Mitigation of soil liquefaction using microbially induced desaturation

Chu, Jian; Wu, Shifan; Peng, Jie; He, Jia

2016

He, J., Chu, J., Wu, S., & Peng, J. (2016). Mitigation of soil liquefaction using microbially induced desaturation. *Journal of Zhejiang University Science A*, 17(7), 577-588.

<https://hdl.handle.net/10356/84610>

<https://doi.org/10.1631/jzus.A1600241>

© 2016 Zhejiang University and Springer. This is the author created version of a work that has been peer reviewed and accepted for publication by *Journal of Zhejiang University Science A*, Zhejiang University and Springer. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [<http://dx.doi.org/10.1631/jzus.A1600241>].

Downloaded on 26 Apr 2023 21:37:46 SGT

Mitigation of soil liquefaction using microbially induced desaturation

Jia He^{1,2*}, Jian Chu³, Shifan Wu³, Jie Peng^{1,2}

1. Geotechnical Research Institute, Hohai University, Nanjing, China

2. Key Laboratory of Geomechanics and Embankment Engineering, Ministry of Education, Nanjing, China

3. School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

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 damages are still widely encountered in major 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 desaturation solution into soil pores by mixing, flushing, or injection. 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 into the soil: the higher the concentration of nitrate in the desaturation solution, the lower the degree of saturation that can be

1 achieved. The existence of gas bubbles in soil is evidenced by computer tomography
2 (CT) technology. The CT images reveals that gas is in the form of small pockets which
3 has a size a little larger than the mean size of sand grains. It is shown in the shaking
4 table tests that microbially induced desaturation can effectively improve the
5 liquefaction resistance of soil by showing a much lower pore pressure generation,
6 much smaller volumetric strain, and much smaller settlement of the structure in
7 desaturated soil, as compared to those in saturated soil. Triaxial consolidated
8 undrained tests reveal that the desaturation treatment of soil can improve the
9 undrained shear strength of loose sand. The stability of gas is tested under hydrostatic
10 and water flow conditions. Gas phase is stable under the hydrostatic condition, but
11 unstable under water flow conditions. So measures ought to be taken to prevent
12 steady flow in practice.

13

14 **1. Introduction**

15 Soil liquefaction is a phenomenon that soil loses its shear strength and behave like a
16 fluid due to the increase in pore water pressure. Liquefaction often accompanies large
17 deformation in soil and can cause disastrous consequences to buildings and human
18 lives. Soil liquefaction is related to many damages in earthquake events, such as slope
19 failure, loss of bearing capacity, and dislocation of retaining walls. Until recent years,
20 soil liquefaction was still encountered in large and mid-size earthquakes, for example,
21 2011 Christchurch Earthquake in New Zealand, 2011 Great East Japan Earthquake, and
22 2008 Sichuan Earthquake in China.

23 Conventional measures against soil liquefaction, such soil densification, soil
24 cementation, lowering of groundwater table, shear strain constraint, are effective in
25 technical performance. However, these methods are usually very expensive. Normal
26 buildings and structures often cannot receive any proper treatments against soil
27 liquefaction. As a result, many existing buildings and structures still face the risk of soil
28 liquefaction. In this situation, the development of cost-effective methods for the

1 prevention or mitigation of soil liquefaction has great practical values.

2 One of the opportunities to obtain an economical method for the
3 mitigation/prevention of soil liquefaction is to use bacteria. Bacteria are omnipresent
4 in natural subsurface environments and can alter the physical and mechanical
5 behaviour of soil in many ways (Mitchell and Santamarina, 2005). These microbial
6 activities can be harnessed to modify the soil behaviour in order to solve specific
7 problems for geotechnical engineering. Soil improvement techniques that use bacteria
8 activities have been gaining increasing research interests in recent years. One of the
9 potential applications is to counter soil liquefaction. There are two potential
10 approaches to achieve this goal. One approach is bio-cementation, that is, to enhance
11 the shear strength of soils through the formation of microbially-induced cementing
12 materials in soil (Whiffin et al., 2007; Ivanov and Chu, 2008). The other approach is
13 bio-desaturation, that is, to lower the degree of saturation of originally saturated soil
14 so that the undrained shear strength can be enhanced (Rebata-Landa and Santamarina,
15 2012; He et al., 2013a; He and Chu, 2014; He et al., 2014). These microbial approaches
16 potentially have a larger scope of applications because of their lower cost in materials
17 and implementation, and the applicability to existing buildings and structures, as
18 compared with regular liquefaction countermeasures.

