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Induced partial saturation for liquefaction mitigation by bio-gas bubbles nucleation

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ABSTRACT: In order to increase the liquefaction resistance of a sand, the paper describes the experiments carried out by injecting non-pathogenic bacteria to generate gas bubbles as final product of their own metabolism. The produced gas is chemically inert, slightly soluble in water and of low environmental impact. A few lineages of denitrification bacteria, which are able to generate nitrogen gas bubbles through the reduction of nitrate, have been isolated in a sludge treatment plant. The tested soil is a silty sand retrieved from a site in Northern Italy where liquefaction evidences were observed during the 2012 earthquake. Laboratory tests were carried out at low stress states to quantify the amount of produced nitrogen gas, demonstrating that degree of saturation as low as 90% can be achieved.

1 INTRODUCTION

Granular soils are generally considered of high drainage capability and no pore pressures build up are recorded during static loads. A fully saturated granular deposit, subjected to a dynamic load, can exhibit an undrained behaviour during earthquakes, because of the rapidity of the seismic event. Such conditions can lead to soil liquefaction, causing a partially or completely shear strength and stiffness loss, due to a reduction in the effective stresses as pore pressure tends to increase. As a consequence, liquefaction of saturated soils can cause several damages to structures due to large deformations, leading to different possible mechanisms such as loss of bearing capacity or lateral spreading, as well as triggering of slopes instability (He & Chu 2014).

Mitigation actions such as drainage, densification, desaturation, as well as add of plastic fine content, can be implemented to reduce pore-pressures build-up and therefore to increase the liquefaction resistance of granular soils under dynamic loads. Even though of well known application, most of the existing techniques are quite expensive and unsuitable for pre-existing structures.

Hence, an induced partial saturation by means of non-invasive injection technique is appealing as it leads to an increase in the compressibility of the pore fluid. Pore pressure build up are reduced and an increase in the soil cyclic resistance is achieved, without affecting the structures nearby. Desaturation can be carried out either by lowering the ground water table or by generating gas bubbles within the soil pores (Yoshimi et al. 1989). The former is more invasive, and a high desaturation is achieved, the latter is less invasive and different degree of saturation can be carried out.

Laboratory triaxial tests (Tsukamoto et al. 2014)(Mele et al. 2018) and centrifuge tests (Zeybek & Madabhushi 2017) have shown that the mechanical behavior of granular soils depends strongly by the degree of saturation. Cyclic undrained tests have demonstrated that even a small reduction in the degree of saturation can lead to a considerable increase of the cyclic resistance ratio. Different methods have been tested in previous studies, such as air injection, water electrolysis (Yegian et al. 2007), chemical-sodium perborate (Eseller-bayat et al. 2013).

Among them, gas bubbles nucleation by means of bio-chemical processes represents an alternative method to induce partial saturation. The aim of this technique is to generate gas bubbles directly within the soil pore spaces, allowing for a more homogeneous distribution of the fluid as well as guarantying the discontinuity of the gas phase. Injections of denitrification bacteria have been tested to generate gas bubbles and different reactions involved in the bio-chemical processes have been studied in order to investigate the main factors that rule the phenomena.

2 PARTIALLY SATURATED SOILS

Soil mechanics and its cyclic behavior strongly depends on the degree of saturation. As the degree of saturation decreases, three different configurations of the soil can be achieved. As shown in recent studies (Tsukamoto 2018) these three categories can be subdivided as fully saturated, partially saturated and unsaturated, depending on the configuration of the gas phase.

2.1 *Gas phases distribution*

In fully saturated layers, interparticle pores are completely filled with water, and no gas phase is present. In such conditions, a soil specimen subjected to an isotropic increase in total stress $\Delta\sigma$, in undrained conditions, assuming the fluid as practically uncompressible, shows an increase in the pore pressure, Δu, equal to the total stress increment. This behavior leads the pore pressure coefficient $B=\Delta u/\Delta\sigma$ to be equal to 1.

In unsaturated soils the presence of a matric suction, due to the surface tension of the water, tends to interact with soil grains and to produce additional compressive normal stresses between soil particles, and therefore is likely to increase the shear strength of soil (Tsukamoto 2018) and an approach in net stress, $(\sigma\text{-}u_a)$ and matric suction, s, must be adopted to model the mechanical behavior. Under a total stress increment pore air and pore water pressure show different rates of increments and can be quantified by specializing the pore pressure parameters, always lower than 1, as $B_a=\Delta u_a/\Delta\sigma$ and $B_w=\Delta u_w/\Delta\sigma$.

