Mitigation of liquefaction using biogas desaturation

Atténuation de la liquéfaction par désaturation du biogaz

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ABSTRACT: One method for mitigation of liquefaction is biogas desaturation, that is, to use gas generated biologically to make fully saturated sand slightly unsaturated. In this paper, the effectiveness of this method is evaluated using model tests. The biogas desaturation method generates tiny inert gas bubbles within liquefaction prone zone to increase the soil resistance to liquefaction. Results of models have shown that as the degree of saturation of the soil is controlled to be less than 90%, the generation of pore pressure in sand during cyclic loading is largely contained. Suggestions for the practical implementation of this method are also made. Methods to enhance the stability of the gas bubbles are also discussed.

RÉSUMÉ : Une méthode d'atténuation de la liquéfaction est la désaturation du biogaz, c'est-à-dire l'utilisation du gaz généré biologiquement pour rendre le sable totalement saturé légèrement insaturé. Dans cet article, l'efficacité de cette méthode est évaluée à l'aide de tests modèles. La méthode de désaturation du biogaz génère de minuscules bulles de gaz inerte dans la zone propulsive de liquéfaction pour augmenter la résistance du sol à la liquéfaction. Les résultats des modèles ont montré que lorsque le degré de saturation du sol est contrôlé pour être inférieur à 90%, la génération de la pression interstitielle dans le sable pendant le chargement cyclique est largement contenue. Des suggestions pour la mise en œuvre pratique de cette méthode sont également faites. Des procédés pour améliorer la stabilité des bulles de gaz sont également discutés.

KEYWORDS: Liquefaction, biogas desaturation, biogas stability, bioclogging.

1 INTRODUCTION

Liquefaction of soil has been identified as one the major geohazards that causes disastrous consequences to human lives and property. Conventional measures against soil liquefaction include densification, grouting, lowering of groundwater table, deep mixing and so on. However, most of these methods are expensive to be used for large-scale. It is also difficult to apply some of the liquefaction mitigating methods for soils beneath existing structures.

Many studies (Fourie et al. 2001; Amaratunga and Grozic 2009; He and Chu 2014) have shown that the mechanical behavior of soil is significantly affected by the presence of gas in either dissolved or free form. One potential cost-effective method for mitigation of liquefaction is biogas disaturation method. By inclusion of a small amount of gas bubbles in sand can lead to an increase in shear strength in cyclic triaxial tests (Sherif *et al.* 1977; Yoshimi *et al.* 1989; Xia and Hu 1991). Use of gas for desaturation of sand to enhance the resistance to liquefaction has been attempted studied before (Yang *et al.* 2004; Okamura and Soga 2006).

Unlike existing soil desaturation methods using air sparging, air injection (Okamura *et al.* 2005) or chemically generated oxygen in sand (Yegian *et al.* 2007), a biogas-desaturation method has been developed in this study as a liquefaction mitigation approach. Biogas can be used to reduce liquefaction potential of sand by making it slightly unsaturated using gas. There is no effective way yet to inject gas bubbles uniformly into soil and keep the bubbles in soil for a long time. Biogas is a promising alternative as very tiny gas bubbles can be produced in situ and the distribution of the bacteria (or bubbles) can be more uniform compare to the injection method.

A denitrification process is employed to generate tiny nitrogen gas bubbles in sand to reduce the degree of saturation of the fully saturated sand and thus increase its resistance against liquefaction. Denitrification is a microbially facilitated process of nitrate reduction that produces molecular nitrogen (N_2) through a series of intermediate gaseous nitrogen oxide products. This method works well under hydrostatic conditions. When there is groundwater flow, the tiny gas bubbles in sand may not be stable. To maintain the long term stability of the generated gas bubbles in sand, bioclogging is also induced through a microbial induced calcite precipitation (MICP) process (DeJong *et al.* 2006; Whiffin *et al.* 2007; van Paassen *et al.* 2010; Chu *et al.* 2012). The MICP has been widely studied in laboratories from micro to macro scale. The formation of bioclogging occurs in where urease producing bacteria (UPB) induce calcite precipitation through the hydrolysis of urea in the presence of dissolved calcium salt solution (DeJong *et al.* 2006; Ivanov and Chu, 2008; Harkes *et al.* 2010).