19 Loose saturated sands are usually susceptible to earthquake liquefaction. However,
20 research evidences have shown that undrained shear strength and liquefaction
21 resistance of loose saturated sand can be improved as the degree of saturation
22 reduces. In cyclic triaxial and cyclic torsional shear tests, if the degree of saturation of
23 initially saturated sand reduced by merely a few percentage points, the cyclic strength
24 can be much increased (Yang et al., 2004; Okamura and Soga, 2006). Likewise, in
25 shaking table tests, liquefaction susceptibility in desaturated sand can be reduced by
26 showing a much lower excess pore water pressure generation and much smaller
27 volumetric deformation, in contrast to its fully saturated counterpart (Okamura and
28 Teraoka, 2005; Yegian et al., 2007; He et al., 2013). In monotonic loading conditions,
29 the stress-strain curves of loose sand changes from a strain-softening manner to a

1 strain hardening manner when the degree of saturation reduces from 100% to a range
2 of lower than 90% (Rad et al., 1994). These experimental results can support the idea
3 of using desaturation as a means to mitigate liquefaction susceptibility of soil.

4 In order to implement the desaturation method in engineering practice, reliable
5 techniques to achieve the desaturation effect in soil are required. Several techniques
6 were proposed and tested in the past. The use of a chemical, sodium perborate, was
7 adopted by Eseller-Bayat et al. (2013) to achieve a controlled desaturation effect. The
8 degree of saturation is reduced through the generation of oxygen gas from the
9 hydrolysis of sodium perborate in soil pores. The desaturation effect of soil can also be
10 attained by water electrolysis, that is, to apply an electric current through soil so that
11 pore water can be decomposed to oxygen and hydrogen gases (Yegian et al., 2007).
12 Direct air injection is a straightforward method and has been tested by Okamura et al.
13 (2011) in a field experiment. The degree of saturation of sandy ground was successfully
14 reduced to 68-98% within 4 meters range from the injecting point. Microbial methods
15 is another option. In this study, we choose denitrification process to produce nitrogen
16 gas for the purpose of soil desaturation. Details are presented in the following part of
17 the paper.

18 **2. Soil desaturation through microbial denitrification**

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

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

27 In the equation above, nitrogen gas (N_2) is the effective product for soil desaturation.

1 N₂ gas has very low solubility in water and its chemical properties are inert. So the
2 stability of N₂ gas bubbles in soil is better than other types of gases. There are also
3 some limiting factors affecting the process of denitrification, as reported in previous
4 studies. High concentration of nitrate in the substrate solution can cause the
5 accumulation of nitrite (NO₂⁻) and further reaction will be impeded (Błaszczuk et al.,
6 1985; Glass and Silverstein, 1998; van Paassen et al., 2010a). The upper limit the
7 nitrate (-N) concentration that does not cause serious nitrite accumulation is around
8 100 mM/L (van Paassen et al. 2010a). This value is by far higher than the requirement
9 of soil desaturation. It is reported that neutral and moderately alkaline pH is preferable
10 for high enzymatic activity and complete reaction of denitrification (Saleh-Lahka et al.,
11 2009). An anaerobic environment with the absence of oxygen gas can help produce
12 more N₂ than some intermediates such as N₂O (Saleh-Lahka et al., 2009). A
13 temperature range from 15 to 35°C is optimal for denitrification (Stanford et al., 1975).
14 From these previous studies, we can see that these limiting factors are unlikely to
15 adversely affect the progress of denitrification in subsurface environments below
16 ground water table. After all, the denitrification is a widespread microbial process in
17 soil ecosystem. Conditions for it to take place in subsurface conditions is not difficult
18 to satisfy.

