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Mitigation of liquefaction of saturated sand using biogas

J. HE*, J. CHU*† and V. IVANOV*

Some recent studies have indicated that the liquefaction potential of saturated sand can be greatly reduced if the sand can be made slightly unsaturated. One way to reduce the degree of saturation of sand is to inject gas into sand. This approach offers a cost-effective solution for mitigating liquefaction hazard over a large area. However, it is not easy to inject gas into sand in a uniform manner. A biogas method was developed in this study to overcome this difficulty. In this method, denitrifying bacteria are used to generate tiny, inert nitrogen gas bubbles in sand. Shaking table tests using a fully instrumented laminar box are conducted on both saturated sand and sand containing microbially generated nitrogen gas bubbles. Comparisons of the results of these tests indicate that the pore water pressure generated in the partially saturated sand was much smaller than that in saturated sand. Thus the proposed method is effective in reducing the liquefaction potential of sand.

KEYWORDS: ground improvement; liquefaction; sands

INTRODUCTION

In recent years, attempts have been made to apply microbiology to geotechnical engineering. Most of these studies have been focused on either enhancement of shear strength (DeJong *et al.*, 2006; Whiffin *et al.*, 2007; Ivanov & Chu, 2008; Harkes *et al.*, 2010) or reduction of permeability of soil (Stabnikov *et al.*, 2011; Chu *et al.*, 2012) by induction of calcite crystallisation using microbial hydrolysis of urea. Another potential application of biotechnologies in geotechnical engineering is to mitigate liquefaction hazard of saturated sand deposits by formation of tiny gas bubbles in situ using a microbial denitrification (i.e. nitrate reduction) process.

Some recent studies have shown that inclusion of gas bubbles in soil leads to a reduction in the degree of saturation and an increase in the liquefaction resistance of sand (Copp, 2003; Pietruszczak *et al.*, 2003; Okamura & Soga, 2006; Okamura & Teraoka, 2006; Okamura *et al.*, 2006, 2011; Yegian *et al.*, 2006, 2007; Pande & Pietruszczak, 2008). Several methods have been proposed to introduce gas bubbles into sand. These include

- (a) air injection (Okamura *et al.*, 2011)
- (b) water electrolysis (Yegian *et al.*, 2006)
- (c) sand compaction pile (Okamura *et al.*, 2006)
- (d) use of sodium perborate (Eseller-Bayat, 2009).

Biogas will offer another method for mitigation of liquefaction after it has been established.

An important question regarding the desaturation method is whether or not gas bubbles in sands can remain for a long time. According to Yegian *et al.* (2007), within a duration of 442 days, there was little change in the degree of saturation (from 82.1% to 83.9%) under hydrostatic conditions. Similar tests were also carried out by He (2012) using biogas. The result was similar to that in Yegian *et al.* (2007). Thus, the

tiny gas bubbles generated by bacteria will be stable at least under hydrostatic conditions.

For the biogas method adopted, nitrogen gas was generated through a dissimilatory reduction of nitrate, or in common terms, denitrification. Denitrification is a biological process in which nitrate (NO_3^-) is reduced stepwise to nitrogen gas (N_2). Electron donors are almost all organic compounds. For example, biogas production in reactions of denitrification using methanol, ethanol, or sodium acetate as electron donors is shown by the following equations

Nitrogen (N_2) produced by the denitrification process is the most suitable biogas for sand desaturation because it is chemically inert and its solubility in water is very low –0.017 g/l, (i.e. 0.014 l of gas per litre of water, at 25°C at atmospheric pressure). Another biogas, carbon dioxide (CO_2), has much higher solubility –1.5 g/l (i.e. 0.76 l of gas per litre of water at 25°C at atmospheric pressure). For the objective of using gas to lower the degree of saturation of initially saturated sand and maintain it for as long as possible, the contribution should come mainly from the nitrogen gas, not the carbon dioxide.

