressure ratio of 1. 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. The method of densification for the control of soil liquefaction has long been proved to be effective. From this result, we can see that the method of desaturation is equally effective. The data on volumetric strain is given in Fig. 9. Volumetric strain decreases with the decrease in saturation degree and increase in relative density. In Fig. 10, volumetric strain is plotted against pore pressure ratio for all tests at various saturation degrees. All the tests seem to follow the same trendline. Volumetric strain gradually increases with pore pressure ratio and the increasing rate becomes steep when pore pressure ratio is larger than 0.5. Such a finding agrees with previous studies (Lee and Albaisa, 1974; Tokimatsu and Seed, 1987). Since a single

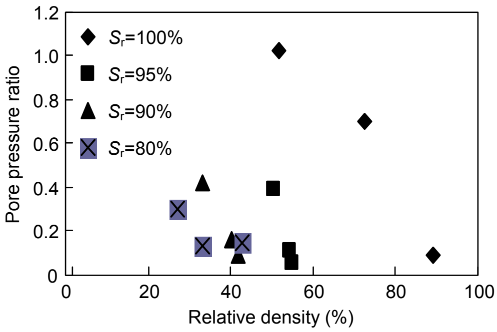

Fig. 8 Plot of pore pressure ratio against relative density for soils with different saturation degrees under a_{max}= 1.5 m/s^2

trendline is formed and is applicable to soils with different saturation degrees and relative densities, we can use either pore pressure ratio or volumetric strain to characterize seismic response in the evaluation of liquefaction susceptibility for desaturated soils. It is also interesting to note from Fig. 11 that both saturated and desaturated soils amplify the input acceleration. However, the amplification factors in desaturated soils are smaller than those in saturated soils. Here the amplification of acceleration is defined as the ratio of acceleration on the soil surface (measured by an accelerometer installed on a laminar frame) to input acceleration (measured by an accelerometer installed on the shaking table surface), as shown in Fig. 5.

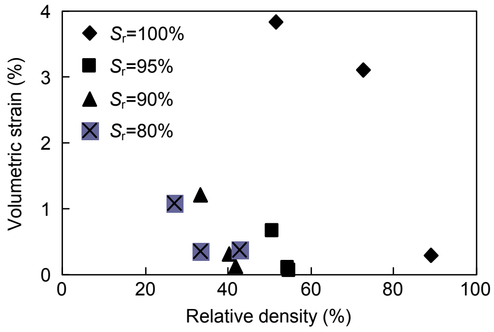

Fig. 9 Plot of volumetric strain against relative density for soils with different saturation degrees under a_{max}=1.5 m/s^2

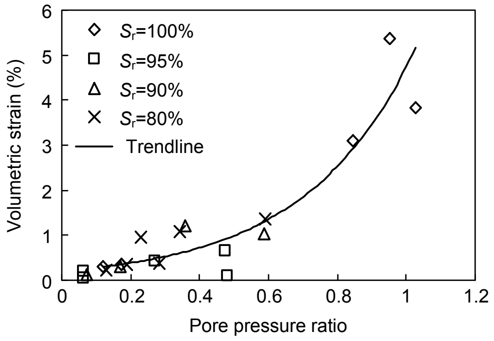

Fig. 10 Relationship between volumetric strain and pore pressure ratio

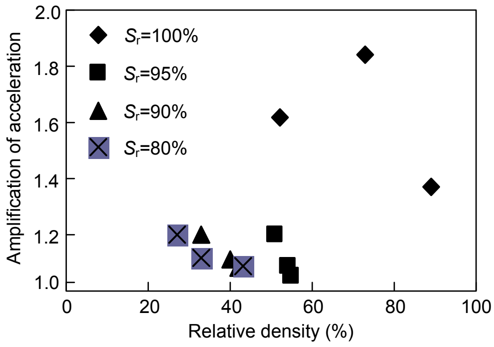

Fig. 11 Plot of amplification of acceleration against relative density for soils with different saturation degrees under a_{max}=1.5 m/s^2