19 After knowing the principles and limiting factors of microbial denitrification process,
20 we have cultivated denitrifying bacteria and use the bacteria in the soil desaturation
21 experiment. The denitrifying bacteria in this study were cultivated from anaerobic
22 sludge in a wastewater treatment plant. Anaerobic sludge often contains various kinds
23 of bacteria and is commonly used as a source to obtain any desired kind of bacteria.
24 The cultivation of denitrifying bacteria was made through two steps, that is, cultivation
25 using enrichment culture and pure culture, respectively. In the enrichment culture of
26 denitrifying bacteria, certain amounts of anaerobic sludge and cultivation medium
27 were mixed and favored growing conditions were provided. Medium of enrichment
28 culture contains nutrients that supports the growth of desired bacteria (here are
29 denitrifying bacteria), while inhibits the growth of others. As a result, denitrifying

1 bacteria gradually dominate. Pure culture of denitrifying bacteria were obtained by
2 diluting and spreading bacteria suspension of enrichment culture on solidified agar
3 plate. Single strain on the agar plate (growing from one single bacterium) can be isolate
4 and cultivated in an aseptic condition. The cultivation medium of enrichment culture
5 comprised the following content: C₂H₅OH, 0.5 g; KNO₃, 1.01 g; NH₄Cl 0.12 g; KH₂PO₄,
6 0.75 g; K₂HPO₄, 2.5 g; MgSO₄•7H₂O, 0.1g; FeSO₄•7H₂O, 0.01 g; CaCl₂•2H₂O, 0.015 g;
7 and addition of tap water to 1 L. The composition of the medium of pure culture was
8 the same as enrichment culture and solidified with the addition of 12g/L agar. Nearly
9 full length 16S rRNA gene sequencing analysis was made on the dominant type of
10 colonies on the solid medium. The result shows that the dominant species in the
11 enrichment culture belongs to *Acodovorax sp.*, which is a common species of
12 denitrifying bacteria in wastewater treatment facilities.

13
14 Soil desaturation tests were conducted to explore the feasibility and effectiveness of
15 the microbial soil desaturation method. A simple set-up as shown in Fig. 1 was adopted
16 to evaluate the soil desaturation process. The soil desaturation solution and bacteria
17 were mixed with certain amount of sand and poured into a 60mL syringe to form an
18 initially saturated soil sample. The syringe was connected to a burette. When gas
19 bubbles were produced in soil, some volume of pore water would be replaced and
20 pushed into the burette. The volume of water replaced can be recorded by a
21 computer-controlled camera. The amount and rate of gas generation, as reflected by
22 the water level in the burette, can thus be measured. Soil used in this test and the
23 other tests presented in the paper is Ottawa Sand (ASTM Graded type). It is a poorly-
24 graded quartz sand with a mean size of 0.4 mm. The particle size distribution curve is
25 presented in Fig. 2.

26 The soil desaturation solution contains the same chemicals used in the cultivation
27 medium but with different concentrations. The concentration of KNO₃ in desaturation
28 solution is determined based on the required volume of gas according to the chemical
29 balance in Eqn. (2). The molar ratio of KNO₃: C₂H₅OH is 1:1.1. The concentrations of

1 the other chemicals used in the soil desaturation solution are one-tenth of those used
2 in the cultivation medium. 1% volume of bacterial suspension with an optical density-
3 based concentration of 0.51 was added into 99% volume of desaturation solution
4 before applying to soils.

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

18 The soil desaturation solution used above is a water solution of low viscosity. This
19 feature enables the microbial desaturation to be implemented in the field simply by
20 injecting or circulating denitrifying bacteria and soil desaturation solution in soil
21 ground. Similar techniques have been adopted in the large-scale experiments of bio-
22 cementation of soil grounds, as reported in van Paassen et al. (2010b). In comparison,
23 conventional cement-based ground improvement methods, such as cement mixing
24 and jet grouting, require heavy machine and relatively high costs.