There are different approaches to study the effect of sand saturation on its liquefaction potential. Shaking table tests in a rigid box have been carried out by Okamura & Teraoka (2006). A strain-controlled model box with flexible walls was used by Yegian *et al.* (2006, 2007). Laminar box tests have been widely used in both 1g shaking table and centrifuge tests to study liquefaction of sand owing to earthquake (Ling *et al.*, 2003; Kagawa *et al.*, 2004; Elgamal *et al.*, 2005; Ueng *et al.*, 2006; Thevanayagam *et al.*, 2009; Sharp *et al.*, 2010; Ueng, 2010; Zhou *et al.*, 2010; Dobry *et al.*, 2011). In this study, the effects of biogas on sand liquefaction were studied by conducting 1g shaking table tests using a fully instrumented laminar box model.

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MATERIALS AND METHODS

Isolation and cultivation of denitrifying bacteria for biogas production

The denitrifying bacteria used for this study were isolated from anaerobic sludge of municipal wastewater treatment plant. Denitrifying enrichment culture was obtained by non-aseptic anaerobic cultivation on the liquid medium of the following content, in mg/l of tap water: ethanol, 500 mg/l; potassium nitrate (KNO_3), 1010 mg/l, ammonium chloride (NH_4Cl), 12 mg/l; monopotassium phosphate (KH_2PO_4), 75 mg/l; dipotassium phosphate (K_2HPO_4), 250 mg/l; magnesium sulfate heptahydrate ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), 10 mg/l; ferrous sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), 1 mg/l; calcium chloride dihydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$), 1.5 mg/l. Isolation of pure culture was made aseptically from the colony on the same but sterile and solidified medium with addition of Bactoagar Difco, 12 000 mg/l. Pure culture was isolated from cells of the dominant type colony and labelled as strain DN1.

The 16S rRNA gene sequence analysis of this pure culture was carried out as described in detail in Chu *et al.* (2012). The dominant species in the enrichment culture was *Acidovorax sp.*, which is known as a common species of denitrifying bacteria in wastewater treatment facilities.

Cells from the colonies of *Acidovorax sp.* strain DN1 were used to inoculate 0.5 l of sterile liquid medium in a 1 l bottle. The medium was purged with nitrogen gas before sterilisation. Cultivation was at 30°C for 5 days. The concentration of biomass in the suspension after cultivation was measured by filtrating 50 ml bacterial suspension through a filter paper with 0.2 μm pores and drying the filter paper at 60°C for 12 h. The volume of introduced bacterial suspension for denitrification in sand was about 1% of pore volume of sand. The content of bacterial biomass introduced into the sand for denitrification was about 0.02 mg dry biomass/kg of sand. The composition of liquid medium used for the soil treatment was similar to that used for the cultivation of bacteria. The concentrations of the nitrate and the electron donor should be adjusted according to the stoichiometric proportions in equations (1)–(3) to obtain the required volume of gas. The concentrations of other chemicals were one-tenth of those used in the cultivation medium to minimise the ground water contamination.

The test set-up

A picture of the test set-up is shown in Fig. 1. It consists of two parts. The upper part is a laminar box and the lower part is a manual shaking table. A metal frame is also installed to surround the laminar box for safety and installation of measuring devices. The details of the design and the test preparation are given below.

Figure 1. Model test set-up

Laminar box

A laminar box was made of ten layers of aluminium laminates stacked together as shown in Fig. 2. Ball bearings were used at the interface of each layer so that the interface friction was very small. This also allowed each layer to move freely in the lateral direction during shaking. The laminar box had an inner size of 45 cm $\times$ 30 cm $\times$ 29.7 cm (length $\times$ width $\times$ height) when all the laminates were used. An impervious plastic sheet was used to line the inner boundary before the sand sample was placed. The plastic sheet was cut and sewn to a size that was a little bigger than the inner size of the laminar box, so that the laminar box could deform freely.

