MICROBIALY INDUCED PARTIAL SATURATION AS REMEDIAL MEASURE AGAINST LIQUEFACTION: A REVIEW OF FUNDAMENTAL CONCEPTS.

Giovanni Ciardi
Dipartimento di Ingegneria Civile e Ambientale - Università degli Studi di Firenze
giovanni.ciardi@unifi.it

Abstract

This note presents a review on the induced partial saturation as a possible liquefaction countermeasure. After the main aspects concerning remedial measures against liquefaction are briefly introduced, the concept of partial saturation and its effects are discussed in detail. An innovative technique to induce partial saturation in sand by using microbiological activity of denitrifying bacteria is proposed: literature review, potential application and drawbacks of the method are presented.

1. Liquefaction countermeasures: an introduction

Soil liquefaction can today be considered as one of the most impressive effect of an earthquake, causing several damages to structure, infrastructures, and human lives too and during the years, several remedial measures have been proposed to mitigate potential injury risks in built environments due to seismic liquefaction. They may be classified into the following two categories: soil improvement techniques and structure reinforcement methods. Soil improvement and interventions on structures can also be used together; for the purposes of the present research project, however, attention is paid only to the first of the aforementioned classes.

The prevention of liquefaction by means of ground improvement methods can be achieved by the increase of the undrained cyclic strength of soil as well as by the improvement of its stiffness, or by the inhibition of the pore pressure excess build-up. The principles of the most common methods are the followings: soil density increasing (e. g. vibro-flotation, compaction by explosion, heavy tamping); soil grouting (e. g. compaction grouting, deep soil mixing, jet grouting); grain size distribution adjustment (e. g. soil replacement); degree of saturation lowering (e. g. air injection); water table lowering (e. g. trenches); dissipation of excess pore pressure (e. g. drainage systems). In recent years, new techniques have continuously been developed to make these innovative approaches effective, highly reliable, low cost and environmentally-friendly. Huang and Wen (2015) proposed a new classification of the liquefaction mitigation techniques, as shown in Tab. I.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Liquefaction mitigation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil reinforcement</td>
<td>- Soil replacement</td>
</tr>
<tr>
<td></td>
<td>- Soil densification: sand compaction pile, vibration compaction,</td>
</tr>
<tr>
<td></td>
<td>dynamic compaction, blast compaction, compaction grouting</td>
</tr>
<tr>
<td></td>
<td>- Bonding of grains: permeation grouting, splitting grouting, jet</td>
</tr>
<tr>
<td></td>
<td>grouting, deep mixing, pile method, biocementation</td>
</tr>
<tr>
<td>Saturation degree reduction</td>
<td>Lowering of ground water table, air injection, biogas</td>
</tr>
<tr>
<td>Drainage</td>
<td>Gravel pile method, dissipation using screen pipes</td>
</tr>
</tbody>
</table>

Giovanni Ciardi

Reference:

Among these innovative techniques, microbially mediated ones have had a great impulse in
the early past. Bacteria, that are widely present in soils near the ground surface, can be addressed to
catalyze appropriate chemical reactions to obtain a desired type and level of improvement. One of the
potential application of using microorganisms' biological activity for ground improvement is
represented by biocementation (e. g. Whiffin, 2004; van Paassen et al., 2010). In biocementation,
precipitation of inorganic compounds, such as calcium carbonate (CaCO₃), within the soil matrix, is
obtained through opportune chemical processes (e. g. ureolysis, or denitrification), and it is favored by
the presence of dedicated bacteria strain, such as *Sporosarcina pasteurii*. As a result, soil grains are
bonded together, and the soil shear strength generally rises; different cementation levels could be
obtained by adjusting bacterial activity, therefore the amount of precipitated compounds. As stated by
Montoya et al. (2013), however, when thinking of biocementation as a specific technique to mitigate
liquefaction risk, particular care should be paid to the amplification of surface acceleration due to the
reduced dissipative capacity of highly cemented soil with respect to that of untreated one. Kavazanjian
et al. (2015) suggested biocementation by means of denitrification as a two-stage process to prevent
liquefaction: a short term phase (gas production via denitrification, inducing partial saturation)
followed by a permanent effect of cementation.

