Microbial soil desaturation for the mitigation of earthquake liquefaction

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ABSTRACT

Soil liquefaction is a common geo-hazard in active earthquake zones. Regular measures against soil liquefaction such as soil densification and soil cementation only have limited scope of applications because of their high costs and complicated implementations. An alternative approach to the mitigation of soil liquefaction is desaturation, that is, to lower the degree of saturation of originally saturated soil. However, the key challenge is to develop a reliable technique to achieve desaturation effect in liquefiable soil ground in a uniform manner. In this paper, an innovative technique, microbial soil desaturation, is introduced and evaluated. Denitrifying bacteria are adopted to produce tiny gas bubbles in-situ from nutrients. The nutrients are dissolved in water and thus can flow like water in sand. The performance of the technique is evaluated using shaking table model tests. It is found that when the degree of saturation of the specimens has decreased from 100% to 90%, the excess pore water pressure generation and the liquefaction potential of sand under seismic loading can be greatly reduced.

Keywords: soil desaturation, soil liquefaction, microbial denitrification

1 INTRODUCTION

Soil desaturation is a method that can be used to mitigate liquefaction hazard for sand deposit (Okamura et al., 2006; Yegian et al., 2007; Okamura et al., 2011; Rebata-Landa & Santamarina, 2012; Eseller-Bayat et al., 2013; He et al., 2013) and control the thermal or hydraulic conductivity of soil (Mitchell, 1981; Catney & Lynch, 2001). For the purpose of liquefaction mitigation, soil desaturation method can potentially be more cost-effective and convenient compared with conventional methods such as densification and cementation. The effectiveness of soil desaturation for liquefaction mitigation has been experimentally demonstrated. In the cyclic triaxial and cyclic torsional shear tests, there was a pronounced improvement in the strength when the degree of saturation of initially saturated soil was reduced by several percents (Okamura & Soga, 2006). In the 1-g shaking table conditions, loose sand with the degree of saturation reduced manifested significant decreases in the pore water pressure generation, soil settlement, and destructive effects on the structures (Yegian et al., 2007; He et al., 2013). In the triaxial undrained monotonic loading conditions, the introduction of gas bubbles into saturated loose sand led to an improvement in the shear strength and the transition from strain softening to strain hardening in the stress-strain behaviour (He & Chu, 2013). These experimental results underpin the idea of using soil desaturation for the mitigation of liquefaction.

In this paper, desaturation methods in previous studies will be reviewed first. Then, a laboratory study on the biogas desaturation method will be presented. A example on the seismic performance of desaturated sand will also be given to demonstrate the effectiveness of this new liquefaction mitigation method.

2 SOIL DESATURATION METHODS

2.1 Air Injection

Direct air injection for soil desaturation has been tested in situ as a method for mitigation of liquefaction (Okamura et al., 2011). By using a specially designed air injector in a saturated sand layer of a reclaimed land, the desaturated zone was formed within 4 m from the injecting point with degree of saturation ranging from 68-98%. However, the flow of air in a saturated porous medium is difficult. As a result, the gas distribution in soil is hardly uniform.

2.2 Water Electrolysis

When an electric current passes though water, hydrogen and oxygen gases can be produced at the cathode and the anode, respectively. This process can be potentially utilized as a method for soil desaturation.
A laboratory trial has been carried out by Yegian et al. (2007). Under a 525 mA current between two electrodes with 29 cm spacing for about 4 hours, the degree of saturation was reduced from 99.5% to 96.2%. However, its suitability for practical applications still needs to be investigated. Furthermore, the stability of oxygen and hydrogen gases in soil can be uncertain as oxygen and hydrogen can react with some substances in soil.

2.3 Chemical Methods

Many chemical processes can produce gas. However, some chemical processes are too radical to be controlled for the purpose of soil desaturation. Eseller-Bayat et al. (2013) used a chemical compound “sodium perborate monohydrate (NaBO₃·H₂O)” for desaturation. With the presence of water, sodium perborate monohydrate can produce hydrogen peroxide (H₂O₂), which in turn can be decomposed to O₂ gas and water. The experimental results showed that the degree of saturation was proportional to the addition of the chemical. As mentioned before, oxygen gas may not be chemically stable in soil.