Shaking table

The design of the manual shaking table follows the concept proposed by Prasad *et al.* (2004) to allow it to provide a horizontal translational seismic loading. A picture of the shaking table is shown in Fig. 1 and a sketch is given in Fig. 3. Two pieces of mild steel plate were installed

Figure 2. Design of the laminar box and instrumentations (acc: accelerometer; pwp: pore water pressure transducer; las: laser displacement transducer)

Figure 3. Design of the manual shaking table

between two wooden boards, fixed by angle bars along the transverse direction. The wooden board dimensions were $1.4 \text{ m} \times 0.5 \text{ m} \times 2 \text{ cm}$ (length $\times$ width $\times$ thickness). The mild steel plates were 0.3 m high (distance between tips of angle bars) and 2 mm thick. Such a shaking table can be treated as a system with one degree of freedom. The frequency of the shaking wave was controlled to around 2 Hz. The acceleration in the test was monitored by an accelerometer adhered to the surface of the shaking table. The real-time monitoring data of acceleration were displayed as a graph on a computer monitor. A typical input acceleration chart is shown in Fig. 4. This test was intended to control the peak acceleration at 1.5 m/s^2 . As can be seen from Fig. 4, the peak values achieved were in the range around $1.5 \pm 0.1 \text{ m/s}^2$, which was sufficiently accurate for the intended purpose.

Sample preparation

ASTM graded sand was used in the test; the basic engineering properties are given in Table 1. The sample was prepared using the following steps.

- The laminar box was assembled. After checking the water-tightness of the liner, 2 l of either liquid medium with addition of 0.02 l of grown bacterial suspension or distilled water (for the fully saturated sample) were poured into the laminar box.
- Dry sand was placed into the liquid through a funnel until the sand level almost reached the water level. During deposition, the funnel moved back and forth to allow the sand to be spread uniformly. The above step was repeated until the sample reached the desired height. The samples prepared in this way gave a relative density of around 20%.
- For tests with biogas, the sample was left for several days to allow sufficient time for the generation of nitrogen gas.

In the shaking table tests, the degree of saturation of sand could not be evaluated by the pore water pressure coefficient B as in triaxial tests. Two other methods were used instead. The first was to measure the concentrations of nitrate before and after the bioreaction and then calculate the gas generation using equations (1)–(3). The second was to measure the water level rise attributable to the gas bubbles generation and replacement in sand. The degrees of saturation measured by these two methods were similar.

Figure 4. Typical input acceleration (test 5c)

Table 1. Typical engineering properties of ASTM graded sand

Description	Grain shape	Mean size: mm	Chemical content	Specific gravity	Maximum void ratio	Minimum void ratio
ASTM graded sand	Round	0.40	99.5 + % SiO_2	2.65	0.8	0.5

Instrumentation

The layout of the transducers is shown in Fig. 2. The following five types of transducers were used

- two accelerometers (acc1 and acc2) to measure the input acceleration of the shaking table and the acceleration of the second top laminate (no. 9), respectively
- three miniature pore water pressure transducers (pwp1 to pwp3) of PDCR81 type to measure the pore water pressures at the bottom, two-thirds depth, and one-third depth of the sample along the centreline, respectively
- four laser displacement transducers (las1 to las4) to measure the lateral movements of the laminar box at three different elevations and the input lateral movement
- two laser displacement transducers (las5 and las6) to monitor the vertical movement of two concrete blocks placed on the sand surface; the blocks will sink when liquefaction occurs
- one linear variable differential transducer (LVDT) to measure the subsidence of the sand surface.

TEST RESULTS

Test conditions

Test conditions and some results are listed in Table 2. Test 8 was fully saturated sand, whereas tests 5, 6 and 7 were biogas-treated sand with degree of saturation of 80%, 90% and 95%, respectively. The volumes of gas produced could be determined by measuring the water level rises in the model box (2.2, 0.9 and 0.5 cm for tests 5, 6 and 7, respectively) owing to the gas bubble replacement in the pore space of sand. The degrees of saturation could then be calculated using the phase relations of sand samples. For each sample prepared, several tests were carried out using different accelerations ranging from 0.05g to 0.2g. The first test was carried out under 0.05g. If liquefaction did not occur and the amount of ground settlement was small (i.e. the change in density of the sand was small), another test using higher acceleration would be carried out. A time interval of 10 min was used between tests for pore water pressure to dissipate fully. If there was no liquefaction and the settlement was small in the second test, a third test at an even higher acceleration would be conducted. This process was repeated until liquefaction or relatively large deformation occurred. For each test, 18 oscillations at the required acceleration were applied for around 10 s, as shown in Fig. 4 as an example. The new relative density was calculated for each test based on the settlement monitored.