25 **3. Observational analysis of microbially desaturated soil using computer tomography**

26 Computer tomography (CT) was used to carry out observational analysis on the
27 microbially desaturated soil samples. The CT apparatus used was a high-resolution
28 digital radiography and computed tomography system. The CT image is a map of

1 density distribution. Denser materials have brighter pixels and lighter materials have
2 darker pixels. Plastic test tubes with an inner diameter of 1.46 cm were used for the
3 preparation of sand samples. The samples were prepared in the same way as that in
4 the soil desaturation tests. For each sample, a 2cm length in the mid range of the tube
5 was scanned.

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

15 **4. Liquefaction resistance and mechanical responses of microbially desaturated soil**

16 To evaluate the liquefaction resistance and mechanical responses of microbially
17 desaturated sand, 1-g shaking table tests and triaxial consolidated undrained tests
18 were conducted. Results presented in this section has been published in several others
19 papers by the Authors and are summarized and discussed here (He et al., 2013a, 2013b;
20 He and Chu, 2014; He et al., 2014).

21 **4.1 Shaking table tests**

22 The tests were conducted using a laminar box model fixed on a shaking table. This
23 laminar box consists of ten layers of frames stacked together as shown in Fig. 5. Ball
24 bearing were placed between the frames to allow free movement in the horizontal
25 shaking direction. An impervious plastic sheet was lined in the laminar box to hold the
26 soil and water inside. This sheet was place in a loose manner in order not to impede
27 the free movement of laminar frames. The laminar box has an inner size of $45 \times 30 \times$
28 29.7 cm^3 (length $\times$ width $\times$ height). Soil desaturation solution was prepared and

1 poured into the laminar box first. Dry sand was then carefully deposited into water
2 through a funnel. Soil samples made in this way can achieve an initial relative density
3 of around 20%. Four samples with 80-100% saturation degrees were prepared and
4 tested. On each sample, seismic loading was applied at several steps. Settlement can
5 be measured after each step of loading using a LVDT, and thus the average relative
6 densities at the start and end of each loading can be calculated. The frequency of the
7 seismic loading was 2 Hz. The instrumentations include pore water pressure, surface
8 settlement, settlement of structure resting on the soil surface, input and surface
9 accelerations, and horizontal displacement of laminar frames at different heights.
10 Based this a testing scheme, we can obtain the seismic performance and liquefaction
11 resistance of soils with various saturation degrees and relative densities.

12 Two examples of test results are provided here to explain the effect of degree of
13 saturation on liquefaction resistance. Fig. 6 gives comparative test results on two
14 relatively loose soil samples with 100% and 90% saturation degrees, and 21% and 17%
15 relative densities, respectively. Both tests were subject to an acceleration of $a_{\max} = 0.5$
16 m/s^2 . Fig. 7 provides comparative test results on two relatively dense samples with
17 100% and 90% saturation degrees, and 73% and 42% relative densities, respectively.
18 These two tests were subject to an acceleration of $a_{\max} = 1.5 \text{ m/s}^2$. In the test results,
19 pore pressure ratio, volumetric strain, and settlement of the structure are presented.
20 Pore pressure ratio here is defined as the ratio of maximum excess pore water pressure
21 to the initial effective overburden pressure. If soil completely liquefies, the pore
22 pressure ratio becomes unit. Data used for the determination of pore pressure ratio is
23 collected by pore water pressure sensor PWP2, which is installed at around 2/3 depth
24 of the soil samples (see Fig. 5). In Fig. 6, clear contrasts can be seen between two tests.
25 In saturated samples, soil manifests a liquefaction manner by showing a high pore
26 pressure ratio, large volumetric strain, and large settlement of structure. In
27 comparison, microbially desaturated soil with 90% saturation degree displays a
28 complete non-liquefaction manner. Pore pressure ratio, volumetric strain, and the
29 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, 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 here. 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 around 60% relative density. 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 of 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 with 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 agree with previous studies (Lee and Albaisa, 1974; Tokimatsu and Seed, 1987). Since a single 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. But 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 soil surface (measured by an accelerometer installed on a laminar frame) to input acceleration (measured by an accelerometer installed on the shaking table surface), see Fig. 5.