4.2 Triaxial tests

Soil liquefaction is usually considered to take place in undrained conditions, so undrained tests, either under cyclic or static loadings, are often used in soil liquefaction-related studies. It has long been understood that the soil strength under cyclic conditions increases with the decrease in the saturation degree (Yang *et al.*, 2004; Okamura and Soga, 2006). He and Chu (2014) and He *et al.* (2014) found that it is also the case for static loading conditions. Triaxial consolidated undrained tests on loose sands with various saturation degrees are briefly presented and discussed.

Triaxial samples were prepared by the moist tamping method. Dry sand was mixed with a small amount of water and packed into a triaxial mould. A sample prepared in this way can achieve a very loose condition. After forming the sample, a small confining pressure was applied to support the sample. The sample was flushed with CO_2 and then soil desaturation solution. A sample prepared in this way can be saturated initially and become desaturated as the denitrification reaction proceeds.

A series of triaxial consolidated undrained test results on soils with various saturation degrees are presented in Fig. 12. As the saturation degree reduces from 100% to 87.5%, the strength improves greatly and the stress-strain response shows a transition from a strain-softening manner to a strain-hardening manner. The pore pressure response shows a decreasing trend as the saturation degree reduces.

5 Stability of desaturation state in soil

The stability of the desaturation state of soils is another concern. The stability of microbially desaturated soil has been investigated under hydrostatic and flow conditions using the set-up shown in Fig. 13. It

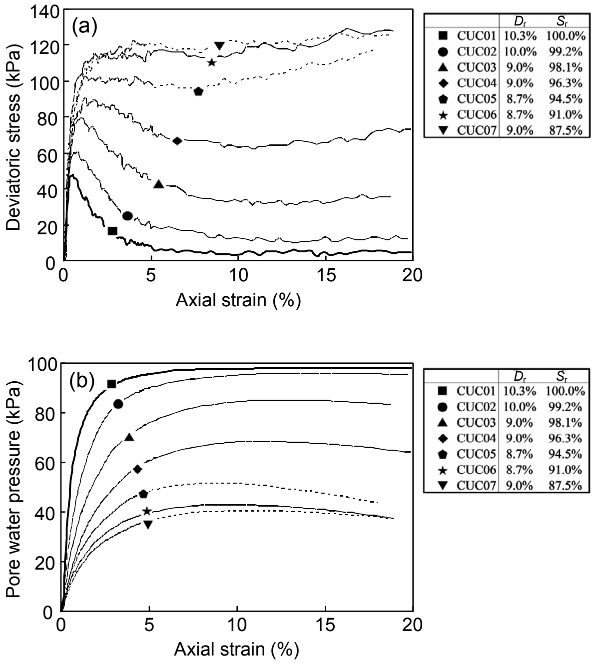

Fig. 12 Triaxial consolidated undrained compression test results: (a) stress-strain curves; (b) pore pressure curves