Since the gas phase is continuous for such degree of saturation lower than 80%, pore water pressure tends to increase faster than the pore air pressure and the matric suction gradually reduces. As consequence, the continuous air phases within soil structures tend to diminish (Tsukamoto et al. 2014). Partially saturated soils separate the two configurations discussed above.

When the air phase is discontinuous, occluded air bubbles are contained within pore spaces among the grains, while the liquid phase is still being continuous. Since air bubbles are contained within the skeleton's void, no interaction between the air phase and grains is involved. Hence, there is not any shear strength mobilization, matric suction becomes negligible and an approach in effective stresses is still being adopted to model the mechanical behaviour: in fact, the presence of occluded gas bubbles only increases the compressibility of the pore fluid without changing the interlocking forces among the grains.

When partially saturated soils experience some increase in the confining stress σ, being the gas phase discontinuous, the difference between pore pressures build up in the liquid and air phases become negligible, leading to the two pore pressure parameters being equal as $B_a \approx B_w$ (Kamata et al. 2009). Therefore a unique value of pore pressure parameter can be considered. In Figure 1 a qualitative and schematic subdivision is shown.

2.2 *Pore pressure increments and equivalent compressibility in partially saturated soils*

In order to distinguish the unsaturated from the partially saturated condition, pore pressure parameter can be suitable. The relationship between the coefficient B and the degree of

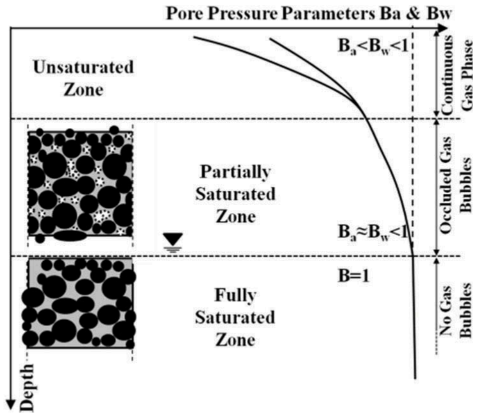

Figure 1. Schematic configurations of gas phases (adapted from Tsukamoto et al. 2014)

saturation has been widely investigated in different studies, and a relation from Kamata et al. (2009) is available as follow:

$$S_r = \frac{C_a - \frac{C_b(1-B)}{nB^2}}{C_a - C_w} = \frac{C_a - \frac{3}{2G_0 n}\frac{1-2\nu_b}{1+\nu_b}\frac{1-B}{B^2}}{C_a - C_w} \quad (1)$$

where C_a,C_w and C_b = compressibility of pore air, pore water and soil skeleton respectively, n = porosity, G_0 = the initial shear modulus and ν_b = skeleton Poisson's ratio.

As shown in Figure 2, the pore pressure parameter B has a sudden decrease as the degree of saturation drops from 100 to 80%. In this range of S_r, soils can be considered partially saturated and occluded air bubbles are contained within the pore spaces. The dependence of B on the initial shear modulus is also shown: the lower is G_0, the higher is the pore pressure parameter value to guarantee the same degree of saturation.

Since the presence of a pore fluid containing gas bubbles affects the resistance of soils to liquefaction, laws controlling gas conditions must be taken into account. Boyle's law (2) and Henry's law (3) must be considered to model the presence of the occluded gas bubbles in the pore water phase:

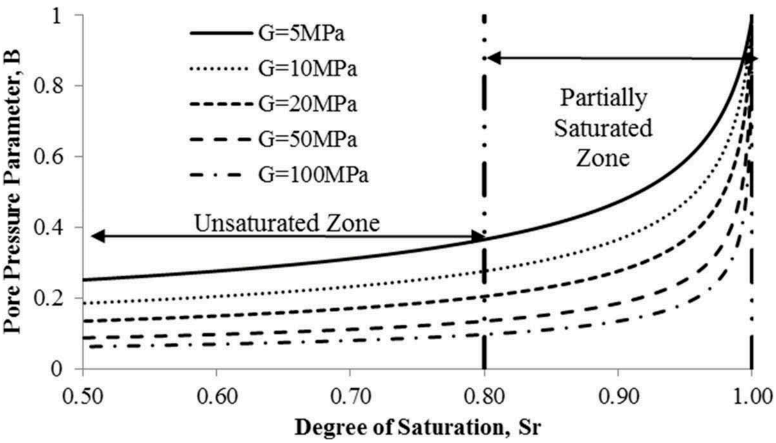

Figure 2. Pore pressure parameter as a function of degree of saturation (Equation 1)