In this project, the use of a low percentage of calcite crystals formed through MICP in sand to form a barrier to reduce the mobility of gas bubbles is studied. Long columns of sand were treated sequentially by both denitrification and bioclogging process. The permeability of biogas desaturated sand under various water flow conditions was monitored in the sand column tests and the results suggest that a small amount of bioclogging will enhance greatly the stability of the gas bubbles under upwards or downwards seepage conditions. A series of shaking table tests were carried out and the results show that the pore pressure generation and settlement in the bio-desaturated sand was largely contained by using the proposed method.

2 MATERIALS AND METHODOLOGY

2 .1 *Sand*

The ASTM C778 graded silica sand was used in this study. It was a poorly graded sand with the following basic physical properties: mean grain size (D_{50}) of 0.36 mm, coefficient of uniformity (C_u) of 1.5, coefficient of curvature of (C_c) of 0.95, and fines content of 0.1%. The maximum (e_{max}) and minimum (e_{min}) void ratios were 0.87 and 0.52, respectively. Sand with a medium loose state (with a relative density between 20 to 30%) was used in the experiments.

2 .2 *Microorganisms*

Denitrification is a microbially facilitated process of nitrate reduction that ultimately produce nitrogen through a series of intermediate steps. The complete denitrification process can be expressed as a redox reaction as Eq. 1.

$$2NO^{\square}_{2} + 10e^{\square} + 12H^{+} \rightarrow N_2 + 6H_2 \qquad (1)$$

Denitrifying bacteria can be isolated from various sources, for example, waste water, soils, sludges and meadows. Most of denitrifiers are heterotrophic bacteria, such as *Paracoccus denitrificans* and *Pseudomonas denitrificans etc.* The source of denitrifying bacteria used in this study was from a mixture of wet soil samples. Batch experiments were performed to obtain the enrichment culture. The nutrient medium used in the batch test was the same as in the previous published work (He *et al*, 2013).

The strain of urease producing bacteria used in this study was obtained from beach sandy soil in Singapore. The probable identity of the bacterial strain was determined most likely to be *Bacillus* sp. The cultivation of bacteria culture followed the same procedures as illustrated in Chu *et al*. (2012). The obtained urease activities were close to those from the pure strain used by other researchers (van Paassen *et al*. 2010; Montoya and DeJong. 2015). Up on completion of cultivation, the bacteria culture was stored in 4°C.

2 .3 *Biogas stability test*

To examine the biogas stability in sand, five long sand columns with different flow conditions were examined. Plexiglas columns with an inner diameter of 7.62 cm and a length of 150 cm were filled with 100 cm height of dry sand (See Fig. 1). The sand was saturated by the denitrification medium solution which contained a 10 percent of denitrifying bacterial suspension. The total amount of nitrate carbon source applied was determined based on the targeted degree of saturation of 85 percent. The final degree of saturation achieved can be estimated through the measurement of water surface level change. On completion of the denitrification process, two sand columns were treated by another around of biocement solution which contained 20 percent of UPB and 0.3M of urea and calcium chloride. The low content of biocement solution could introduce bioclogging between sand grains and reduce the risk of chemical precipitation during the treatment (Phillips *et al.* 2013). Table 1 gives the testing conditions in all sand columns.