The efficiency in the conversion of nitrate to nitrogen gas bubbles that were retained in the sand samples was also measured using a set-up under conditions similar to those used for the model tests. The set-up is shown in Fig. 5. A sand sample was prepared in a syringe by following the same procedure as was used for the sample preparation in the model tests. Bacteria and substrates were supplied to generate gas bubbles. The syringe was linked to a burette. When gas bubbles were generated, the bubbles squeezed some liquid from the syringe into the burette. Because no gas bubbles were observed to come out of the water into the burette, the change in water level in the burette was a good indication of the volume of gas generated. An automatic photography system was used to take pictures of the water

Table 2. Test conditions and test results

	Acceleration: m/s^2			Relative density	Volumetric strain	Settlement of structure: mm		Pore pressure ratio			Cyclic stress ratio		
	Input	Soil surface response	Amplification coefficient			At centre	At edge	Bottom	2/3 depth	1/3 depth	Bottom	2/3 depth	1/3 depth
Test 5 ($S_r = 80\%$)	Test 5a	0.50	0.57	1.13	20%	—	—	0.14	0.14	0.13	0.064	0.081	0.147
	Test 5b	1.00	1.18	1.18	21%	—	—	0.29	0.34	0.23	0.099	0.118	0.186
	Test 5c	1.50	1.80	1.20	27%	—	—	0.25	0.30	0.34	0.230	0.310	0.626
	Test 5d	1.50	1.68	1.12	33%	—	—	0.12	0.13	0.19	0.192	0.245	0.459
	Test 5e	2.00	3.00	1.50	35%	—	—	0.40	0.41	0.59	0.197	0.262	0.462
Test 6 ($S_r = 90\%$)	Test 5f	1.50	1.64	1.09	43%	—	—	0.11	0.15	0.28	0.230	0.303	0.628
	Test 6a	0.50	0.54	1.07	17%	0.39	0.13	0.08	0.11	—	0.049	0.057	0.085
	Test 6b	1.00	1.27	1.27	18%	0.00	2.14	0.42	0.60	—	0.153	0.209	0.413
	Test 6c	1.50	1.80	1.20	33%	0.77	0.86	0.29	0.42	0.36	0.192	0.250	0.475
	Test 6d	1.50	1.67	1.11	40%	0.55	0.94	0.08	0.16	0.17	0.148	0.174	0.280
Test 7 ($S_r = 95\%$)	Test 6e	1.50	1.62	1.08	42%	0.66	0.58	0.03	0.09	0.07	0.229	0.300	0.610
	Test 6f	2.00	2.72	1.36	43%	4.27	4.02	0.36	0.56	0.59	0.256	0.352	0.719
	Test 7a	0.50	0.54	1.08	20%	0.08	0.00	0.10	0.11	0.06	0.077	0.099	0.191
	Test 7b	1.00	1.44	1.44	22%	15.56	6.08	0.55	0.63	—	0.128	0.179	0.354
	Test 7c	1.50	1.80	1.20	51%	2.60	2.22	0.39	0.40	0.47	0.148	0.181	0.313
Test 8 ($S_r = 100\%$)	Test 7d	1.50	1.64	1.09	54%	1.61	0.84	0.14	0.11	0.48	0.231	0.306	0.673
	Test 8e	1.50	1.58	1.05	55%	0.83	0.73	0.10	0.06	0.06	0.193	0.243	0.489
	Test 8f	2.00	3.56	1.78	55%	5.75	6.54	0.54	0.63	0.27	0.198	0.286	0.571
	Test 8a	0.50	0.54	1.07	21%	17.42	15.85	0.55	0.81	0.95	0.064	0.080	0.144
	Test 8b	1.50	2.43	1.62	52%	>20	>20	0.86	1.02	1.03	0.148	0.205	0.396
	Test 8c	1.50	2.76	1.84	73%	22.77	17.19	0.47	0.70	0.85	0.231	0.388	1.123
	Test 8d	1.50	2.06	1.37	89%	2.70	0.38	0.06	0.09	0.12	0.194	0.276	0.746
	Test 8e	2.00	2.86	1.43	91%	0.71	1.38	0.09	0.13	0.17	0.198	0.264	0.590