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) have 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 here. Triaxial samples were prepared by the moist tamping method. Dry sand was mixed with small amount of water and packed into triaxial mould. The 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 CO₂ and then soil desaturation solution. The 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 desaturation state of soils is another concern. The stability of microbially desaturated soil has been investigated under hydrostatic and flow conditions using a set-up as shown in Fig. 13. It consisted of a Plexiglas column with an inner diameter of 7.04 cm, and two water reservoirs was 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 25cm-thick layer of gravels 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

1 method was the same as that used in the shaking table tests. The change in the degree
2 of saturation over time can be calculated based on the mass change of the column
3 (due to the volume replacement of gas bubbles by water). The change in the degree
4 of saturation can also be indirectly reflected by the change in the permeability, as can
5 be determined by measuring the flow rate through the column. The change in the void
6 ratio can be calculated from the volume change of soil sample, which can be
7 monitored in the test.

8 After the desaturation treatment, the content of gas bubbles (which is a reflection of
9 saturation degree) was uniform throughout the column, based on the visual
10 observation. Only a very small amount of gas bubbles were escaped from the top
11 surface of the soil. Three test were carried out under hydrostatic, upflow and
12 downflow conditions, respectively. The test results are presented in Figs. 14 – 16. As
13 can be seen in Fig. 14, the degree of saturation under the hydrostatic condition almost
14 unchanged during 10 days. The stability of gas bubbles can also be visually observed.
15 However, under both upflow and downflow conditions, gas bubbles in soils are
16 gradually taken away, and the degree of saturation increases from 89% to 100% in
17 about 4 days. The change in the permeability can also reflects the change in the degree
18 of saturation. As shown in Fig. 15, the permeability in the hydrostatic condition keeps
19 almost constant within 10 days. But in water flow conditions, the permeability
20 gradually increases, which is consistent with the change in the degree of saturation as
21 presented in Fig. 14. The change in the degree of saturation in water flow conditions
22 also accompanies the decrease in the void ratio (Fig. 16). This could be due the collapse
23 of local metastable structure formed around the gas bubbles. The test results
24 presented here prove that, the desaturation state can be stable under hydrostatic
25 condition. This result agrees with Okamura et al., (2011), which shows that the
26 desaturation state in soil ground below groundwater table can be sustained over more
27 than 20 years. But the desaturation state become unstable under constant water flow.
28 In water flow conditions, measures should be taken to prevent the flow path though
29 desaturation zone to ensure the stability of gas bubbles in soil. Wu (2015) has

1 proposed a method to use microbially induced cementation to fix the gas bubbles and
2 control the water flow in soil, so that the desaturation state of soil can be maintained
3 for a longer time.

4 **6. Conclusions**

5 A new method for the mitigation of soil liquefaction, using microbially induced soil
6 desaturation, is proposed and tested. The desaturation effect in soil is achieved
7 through the generation of nitrogen gas produced from the microbial denitrification
8 process. The method is experimentally investigated in several aspects. Major
9 conclusion can be drawn as,

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

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

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

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

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

27

Acknowledgements

This work is financially supported by China national Science Foundation Project 51578214, Jiangsu Science Foundation Project BK20150814, China Postdoctor Science Foundation Project 2015M581714, and Jiangsu Postdoctor Research Foundation Project 1501026C.