$$P_g V_g = N_{mg} R T_k \tag{2}$$

$$P_{pg} = h_{wg}\left(\frac{N_{msg}}{N_{mw}}\right) \tag{3}$$

where N_{mg}= number of moles of gas, R = universal gas constant, T_k= absolute temperature, h_{wg}= constant of dissolution of gas in water, N_{msg}= number of moles of dissolved gas and N_{mw} = total number of moles of water.

In order to model the undrained behaviour of a partially saturated soil, the compressibility of the equivalent pore fluid gas-water must be taken into account too, considering the compressibility of the free gas and of the water, and the effect of the gas going into solution under increasing pressure. In previous studies (Fredlund & Rahardjo 1993) the following expression for the compressibility of an air-water mixture is derived:

$$C_{aw} = S_r C_w B_w + (1 - S_r + HS_r)_{u_a}^{B_a} \tag{4}$$

where C_w = compressibility of the pore water, Sr= degree of saturation, H = volumetric coefficient of solubility for air in water and u_a= absolute air pressure. The presence of air-water mixture leads to consider an equivalent pore fluid having a higher compressibility than that of the water. Hence, during dynamics loads, the higher compressible mixture leads to lower pressures build up, increasing the cyclic resistance ratio of the soil.

3 BIOCHEMICAL PROCESSES

The bio-chemical process used to induce partial saturation leads to the nucleation of gas bubbles within the soil pores by means of bacteria's activity, which are able to generate gas as final product of their own metabolism.

3.1 *Denitrification process*

Denitrification is a biological anoxic process where nitrates are reduced to nitrogen gas by the following reaction:

$$NO_3^- \underset{nitrate\,reductase}{\longrightarrow} NO_2^- \underset{nitrite\,reductase}{\longrightarrow} NO \underset{nitrite\,oxide\,reductase}{\longrightarrow} N_2O \underset{nitrous\,oxide\,reductase}{\longrightarrow} N_2 \tag{5}$$

This process does not lead to a 100% efficiency of the N_2 generation. In fact, N_2O is produced anyway, and its amount depends on several factor such as: the presence of specific genes encoding the required enzymes in the bacterial species involved in the process (Rebata-Landa & Santamarina 2012), the ratio C/N (Chung & Chung 2000); the soil acidity and aeration (Johns et al. 2004); the soil texture and nutrient status (Johns et al. 2004); and the soil moisture (Davidson et al. 1993).

Although denitrification is the main reaction producing N_2, it is not the only path through which nitrates are reduced.

A parallel path, named ammonification, through which ammonium NH_4^+ is produced, is involved in the bio-chemical process. The ammonia production leads to another type of bio-chemical step able to reduce the NH_4^+ ion into N_2 by means of the anammox reaction (Anoxic-Ammonia-Oxidation) as follow:

$$NH_4^+ \rightarrow NH_2OH \rightarrow N_2H_2 \rightarrow N_2 \tag{6}$$

Accordingly, the amount of nitrogen gas bubbles produced is carried out by the denitrification and concurrently by the anammox: the former is the main process and a higher quantity

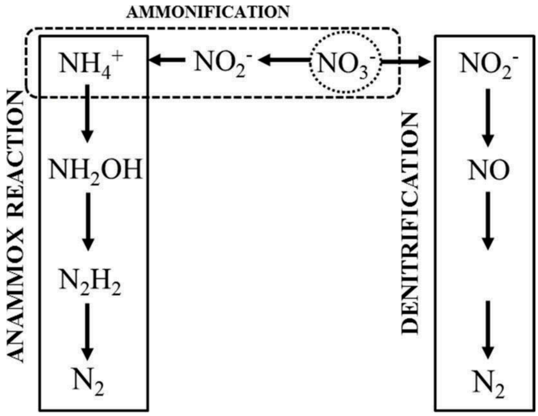

Figure 3. Biochemical paths involved in the nucleation process

of N_2 is produced; the latter leads to a lower production of nitrogen gas and in the same time allowing to the ion ammonium reduction. Figure 3 shows schematically the different biochemical paths involved in the production of nitrogen gas bubbles.