Figure 5. Set-up for the measurement of gas volume

level in the burette at a given time interval, so that not only the yield of the gas, but also the rate of gas production could be measured.

Three samples were tested. The initial concentrations of nitrate-N used were 125, 250 and 374 mg/l, respectively. The initial concentrations of ethanol used were 446, 893 and 1336 mg/l, respectively. The volumes of gas produced were 8.1%, 17.3% and 23.5% per volume of pore space, respectively. The average efficiency measured was around 80% for a nitrate concentration in the tested range. According to the test results, the relationship between the gas production and the initial nitrate concentration manifests a linear correlation as shown in Fig. 6. This relationship indicates that the amount of gas produced can be controlled by adjusting the initial nitrate concentration. The reasons that some nitrate could not be transformed into gas bubbles might be that

- some gas bubbles close to the sand surface might escape (although this was not observed in the syringe test)
- some gas could dissolve in water, although the solubility of nitrogen gas in water is very low
- the reaction was not fully completed, so some nitrate or intermediates might be retained in the system.

Previous studies have shown that some strains of denitrifying bacteria can denitrify from nitrate to nitrogen completely, provided that some factors, such as pH (Saleh-Lakha *et al.*, 2009), level of nitrate concentration (Glass & Silverstein, 1998), composition of medium (Błaszczuk, 1993), temperature (Stanford *et al.*, 1975) and so on, are suitable. The rate of gas production was around 0.5% of pore volume of sand per hour.

Pore water pressure generation

A comparison of the pore water pressure generations in tests on samples with various degrees of saturation is presented in Fig. 7. The pore water pressures were measured

Figure 6. Relationship between the volume of gas produced and the initial nitrate concentration

by the pore water pressure transducers in kPa, but were converted to water heads for convenience of comparison. The three samples had similar relative densities and experienced the same input acceleration of $a_{\max} = 1.5 \text{ m/s}^2$. A drastic increase in pore water pressure was observed in Fig. 7(a) for test 8b with $S_r = 100\%$. The pore water pressure increased to a peak in less than 3 s and then was maintained at almost the peak value for 5–10 s. The pore water pressure generations for test 7c were substantially smaller than those in test 8b, as shown in Fig. 7(b), even though S_r was reduced to merely 95%. The smallest pore water pressures were observed in test 5f for a sample with $S_r = 80\%$, as shown in Fig. 7(c), even though the relative density of the sample used for this test was a little smaller.

The pore water pressure ratio against relative density of sand curves are plotted in Fig. 8 using pore water pressure data measured at different elevations. The pore water pres-

Figure 7. Pore water pressure: (a) test 8b ($D_r = 52\%$, $S_r = 100\%$); (b) test 7c ($D_r = 51\%$, $S_r = 95\%$); (c) test 5f ($D_r = 43\%$, $S_r = 80\%$)

Figure 8. Plots of pore water pressure ratios against relative densities under $a_{\max} = 1.5 \text{ m/s}^2$ when pore water pressure was measured by pore water pressure transducers at (a) bottom, (b) two-thirds depth and (c) one-third depth

sure ratio is defined as the ratio of maximum excess pore water pressure to initial effective overburden stress. It can be seen that at a relative density of 52%, the saturated sample liquefied with a pore water pressure ratio of 1. When the degree of saturation was lowered to 95% for soil with the same relative density, the pore water pressure ratio reduced to be less than 0.5, as shown in Fig. 8. Similar observations can be made in Fig. 8 for samples with $S_r = 90$ and 80% at lower relative density ranging from 27 to 43%. Thus the use of biogas generated in situ to reduce the degree of saturation of sand is an effective way to increase the liquefaction resistance of sand. Fig. 8 also indicates that for the fully saturated sample to attain the same pore water pressure ratio

as for partially saturated sand, the relative density of the sample has to be around 90%.