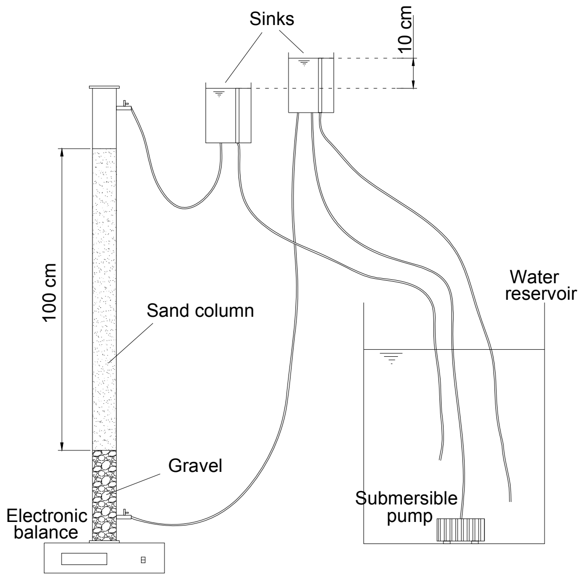

Fig. 13 Set-up of gas stability test

consisted of a Plexiglas column with an inner diameter of 7.04 cm, and two water reservoirs were linked to the bottom and top of the column to regulate the water head of the flow through the sample. The length of the column was 1.5 m. The length of the sand sample was around 1 m. There was a 25-cm thick layer of gravel placed at the bottom of the column. Samples were tested under either upward or downward seepage flow condition at a water head of 10 cm. Thus, the hydraulic gradient was maintained at 0.1. The flow of water was supplied by pumping tap water from the pail using a submersible pump. The sample preparation method was the same as that used in the shaking table tests. The change in the degree of saturation over time can be calculated based on the mass change of the column (due to the volume replacement of gas bubbles by water). The change in the degree of saturation can also be indirectly reflected by the change in the permeability, as can be determined by measuring the flow rate through the column. The change in the void ratio can be calculated from the volume change of soil sample, which can be monitored in the test.

After the desaturation treatment, the content of gas bubbles (which is a reflection of saturation degree) was uniform throughout the column, based on visual observation. Only a very small amount of gas bubbles escaped from the top surface of the soil. Three tests were carried out under hydrostatic, upflow, and downflow conditions, respectively. The test results are presented in Figs. 14–16. As can be seen from Fig. 14, the degree of saturation under the hydrostatic condition remained almost unchanged during 10 d. The stability of gas bubbles can also be visually observed. However, under both upflow and downflow conditions, gas bubbles in soils are gradually taken away, and the degree of saturation increases from 89% to 100% in about 4 d. The change in the permeability can also reflect the change in the degree of saturation. As shown in Fig. 15, the permeability in the hydrostatic condition remains almost constant within 10 d, but in water flow conditions, the permeability gradually increases, which is consistent with the change in the degree of saturation as presented in Fig. 14. The change in the degree of saturation in water flow conditions also accompanies the decrease in the void ratio (Fig. 16). This could be due to the collapse of local metastable structure formed around the gas bubbles. The test results presented here prove that the desaturation state can be stable under hydrostatic conditions. This result agrees with Okamura *et al.* (2011), which showed that the desaturation state in soil ground below groundwater table can be sustained over more than 20 years. But the desaturation state becomes unstable under constant water flow. In water flow conditions, measures should be taken to prevent the flow path through the desaturation zone to ensure the stability of gas bubbles in the soil. Wu (2015) proposed a method to use microbially induced cementation to fix the gas bubbles and control the water flow in soil, so that the desaturation state of soil can be maintained for a longer time.