Nitrogen gas is of low solubility in water, chemically inert and of low environmental impact, which makes this technique suitable to lower the degree of saturation as well as relevant for field applications.

3.2 *Bubbles dimensions*

The main benefit of bubbles nucleation directly within the pore spaces is the homogeneous distribution of gas among the grains, which leads to a lower dimension of the bubble itself. Actually, the tiny bubbles that form at bubble nucleation sites are stable only after reaching a critical size (Mer 1952, Ward et al. 1970). The critical radius has been defined in previous studies as follow (Lubetkin 2003):

$$r_{cr} = \frac{2 \cdot T_s}{\sigma \cdot u} \tag{7a}$$

$$\sigma = \frac{c_{gen}}{c_{eq}} - 1 \tag{7b}$$

where T_s = the surface tension, u = the pressure at which bubbles nucleate σ = the supersaturation, in which c_{gen} = the gas concentration in the fluid and c_{eq} = the gas concentration soluble in the liquid under the prevailing experimental conditions (Rebata-Landa & Carlos Santamarina, 2012). Once the bubble nucleates, it is stable only for radius $r>r_{cr}$, vice versa it goes under solution again.

Figure 4 shows the critical radius as a function of the supersaturation for different experimental pressures: for the same value of superstaturation, the higher is the absolute pressure, the lower is the critical radius, hence the minimum size of the single bubble is lower. On the other hand, according to Henry's law, the higher is the absolute pressure, the lower is the amount of gas bubbles within the solution.

4 LABORATORY TESTS

In order to quantify the amount of produced gas, different desaturation tests have been carried out in the lab. A few lineages of denitrification bacteria have been isolated in a sludge

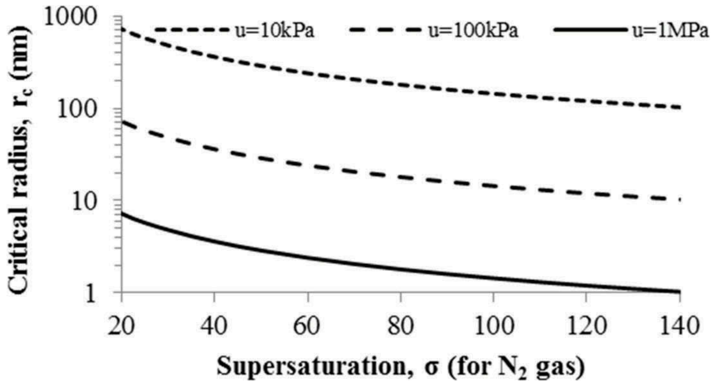

Figure 4. Critical radius

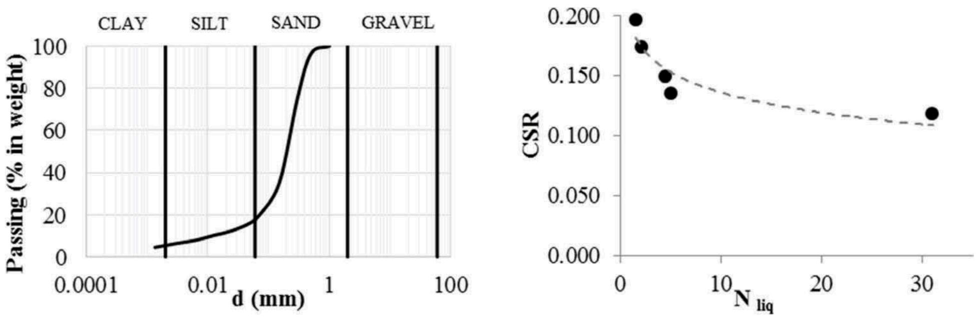

Figure 5. Grain size distribution of the tested soil and cyclic resistance curve for saturated samples

treatment plant. The tested soil is a liquefiable silty sand retrieved from a trial site in North of Italy and its size distribution is showed in Figure 5. Bacteria solution has been mixed with a broth containing nitrates, thanks to which metabolism is activated.