References

- Blaszczyk, M., Galka, E., Sakowicz, E., Mycielski, R., 1985. Denitrification of High-Concentrations of Nitrites and Nitrates in Synthetic Medium with Different Sources of Organic-Carbon .3. Methanol. *Acta Microbiologica Polonica*, **34**(2): 195-205.
- Eseller-bayat, E., Yegian, M., Alshawabkeh, A., Gokyer, S., 2013. Liquefaction Response of Partially Saturated Sands. I: Eperimental Results. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **139**(6): 863–871.
- Glass, C., Silverstein, J., 1998. Denitrification Kinetics of High Nitrate Concentration Water: pH Effect on Inhibition and Nitrite Accumulation. *Water Research*, **32**(3): 831-839.
- He, J., Chu, J., Ivanov, V., 2013a. Mitigation of Liquefaction of Saturated Sand Using Biogas. *Geotechnique*, **63**(4): 267–275.
- He, J., Chu, J., Ivanov, V., 2013b. Remediation of Liquefaction Potential of Sand Using the Biogas Method. Geo-Congress, San Diego, California, United States, p. 879-887.
- He, L., Chu, J., 2014. Undrained Responses of Microbially Desaturated Sand under Monotonic Loading. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, **140**(5): 04014003.
- He, J., Chu, J., Liu, H., 2014. Undrained Shear Strength of Desaturated Loose Sand under Monotonic Shearing. *Soils and Foundations*, **54**(4): 910-916.
- Ivanov, V., Chu, J., 2008. Applications of Microorganisms to Geotechnical Engineering

1 for Bioclogging and Biocementation of soil in situ. *Reviews in Environmental Science*
2 *and Biotechnology*, **7**(2): 139-153.

3 Lee, K.L., Albaisa, A., 1974. Earthquake Induced Settlements in Saturated Sands.
4 *Journal of Geotechnical Engineering Division, ASCE*, **100**(4): 387-406.

5 Mitchell, J., Santamarina, J., 2005. Biological Considerations in Geotechnical
6 Engineering. *Journal of Geotechnical and Geoenvironmental Engineering*,
7 *ASCE*, **131**(10): 1222–1233.

8 Okamura, M., Teraoka, T., 2005. Shaking Table Tests to Investigate Soil Desaturation as
9 a Liquefaction Countermeasure. Proc., Seismic Performance and Simulation of Pile
10 Foundations in Liquefied and Laterally Spreading Ground (GSP 145), University of
11 California, Davis, CA, USA, p. 282-293.

12 Okamura, M., Soga, Y., 2006. Effects of Pore Fluid Compressibility on Liquefaction
13 Resistance of Partially Saturated Sand. *Soils and Foundations*, 2006, **46**(5): 695-700.

14 Okamura, M., Takebayashi, M., Nishida, K., Fujii, N., Jinguji, M., Imasato, T., Yasuhara,
15 H. Nakagawa, E., 2011. In-situ Desaturation Test by Air Injection and Its Evaluation
16 Through Field Monitoring and Multiphase Flow Simulation, *Journal of Geotechnical*
17 *and Geoenvironmental Engineering, ASCE*, **137**(7), 643-652.

18 Rad, N.S., Vianna, A.J.D., Berre, T., 1994. Gas in Soils. II: Effect of Gas on Undrained
19 Static and Cyclic Strength of Sand. *Journal of Geotechnical Engineering, ASCE*, **120**(4),
20 716-736.

21 Rebata-Landa, V., Santamarina J.C., 2012. Mechanical Effects of Biogenic Nitrogen Gas
22 Bubbles in Soils. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*,
23 **138**(2): 128–137.

24 Saleh-Lakha, S., Shannon, K.E., Henderson, S.L., Goyer, C., Trevors, J.T., Zebarth, B.J.,
25 Burton, D.L., 2009. Effect of pH and Temperature on Denitrification Gene Expression
26 and Activity in *Pseudomonas mandelii*. *Applied and Environmental Microbiology*,
27 **75**(12): 3903-3911.