Table 2 also shows that the pore water pressure ratio became smaller with increasing depth, although this was not always the case. This trend can be explained from two aspects: the shear strength of soil (termed cyclic resistance ratio, CRR) and the mobilised shear stress (termed cyclic stress ratio, CSR). Because the sample was uniform, the total and effective overburden stress increased with depth. The increase in the effective confining stress gave a higher cyclic resistance ratio (CRR). Another reason could be the magnitudes of cyclic stress ratio (CSR), which can be calculated as (Seed & Idriss, 1971)

$$\text{CSR} = \frac{\tau_{av}}{\sigma'_{vo}} = 0.65 \frac{a_{\max} \sigma'_{vo}}{g \sigma'_{vo}} r_d \quad (4)$$

where r_d is a stress reduction coefficient and in this test a value of 1 was used because the soil model was relatively shallow. It is shown in Table 2 that the cyclic stress ratios calculated by equation (4) were larger at shallower locations for all tests.

Volumetric change

Compared with the fully saturated sand, partially saturated sand manifested a much smaller volumetric change, as shown in Fig. 9. The volumetric strain was calculated using the surface settlement by assuming the soil deformed one-dimensionally. Tokimatsu & 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. Fig. 9 also shows that the higher the relative density, the lower the volumetric strain, given that other conditions are the same. It is also interesting to note that the data shown in Fig. 9 follow the same pattern as seen in Fig. 8. This implies that when the pore water pressure ratio was higher, the volumetric change would be higher too.

Sinking of structures in sand

It is well known that when soil liquefies, a structure which is heavier than the unit weight of the underlying liquefied soil will sink into the soil. Two circular concrete blocks 40 mm high and 73 mm in diameter were used to simulate the structure resting on the sand surface in the model. One

Figure 9. Plots of volumetric strains against relative densities ($a_{\max} = 1.5 \text{ m/s}^2$)

block was placed along the centreline and the other near the edge of the laminar box, as shown in Fig. 2. The base pressure acting on the soil was 4.8 kPa.

A comparison of the amount of sinking of the concrete block into the ground measured in two tests for sand with degrees of saturation of 100% and 90% is shown in Fig. 10. The relative density of the soil in the two tests was similar, 17% for test 6a and 21% for test 8a. It can be seen that the structure sank 18 mm in test 8a for saturated soil when liquefaction occurred, whereas little sinking occurred for test 6a for partially saturated soil. A significant amount of sinking was also observed in test 8c in saturated sand, even when the relative density of the sand was 73%, as shown in Table 2.

Response of the laminar box

During the model tests, the accelerations at the sand surface were amplified to some extent, as measured by the accelerometer installed on the second top (or ninth) layer of the laminar box. The acceleration amplification coefficients, defined as the ratio of acceleration measured at the soil surface to that at the base, are plotted against relative density in Fig. 11. It can be seen that the acceleration amplification coefficients decreased with the increase in void ratio and the decrease in the degree of saturation, which is similar to the trends shown in Figs 8 and 9.

The lateral displacements of the laminar box at different elevations were monitored during tests. As an example, the lateral displacements, measured at the second top (or ninth) layer of the laminar box in a non-liquefied test (test 5c) and

in a liquefied test (test 8c), are shown in Fig. 12. In both cases, the lateral displacements were too small to be discussed. This might be because the laminar box was placed in the horizontal position and thus there was a lack of a triggering factor to cause a large lateral movement.