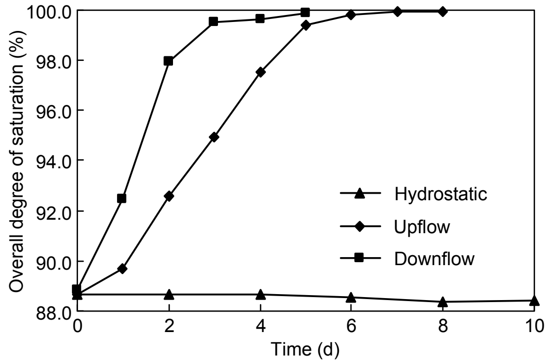

Fig. 14 Variation of saturation degree with time

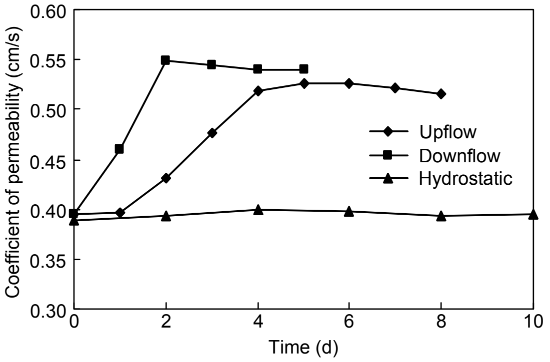

Fig. 15 Variation of permeability with time

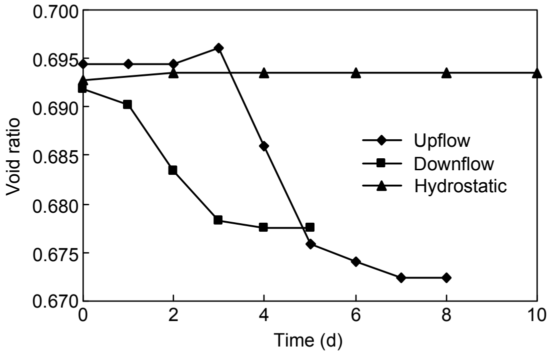

Fig. 16 Variation of void ratio with time

6 Conclusions

A new method for the mitigation of soil liquefaction, using microbially induced soil desaturation, is proposed and tested. The desaturation effect in soil is achieved through the generation of nitrogen gas produced from the microbial denitrification process. The method is experimentally investigated in several aspects. The major conclusions can be stated as follows:

1. The saturation degree of sands can be effectively reduced by the microbial method. The final saturation degree is related to the initial nitrate concentration used in the desaturation solution: the higher the nitrate concentration, the lower the saturation degree.

2. CT images reveal that the gas phase of the desaturated soil is in the form of small pockets of gas bubbles. The small pockets have a size a little larger than a sand grain.

3. In the shaking table tests, microbially induced desaturation can effectively improve the liquefaction resistance of soil by showing much lower pore pressure generation, much smaller volumetric strain, and much smaller settlement of the structure in desaturated soil, in contrast to those in saturated soil.

4. In the triaxial consolidated undrained tests, as the saturation degree reduces, loose desaturated sand shows an improvement in strength, a transition in the stress-strain response from strain softening to strain hardening, and a decreasing trend in the pore pressure generation.

5. The gas phase in microbially desaturated soil is stable in the hydrostatic condition, but becomes unstable in steady flow conditions. So measures should be taken to prevent steady water flow if the desaturation method is used.

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中文概要

题　目：基于微生物诱导减饱和作用降低地基液化风险的研究

目　的：常规的地基抗液化技术成本较高或实施复杂，因此有大量的工程建设未得到有效的抗液化处理。本文旨在提出一种新型的、基于微生物诱导减饱和作用的地基液化治理技术，期望能应用到普通的建筑和结构的抗液化治理中。

创新点：1. 获得一种基于微生物反硝化过程的砂土减饱和方法；2. 试验验证微生物减饱和法处理砂土的抗液化性能，获得微生物减饱和法处理砂土中的气泡分布形态以及气泡在静水和渗流条件下的稳定性规律。

方　法：1. 利用微生物反硝化过程中产生的氮气降低饱和液化砂土的饱和度；2. 利用电脑断层扫描（CT）技术研究微生物减饱和法处理的砂土中气泡的分布形态；3. 利用振动台实验和三轴固结不排水试验研究微生物减饱和法处理的砂土的力学性能和抗液化性能；4. 采用一种自行研制的模型试验（图 13）研究微生物减饱和法处理的砂土在静水和渗流条件下气泡的稳定性。

结　论：1. 利用微生物反硝化过程可以实现可控的砂土饱和度降低；2. 微生物气泡在砂土中以小空隙的形态存在，小空隙的尺寸略大于砂土的平均粒径；3. 将饱和松砂的饱和度略作降低，其不排水强度和抗液化性能得到显著提升；4. 微生物减饱和法处理的砂土中的气泡在静水条件下是稳定的，但是在稳定渗流条件下会被水流缓慢带走，此时，需要采用一些手段来控制通过减饱和区的渗流。

关键词：地基液化；减饱和；微生物反硝化；细菌