- 1 Stanford, G., Dzienia, S., Vanderpol, R.A., 1975. Effect of Temperature on
2 Denitrification Rate in Soils. *Soil Science Society of America Journal*, **39**(5): 867-870.
- 3 Tokimatsu, K., Seed, H. B., 1987. Evaluation of Settlements in Sands Due to Earthquake
4 Shaking. *Journal of Geotechnical Engineering Division, ASCE*, **113**(8): 861-878.
- 5 van Paassen, L.A., Daza, C.M., Staal, M., Sorokin, D.Y., van der Zon, W., van Loosdrecht,
6 M.C.M., 2010a. Potential Soil Reinforcement by Biological Denitrification. *Ecological
7 Engineering*, **36**(2): 168-175.
- 8 van Paassen, L.A., Ghose, R., van der Linden, T., van der Star, W., and van Loosdrecht,
9 M., 2010b. Quantifying Biomediated Ground Improvement by Ureolysis: Large-Scale
10 Biogrout Experiment. *Journal of Geotechnical and Geoenvironmental Engineering,
11 ASCE*, **136**(12): 1721-1728.
- 12 Whiffin, V.S., van Paassen, L.A., Harkes, M.P., 2007. Microbial Carbonate Precipitation
13 as a Soil Improvement technique. *Geomicrobiology Journal*, **24** (5): 417–423.
- 14 Wu, S., 2015. Mitigation of Liquefaction Hazards Using the Combined Biodesaturation
15 and Bioclogging Method. Doctoral thesis, Iowa State University, the United States.
- 16 Yang, J., Savidis, S., Roemer, M., 2004. Evaluating Liquefaction Strength of Partially
17 Saturated Sand. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*,
18 **130**(9): 975-979.
- 19 Yegian, M.K., Eseller-Bayat, E., Alshawabkeh, A., Ali, S., 2007. Induced-Partial
20 Saturation for Liquefaction Mitigation: Experimental Investigation. *Journal of
21 Geotechnical and Geoenvironmental Engineering, ASCE*, **133**(4), 372-380.

List of tables and figures

2

3 Table 1 Results of soil desaturation test

4 Fig. 1 Set-up of soil desaturation test

5 Fig. 2 Particle size distribution curve of Ottawa sand (ASTM Graded)

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

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

9 Fig. 5 Set-up and instrumentation of shaking table test

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

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

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

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

18 Fig. 10 Relationship between volumetric strain and pore pressure ratio

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

21 Fig. 12 Triaxial consolidated undrained compression test results. (a) Stress-strain
22 curves; (b) pore pressure curves

23 Fig. 13 Set-up of gas stability test

24 Fig. 14 Variation of saturation degree with time

25 Fig. 15 Variation of permeability with time

26 Fig. 16 Variation of void ratio with time

27

1 1 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

2

3

1

2

3

4

Fig. 1 Set-up of soil desaturation test

5

Figure 1 is a line graph showing the particle size distribution of the feed. The x-axis represents Particle size (mm) on a logarithmic scale from 0.01 to 10. The y-axis represents Percentage passing (%) from 0 to 100. The curve shows that approximately 0% of the feed passes through a 0.075 mm sieve, about 1% passes through a 0.15 mm sieve, and about 17% passes through a 0.3 mm sieve. The majority of the feed, approximately 97%, passes through a 0.75 mm sieve, and nearly 100% passes through a 1.5 mm sieve.

Particle size (mm)	Percentage passing (%)
0.075	0
0.15	1
0.3	17
0.75	97
1.5	100

20

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

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1

2

3

4

(a)

5

6

1 - 1' Cross-section

(b)

(c)

(d)

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

1

2

3

Fig. 5 Set-up and instrumentation of shaking table test

4

(a)

(b)

(c)

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

(a)

(b)

(c)

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

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

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

1

2

3

Fig. 10 Relationship between volumetric strain and pore pressure ratio

4

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

	D_r	S_r
■ CUC01	10.3%	100.0%
● CUC02	10.0%	99.2%
▲ CUC03	9.0%	98.1%
◆ CUC04	9.0%	96.3%
● CUC05	8.7%	94.5%
★ CUC06	8.7%	91.0%
▼ CUC07	9.0%	87.5%

2

3

(a)

4

5

(b)

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

8

1

2

3

Fig. 13 Sett-up of gas stability test

4

Fig. 14 Variation of saturation degree with time

Fig. 15 Variation of permeability with time

Fig. 16 Variation of void ratio with time