Table 1. Biogas stability test conditions

Column No.	*Sand Treatment*	*Flow condition*
T1H[1]	Denitrification process	Hydrostatic
T2U	Denitrification process	Upward flow
T3D	Denitrification process	Downward flow
T4UM	Denitrification process & Bioclogging	Upward flow
T5DM	Denitrification process & Bioclogging	Downward flow

[1]H, hydrostatic flow; U, upward flow; D. downward flow; M, MICP

A flow stream was introduced into sand columns via a peristaltic pump in a considerable low rate (5 ml/min). The variation of degrees of saturation during the whole seepage flow process was monitored and assessed in an assumption that water flow through pore voids and replace the same volume of biogas bubbles trapped inside. Thus the water flow in and out of the tube was recorded and could be seen as an indicator for how much water replaced the biogas bubbles and stayed in sand pore voids. The permeability was measured by adopting constant head method. The hydraulic gradients of the flow stream were kept at 0.1 during the tests for sand columns subject to upward or downward flow conditions. For tests T4UM and T5UM, UPB and biocement solution were percolated through sand columns at a constant 0.1 hydraulic gradient instead of distill water used in other tests.

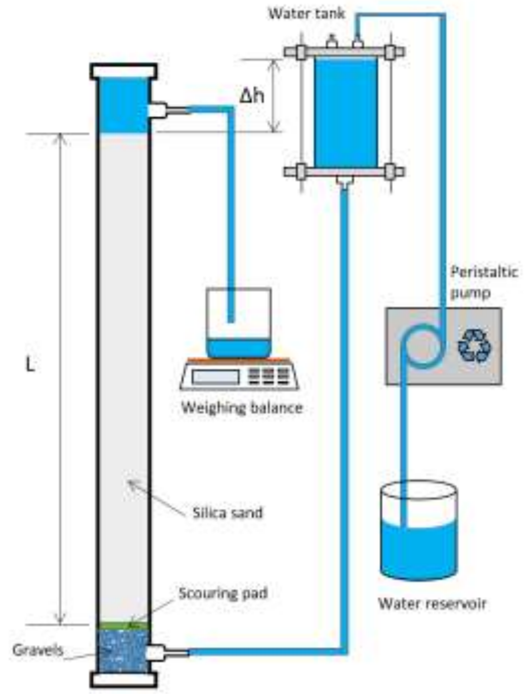

Figure 1. Biogas desaturated sand flow test

2 .4 *Shaking table tests for biogas desaturated sand*

The seismic response of biodesaturated sand were investigated through a series of shaking table test by using an instrumented shaking table system as shown in Fig. 2. The system consists of a manual shaking table and a laminar box with 10 laminate rings. Ball bearings are arranged between adjacent rings to allow free lateral movement with minimal friction and prevent vertical displacement or tilt of the rings during the cyclic motion.

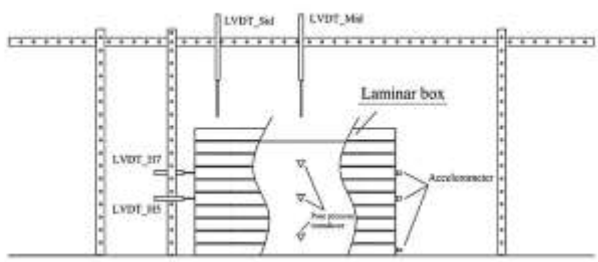

Figure 2. Instrumented shaking table system

Before spraying sand into the laminar box, two liters of inoculated enrichment denitrifying bacterial medium (for desaturated samples) or distilled water (for fully saturated samples) was poured into the laminar box first. Dry sand was rained down slowly into the laminar box through a funnel until the sand level reached the water surface. The samples prepared in this way gave a relative density of 25 to 30%. The denitrification process usually took 3 to 4 days to generate sufficient gas bubbles to reduce the degree of saturation to a desired value.

3 RESULTS

3 .1 *Stability of biogas bubbles in sand*

The stability of biogas bubbles was evaluated through the change of permeability. The generation of biogas bubbles within pore fluids inevitably change the degree of saturation of the sand. The permeability in partially saturated sand is expected to be lower than that in fully saturated sand and it is related to other factors such as degrees of saturation and the water content (Fredlund and Rahardjo, 1993). In the biogas stability test, the permeability of sand was obtained by measuring the water flow out of the sand column in a time interval. A constant water head with a hydraulic gradient of 0.1 was maintained in the permeability test.