2.4 Microbial Methods

Another way to achieve soil desaturation is to use biogenic gases. Several types of microbial processes can produce gases, including fermentation, and anaerobic or aerobic respiration. Common biogenic gases are methane (CH₄), hydrogen (H₂), carbon dioxide (CO₂), hydrogen sulphide (H₂S), and nitrogen (N₂) (Rebata-Landa & Santamarina, 2012). CH₄, H₂, and H₂S are combustible gases, and CO₂ and H₂S are highly soluble in water. Thus, these four gases are not suitable for soil desaturation. N₂ gas is a good candidate, because it is non-soluble, and its chemical properties are inert. One of the microbial processes that can produce N₂ gas is named denitrification. The microbial denitrification process has been adopted by Rebata-Landa & Santamarina (2012) and He et al. (2013) to evaluate the effect of soil desaturation for the mitigation of soil liquefaction. This method will be further introduced and evaluated in this paper.

2.5 Other Indirect Methods

Sand compaction pile (SCP) is a soil improvement technique that installs sand piles in soil. It was reported by Okamura et al. (2006) that, accompanying the installation of SCP, large amount of air could be brought into the piles and surrounding soils, causing the overall degree of saturation of the soil to be reduced. This side effect of SCP also benefits the liquefaction resistance of liquefiable soil ground in addition to its major function.

3 BIOGAS DESATURATION

3.1 Microbial Denitrification Process

Microbial denitrification involves a series of reduction reactions from nitrate (NO₃⁻) to nitrogen gas. The overall reaction equation using ethanol as the electron donor is,

\[5C₂H₅OH+12KNO₃ → 10CO₂+6N₂↑ +9H₂O+12KOH \]

Nitrogen (N₂) gas is the effective product that is used for soil desaturation. Another gas, CO₂, will dissolve in water in this case due to its high solubility in water.

N₂ gas has low solubility in water and it can hardly react with other substances. This means that it can stay in soils for longer time than other types of gases. Another advantage of using microbial processes as means for soil desaturation is that the processes can be controlled by adjusting the nutrient availability and other growth factors for the microbes. Rebata-Landa & Santamarina (2012) reported that controlled nutrient injection could be used to regulate the denitrification process for gas production.

There are some limiting factors for the microbial denitrification. High concentration of nitrate could cause an accumulation of nitrite, resulting in an incomplete denitrification, as reported by some studies (van Paassen et al., 2010). The upper limit of nitrate concentration that does not cause nitrite accumulation is about 100 mM/L (van Paassen et al., 2010). 100mM/L of nitrate can produce 1.1 L of N₂ gas out of 1 L of water, which is much higher than the requirement of soil desaturation. Other limiting factors include pH, temperature, and presence of oxygen, etc. Previous studies showed that neutral and moderately base pH environment was the preferential condition for high activity and complete reaction of denitrification (Saleh-Lakha et al., 2009). A range of temperature from 15 to 35°C was an optimal temperature condition for denitrification (Stanford et al., 1975). An anaerobic condition with the absence of O₂ could yield more N₂ gas than the intermediates such as N₂O gas (Saleh-Lakha et al., 2009). For the purpose of soil desaturation, these limiting factors will not hinder the progress of gas generation if proper cautions can be given. In fact, the microbial denitrification is a natural process and is widely present in soil ecosystem. Conditions for it to take place in soil are relatively easy to satisfy.

3.2 Soil desaturation tests

After understanding the principle of biogas desaturation, we need to establish quantitatively how to control the generation of biogas in sand to achieve a required degree of saturation. For this purpose, soil desaturation tests were carried out using a simple setup as shown in Fig. 1. A saturated sand sample after mixing with denitrifying bacteria and nutrients was placed in a syringe. The syringe was linked to a burette. When gas bubbles were generated in the sand sample, some water in sand was replaced and pushed the water level up in the burette. The amount and rate of the gas
generation, as reflected by the change in the water level in the burette, were recorded by a camera.