DISCUSSION

Based on the model tests, a relationship between volumetric strain and pore water pressure ratio is established in Fig. 13. It can be seen that the volumetric strain starts to increase at an accelerating rate when the pore water pressure ratio is higher than 0.4. This observation is consistent with those made in other studies (Lee & Albaisa, 1974; Tokimatsu & Seed, 1987). As a single relationship is formed, the trend line appears to be applicable to soil with different densities and degrees of saturation. Hence, the pore water pressure

Figure 10. Sinking of structures

Figure 11. Acceleration amplification coefficients plotted against relative densities ($a_{max} = 1.5 \text{ m/s}^2$)

Figure 12. Lateral displacement of the ninth laminate in (a) test 5c and (b) test 8c

Figure 13. Plot of volumetric strains against pore water pressure ratios

ratio may be a good parameter to use in the design for deformation control.

Figure 13 also shows that reducing the degree of saturation of saturated sand using biogas is an effective method in the mitigation of liquefaction. Most of the pore water pressure ratios for partially saturated samples were smaller than 0.5.

In this study, the effect of the increase of biomass and mineralisation did not have any apparent effect on the mechanical behaviour of sands. The initial amount of mineral substrates and biomass introduced into sands was around 1 g/l of pore volume. The specific amounts of each chemical and biomass have been introduced previously. So the increment of solid materials (both biomass and mineral precipitation) was supposed to be less than this value, which was also by far smaller than the mass of sands. Hence, the effects of liquefaction resistance improvement should be attributable to the gas bubbles, not to other factors such as biomass or mineral precipitation.

It is worth pointing out that denitrification can also potentially be used as a biocementation technique and this has been explored by van Paassen *et al.* (2010). One major difficulty for biocementation using the denitrification process is that nitrate reduction can be limited at a nitrate concentration higher than around 100 mmol (van Paassen *et al.*, 2010). According to Whiffin *et al.* (2007), at least 60 kg of calcium carbonate per cubic metre of soil is needed to obtain a sufficient cementation effect. This requires around 2400 mmol potassium nitrate (KNO_3) for the reaction to complete when ethanol is used as the electron donor. (It does not make much difference when other types of electron donors are used according to equations (1)–(3).) This amount of calcite cannot be achieved at one time. The amount of nitrate required in the biogas method, on the other hand, is much less than 100 mmol; 26.7 mmol/l of nitrate (or 374 mg/l of nitrate-N) is enough to reduce the degree of saturation to 77% according to Fig. 6. This comparison indicates that, for the purpose of mitigation of liquefaction, the biogas method is more cost effective and the process for nitrogen gas production is also simpler than that for mineral precipitation as required for biocementation. However, biocementation may also serve other purposes, such as increasing the shear strength of soil.

CONCLUSIONS

The feasibility of using microbially generated gas bubbles in sand as a liquefaction remedial method has been explored in this paper. Denitrifying bacteria were used to generate tiny, inert nitrogen gas bubbles in situ to reduce the degree of saturation of sand from 100% to the range of 80–95%. The suspension of bacterial cells and substrates of nutrients have low viscosity and can be easily distributed in sand. The gas generated in this way tends to be more uniform than gas injected into soil.

Shaking table tests with a fully instrumented laminar box were conducted on samples with various degrees of saturation. Test results showed that liquefaction occurred for saturated samples at loose states under $a_{\max} = 0.5 \text{ m/s}^2$ and at medium dense states under $a_{\max} = 1.5 \text{ m/s}^2$. However, liquefaction did not occur for biogas desaturated samples at the same range of relative density under the same input accelerations. The pore water pressure ratios observed in those tests were also lower than 0.5 in most cases, and ground settlements and volumetric strains were small as well. The shaking table test data also show that the pore water pressure ratio is a good parameter to be used to describe the potential of liquefaction. Under the test conditions, a single relationship between volumetric strain and pore water pressure ratio was established for tests with

different degrees of saturation, relative densities and input accelerations. The model tests have demonstrated that the biogas method is effective in lowering the degree of saturation and reducing significantly the liquefaction potential of saturated sand deposit.

NOTATION

$a_{\max}$	maximum acceleration
D_r	relative density
g	gravitational acceleration
r_d	stress reduction coefficient
S_r	degree of saturation
σ_{vo}	total overburden stress
σ'_{vo}	effective overburden stress
τ_{av}	average shear stress

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