During the tests, calculations of the degree of saturation are made by the assumption that the generated nitrogen gas volume is equal to the expelled pore fluid.

Furthermore, cyclic triaxial tests have been performed in order to obtain a cyclic resistance curve for the fully saturated soil, showed in Figure 5.

4.1 *Testing procedures*

Desaturation tests are carried out using classic permeameters in which the silty sand is pluviated at the same void ratio and in a fully saturated condition. The wet pluviation is made directly in the solution containing both bacteria and nitrates. In each test a different concentration of bacteria and nitrates is tested. Measurements of the expelled pore fluid are made by an upper drainage of the permeameter connected to a graduate burette. In addition, during some of the tests, measurement of NH_4^+ concentration have been developed to verify the biochemical paths previously discussed. Table 1 shows the different test conditions and the relative measurements carried out, while Table 2 shows cyclic triaxial tests performed to assess the cyclic resistance for the fully saturated soil.

4.2 *Tests results*

Figure 6 shows the desaturation tests results. For DTC, DTP1 and DTP2 tests, the same initial nitrate concentration has been used. The amount of produced gas, and therefore the

Table 1. Desaturation tests

	Bacteria concentration, C.F.U.	Nitrate concentration, mg/L	NH_4^+ Measurements	Sr (%)
DTC	1.00E+08	2500	Yes	57.0%
DTP1	1.00E+08	2500	Yes	59.9%
DTP2	1.00E+04	2500	Yes	62.8%
DTP3	1.00E+04	240	No	81.9%
DTP4	1.00E+04	24	No	94.9%

Table 2. Cyclic triaxial tests

CSR	N_{liq}	e
0.135	5	0.696
0.149	4.5	0.700
0.174	2.1	0.708
0.196	1.5	0.711
0.118	31	0.703

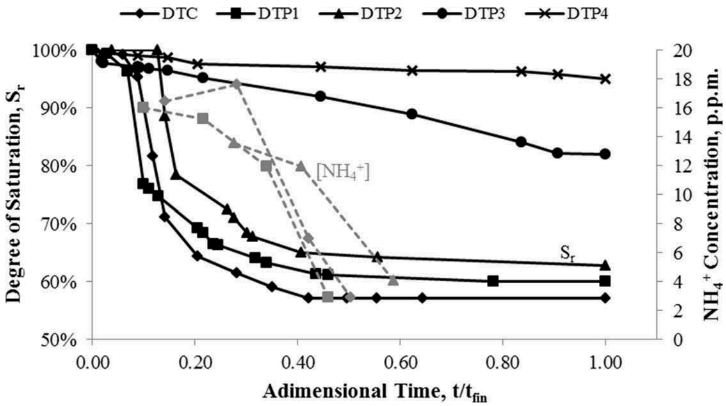

Figure 6. Desaturation tests results

degree of saturation achieved, is practically the same. Only for DTC the curve is slightly lower than the other two. This is probably due to a scale factor that slightly increase bacteria efficiency, being the soil sample volume higher. Even though bacteria concentration is lower for DTP2, test results show that the limiting factor for the bacteria metabolism is the initial nitrate concentration, since the final degree of saturation is the same.

Furthermore, after an initial increment, the NH_4^+ tends to be reduced as low as 2/3 p.p.m. Since in the first step both denitrification and ammonification are involved in the process, the gradient of N_2 nucleation is high as well as the production of NH_4^+. Once nitrates are reduced mostly, expelled pore fluid's gradient tends to decrease and the relative production of N_2 is due mainly to the ammonium reduction performed by the anammox reaction.

Tests DTP3 and DTP4 show the same behavior in terms of biochemical processes. Since the initial concentration of nitrates is much lower than the other tests, the achieved degree of saturation is lower too and the metabolism is slower.

5 CONCLUSIONS

In this paper induced partial saturation by means of bacteria metabolism has been tested. Desaturation tests show the applicability of the technique, demonstrating that even degree of saturation lower than 80% can be achieved. The different paths involved in the biochemical process are verified by means of NH_4^+ measurements, showing that the final values are always lower than 3 p.p.m.. In addition, the different tests performed changing the initial conditions show that the limiting factor for the bacteria metabolism is the initial concentration of nutrients.

Cyclic triaxial tests on desaturated samples have been planned in order to assess the increase in the cyclic resistance due to the biological IPS and they are currently ongoing.

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