The species of denitrifying bacteria used was isolated from an anaerobic digester in a wastewater treatment plant. The isolated strain of denitrifying bacteria belonged to Acidovorax species, according to the results of 16s rRNA gene sequencing. Three tests were carried out with initial nitrate (KNO₃-N) concentrations ranging from 125 – 374 mg/L. The molar ratio of ethanol:nitrate was 1.1:1. Other nutrients (NH₄Cl, 12; KH₂PO₄, 75; K₂HPO₄, 250; MgSO₄·7H₂O, 10; FeSO₄·7H₂O, 1; CaCl₂·2H₂O, 1.5, mg/L, prepared with tap water) were also added. Some test conditions and results are shown in Table 1.

The degree of saturation for each sample is determined as the volume of the gas generated over the initial pore volume. It can be seen in Fig. 2 and Table 1 that, the degree of saturation becomes smaller with the increasing amount of nitrate addition. Based on this result, a desired degree of saturation can be obtained by adjusting the addition of nitrate to soils. It can also be seen from Fig. 2 that, there is a lag of around 2 days before gas starts to be generated and the gas generation is completed within 4 days. The rates of gas generation are similar for all the samples irrespective of the nitrate concentrations.

Table 1 indicates that, almost all the nitrate in sand is consumed in Tests 1 and 2. However, there is a small percentage of nitrate and nitrite left in the sample for Test 3. The reason could be the heterogeneous distribution of bacteria and nutrients so that bacteria cannot “meet” all the nutrients. The pH values for all three samples also increase as shown in Table 1. This increase in pH is in agreement with the reaction shown in Eqn. 1, which indicates that hydroxyl is one of the by-products in the reaction.

![Fig. 1. Design of the soil desaturation test.](image)

### Table 1 Test conditions and results of soil desaturation tests

| Void ratio | Degree of saturation | Concentration, N element (mg/L) | pH |
|------------|----------------------|-------------------------------|-----|
|            |                      | Nitrate (Start) | Nitrate (end) | Nitrite (end) | Start | End |
| 1          | 0.678                | 91.9%            | 124.8         | 0.5           | Trace | 7.2 | 7.7 |
| 2          | 0.678                | 82.7%            | 249.5         | 1.0           | 0.2   | 7.2 | 8.2 |
| 3          | 0.678                | 76.5%            | 374.3         | 35.5          | 25.4  | 7.2 | 8.5 |

4 **SEISMIC PERFORMANCE**

An example of the seismic performance of desaturated sand in the shaking table condition is provided here. The design of the test is shown in Fig. 3. Comparisons of two tests, one saturated specimen and one desaturated specimen with $S_v = 90\%$, are provided in Fig. 4. Both specimens are at medium dense state. Under the same test conditions, saturated sand shows a liquefaction behavior, while desaturated sand manifests a non-liquefaction behavior. Both pore water pressure generation and volume change in desaturated sand are by far smaller than those in saturated sand. Here the pore pressure ratio shown in Fig. 4(a) is defined as the pore water pressure generation normalized by initial effective confining pressure. Besides, the structure resting on the saturated sand experiences a great settlement into the soil; while in the desaturated sand the settlement of the structure is rather small. These comparative results demonstrate that desaturation is an effective way to reduce the liquefaction potential of sandy soil. A detailed study on the seismic performance of sands with various degrees of saturation is given in He et al. (2013).
several soil desaturation techniques, including air injection, water electrolysis, chemical methods and microbial methods, a detailed evaluation on a microbial method, the use of microbial denitrification process for liquefaction mitigation, is provided. The microbial denitrification process can produce nitrogen (N₂) gas in sand and lead to the desaturation effect of sand. The more the nitrate is added into the soil, the lower the degree of saturation is obtained. Shaking table model tests demonstrate that, lowering the degree of saturation from 100% to 90% can greatly reduce the liquefaction potential of sand.

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