1.1 Induced Partial Saturation

Since the late '70, researchers have noted that liquefaction resistance increases if a soil
susceptible to liquefaction is not in a condition of full saturation (e. g. Tsukamoto et al., 2002);
however, most of the older studies were focused on understanding the overestimation of liquefaction
resistance from laboratory tests on unsaturated soil samples. Only more recently, the possibility of
applying partial saturation as remedial measure has come out. Two different mechanisms affect the
increase in liquefaction resistance of a partially saturated sand. The first is the compression of pore gas
and therefore the absorption of the induced pore pressure excess, whereas the second is represented by
the matric suction, that is responsible for shear resistance increasing of an unsaturated soil. For clean
sands, under the usual in field conditions at which liquefaction can occur, it is believed that the fist
mechanism is predominant with respect to the second one. The role of matric suction has therefore
often been neglected, by assuming the pore water and gas pressures to be equal. However, if the role
of matric suction is considered to be relevant (e. g. due to the presence of fines), then its effect needs
to be taken into account.

Different techniques have been proposed to induce partial saturation in sand to mitigate
liquefaction hazard: water electrolysis and drainage-recharge (Yegian et al., 2007), air injection
(Okamura and Teraoka., 2006), use of chemicals (Eseller-Bayat et al., 2012a), use of denitrifying
bacteria (Rebata-Landa and Santamarina, 2012; He et al., 2013). It has also been evidenced that
ground improvement by sand compaction pile (SCP) can produce a significant effect of partial
saturation in the treated soil layers during the construction phases; besides, it was found that air
remained entrapped in the sandy soil for very long periods, up to 26 years. Moreover, according to
Yegian et al. (2007), gas bubbles in the soil are stable at least under hydrostatic conditions.

2. Microbially induced partial saturation

The use of microbiological activity to induce partial saturation in soil was first evaluated by
Rebata-Landa and Santamarina (2012); in their study, the Authors evaluated the ability of bacterium
*Paraccocus denitrificans* to produce gas bubbles in saturated soils through denitrification.
Denitrification is a chemical process that can be defined as "the dissimilatory reduction, by essentially
aerobic bacteria, of one or both of the ionic nitrogen oxides (nitrate, NO₃⁻, and nitrite, NO₂⁻) to
gaseous oxides (nitric oxide, NO, and nitrous oxide, N₂O), which may themselves be further reduced
into dinitrogen N₂. The nitrogen oxides act as terminal electron acceptors in the absence of oxygen.

Giovanni Ciardi
The gaseous nitrogen species are major products of these reductive processes” (Knowles, 1982, p. 43). Dinitrogen is chosen because of its low solubility in water and because it is chemically inert. He et al., 2013, He and Chu, 2014, He et al., 2014, and He et al., 2016, were able to successfully induce partial saturation in potentially liquefiable sand by using a cultivation of denitrifying bacteria collected from a wastewater municipal treatment plant, showing a significant increase of liquefaction resistance of partially saturated sand through shaking table tests and a strain hardening behaviour of the bio-treated material under monotonic compression loading, together with a reduction of pore pressure as the degree of saturation was reduced. It was also confirmed that gas bubbles were stable in the sand specimen under hydrostatic conditions, whereas both upward and downward flows (under a hydraulic gradient equal to 0.1) allowed them to flow away, letting the degree of saturation of the soil to increase up to 100% after about 4 days. This result is different from that obtained by Eseller-Bayat et al. (2012a), according to which no significant increase of the degree of saturation was detected under upward flow and horizontal cyclic base excitation for a sand column specimen made unsaturated by the use of the drainage-recharge technique.

In previous studies, the environmental problems connected to the use of nitrate within a soil was not the main concern. However, according to the European and then Italian laws (nitrates directive 91/676/EEC and DL 152 11/05/99, DL 152 03/04/06, DL 30 16/03/09), nitrates are considered to be harmful especially for water; thus, it is not possible e. g. to inject nitrate into the liquefiable soil to let the denitrification process start. Therefore, the potential application of this method in field would seem to be hindered. However, it is also known that groundwater in some potentially liquefiable sites (e. g. Ferrara district, Italy, that experienced liquefaction phenomena during 2012 Emilia Earthquake) is already contaminated by nitrates (Fig. 1): this indicates that microbially induced partial saturation via denitrification gains the potentiality of removing nitrates from groundwater and desaturating a liquefiable layer at the same time.