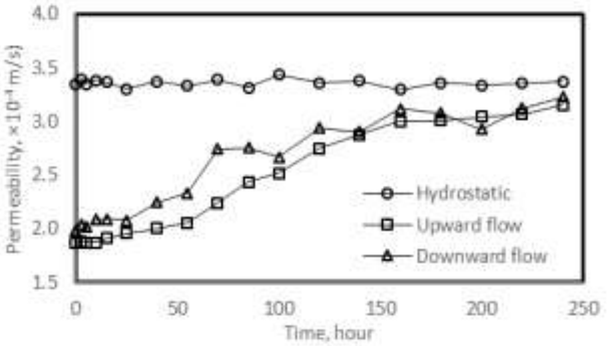

Figure 3. Change of permeability under flow conditions

Fig. 3 compares the testing results obtained among three flow conditions – hydrostatic, upward flow and downward flow. The permeability of sand in the hydrostatic condition was stable indicating that without the seepage flow, the biogas trapped in the sand column was likely to be stable. By contrast, the permeability of sand changed when a flow was introduced. The increase in permeability (from about 2×10^{-4} m/s to 3×10^{-4} m/s) suggests that the biogas bubbles in the sand columns were shifted out with the flow.

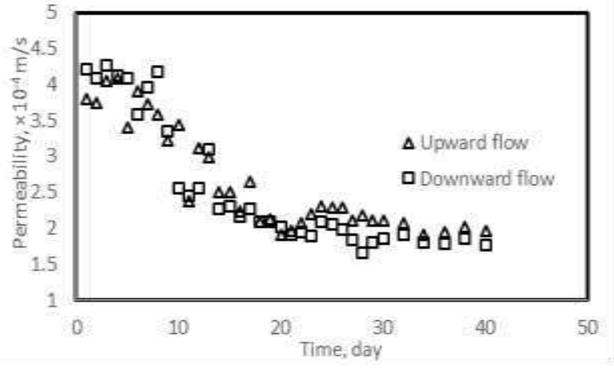

Figure 4. Change of permeability in the bioclogging sand

Bioclogging or biosealing using the MICP process was incorporated into Test T4UM and Test T5DM after the denitrification process to examine the effectiveness of trapping biogas bubbles using the bioclogging effect under a seepage flow condition. The results of the permeability tests are given in Fig. 4. It can be seen that there is a gradual decrease in permeability with time. In contrast to the data shown in Fig. 3, a reduction in permeability implied bioclogging took effect. The seepage flow in sand that had been treated using bioclogging seemed not affect the stability of the gas bubbles too much. The small decrease in the permeability might be attributed to the presence of calcite crystals formed among sand grains which was roughly 0.8 percent w/w of calcite content in this case according to the post-test calcium content measurement.

3 .2 *Seismic response of biogas desaturated sand*

A series of shaking table test were conducted to investigate seismic response of biogas desaturated sand. Fig. 5 shows the development of pore pressure ratio in sand with different degrees of saturation under the same input acceleration of a = 1.5 m/s^2. R_u is defined as the ratio of maximum excess pore pressure generated by the cyclic load to the initial effective overburden stress. The pore pressure increased during the cyclic loading and dissipated afterwards. For fully saturated sand, there was a considerable amount of increase in excess pore pressure as the shaking took place. The pore pressure ratio exceeded 0.9 which indicates that the liquefaction occurred (He *et al.* 2013). The pore pressure generated in biogas desaturated sand were substantially lower than that in fully saturated sand. When the degree of saturation Sr dropped to 90%, the increase in pore pressure becomes insignificant. The maximum R_u ratio in the biogas desaturated sample (Sr = 90%) was only about a tenth of that found in the fully saturated ones.

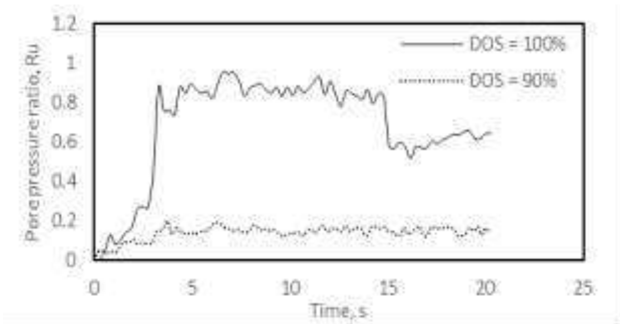

Figure 5. Change of pore water pressure

Fig. 6 shows the response of volumetric strain and relative density to the seismic loading. Compared with the fully saturated sand, biogas desaturated sand developed a much smaller volumetric change during the cyclic loading. The status of the sand deposit turned from medium loose to dense as the cyclic loading increase. For fully saturated sand, even packed in a high relative density condition, the volumetric strain still much bigger than ones developed in slightly desaturated sand. Tokimatsu and Seed (1987) pointed out that pore water pressure generation and volumetric strain also occurred in a non-liquefiable soil; however, the magnitude was often much smaller and the volumetric strains observed in non-liquefiable cases were usually less than 1%. The levels of volumetric strains for partially saturated soil were mostly within 1% strain, indicating that the partially saturated soil had strong resistance to liquefaction and volumetric change. The volumetric strain in saturated sand as observed in the model tests was about 3 to 4%. To achieve a non-liquefaction response, we can either densify the soil to 90% relative density, or desaturate the soil to 95% saturation degree or lower. However, the cost involved in the two methods are considerably different. Biogas desaturation is much cheaper and easier to be applied and also requires much less heavy machineries. Therefore, this is a much more cost effective method than the densification method.

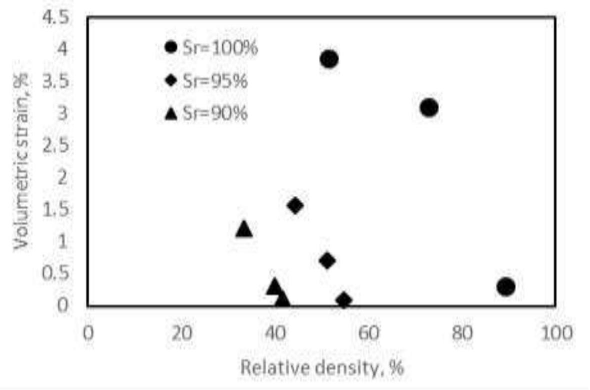

Figure 6. Volumetric strain against relative density

4 CONCLUSIONS

A study to apply biogas desaturation method to mitigate liquefaction hazard in sand is presented. The denitrification process applied in sand is able to produce gas bubbles in pore voids and reduce the degree of saturation. The shaking table test results show that the liquefaction occurs only in fully saturated loose sand under an acceleration of a = 1.5 m/s^2. Liquefaction does not happen when the sand sample is desaturated by the biogas desaturation method to a degree of saturation of 90 percent. The pore pressure ratio in biogas desaturated sand is only tenth of that in fully saturated sand. Accompanied with the reduction of excess pore pressure, the volumetric strain developed in cyclic loading are also largely contained. In the sand column test, a small quantity of calcite precipitation (1% w/w) is found to be effective to help maintain the permeability of biogas desaturated sand under a seepage flow condition. The bioclogging of partially saturated sand has shown its high efficiency of stabilization of biogas bubbles that produced in saturated sand.

This study has shown that a combined biogas desatuation using biogas bubbles generated in situ and bioclogging of the gas bubbles and sand matrix is effective for mitigation of sand liquefaction. Since the bioclogging applied in this research only contained a small quantity of the calcite precipitation, it requires far less UPB and cementation solutions than the solely biocementation method which requires the formation of a large quantity (about 5 to 10 percent) of calcite crystals in sand grains in order to increase the shear strength of sand to resist liquefaction.

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