2.1 Preliminary experimental investigations

At date, our research is at preliminary stage. The bacterial activity of denitrifying microorganisms is currently being investigated to better understand the phenomenon of denitrification within the soil matrix. For this purpose, a set of OxiTop® bottles, containing only bacterial solution or both bacterial solution and sand, has been prepared; this kind of device allows a direct measure of the produced biogas by measuring the pressure differences recorded within the head volume of each bottle by an opportune pressure transducer. Denitrifying microorganisms have been collected from an activated sludge (wastewater treatment plant of S. Colombano, Lastra a Signa, Firenze, IT). More complex and adequate test setups are yet been studying. A typical denitrification reaction, which uses acetate as electron donor, is shown in Eq. (1).

\[
5\text{CH}_3\text{COO}^- + 8\text{NO}_3^- \rightarrow 4\text{N}_2 + 10\text{CO}_2 + \text{H}_2\text{O} + 13\text{OH}^- \quad (1)
\]

Since denitrification is a temperature-dependent process, all the experiments, except the setup phase, are being carried out in an incubator, at 20°C. As a reference, the initial concentrations of substrates (acetate and nitrate in this case) are equal to those proposed by He et al. (2013), and they are indicated in Tab. II; it is worth noting that the indicated concentration of NO\textsubscript{3}-N corresponds to an extremely
high concentration of NO$_3$ (approximately 553 mg/L), if compared to the usual concentrations that is possible to find in groundwater (Fig. 1).

<table>
<thead>
<tr>
<th>Table II - Initial substrates concentrations.</th>
</tr>
</thead>
<tbody>
<tr>
<td>gCOD/gN</td>
</tr>
<tr>
<td>mgNO$_3$-N/L</td>
</tr>
<tr>
<td>mgCOD/L</td>
</tr>
<tr>
<td>mgAc/L</td>
</tr>
<tr>
<td>mgNaAc/L</td>
</tr>
<tr>
<td>gNaAc/gNO$_3$-N</td>
</tr>
</tbody>
</table>

First, a set of 7 bottles was prepared: each bottle contained 98 ml of bacterial solution (made up of 49 ml of tap water and 49 ml of pure activated sludge) and 2 ml of substrates. The first 4 bottles (b1-b4) (Fig. 2a) were prepared by introducing NaOH pills under the top cap to remove the produced carbon dioxide, with the aim of measuring only the produced N$_2$ volume. However, a different trend was evidenced for bottles b3-b4, despite the initial conditions were the same for all; this may be due to a too fast adsorption of CO$_2$, causing a negative trend in the recorded pressures. For this reason, bottles b5-b7 (Fig. 2b) were installed without NaOH pills. It is evident (Fig. 2) that in approximately 1 day the gas production stopped for all the considered experiments. The rate of production (dp/dt) was essentially the same. However, it can be noticed that, even if all bottles were prepared in the same way, some differences were observed in their initial states (e.g. b5-b7); it is thought that this effect can be mainly related to temperature variation before all bottles were put in the incubator. These tests were performed to estimate the denitrification potential of the activated sludge and to understand the reliability of the process to be addressed for geotechnical purposes.

Fig. 2b shows the results obtained from two bottles prepared with the same quantities of reactant fluids with the addition of 366.6 g of siliceous sand. Grain distribution of the material is shown in Fig. 3a. The sand has $e_{\text{max}}$ and $e_{\text{min}}$ equal to 0.793 and 0.520 respectively, and $G_s$ equal to 2.64. The specimens were assembled following two different procedures: in the first one, sand was rained through a funnel into the bottle filled with 98 ml bacterial solution, and then, once sand was put in, 2 ml of nutrients were added; in the second one, bacterial solution and nutrients were put together (100 ml total) and then sand was poured into the bottle in the same way as described before. A thin liquid film was kept above the sand surface of both samples. This test was made to evaluate the differences between the two preparation methods and to gain helpful information about specimen preparation for further

Giovanni Ciardi
analysis. The main difference between the two methods is the availability of nutrients: if in the second method nutrients can be available within the whole soil matrix, in the first one nutrients pathway is subjected to a diffusion throughout the medium: this means that deeper layers could not contribute to gas production. Even if both tests were prepared with NaOH pills below the top cap (because they were run at the same time of the first 4 bottles), it can be noted that a marked difference between the two methods resulted. Furthermore, $\Delta p$ was higher than that recorded in previous tests because of the reduced head volume within each bottle, due to the presence of water and sand together.

![Graph](image1.png)

**Figure 3** - Grain distribution (a) and tests on substrates supply (b).

3. **Conclusion and further developments**

Even if the use of denitrifying bacteria to induce partial saturation in sand can several advantages (e.g. potential low cost, possibility of removing existing nitrate and desaturating the sand layer at the same time, potentiality of inducing a desired level of saturation by addressing bacteria placement and their biological metabolism), some issues remain of practical concern. Further research needs to investigate the denitrification process in the presence of soil by simulating in field conditions, studying e.g. the role that confining pressure plays on bacterial growth, the effects of different relative densities and different grain distributions and grain size on the formation of gas bubbles; durability of bubbles in the soil can represent a concern if a groundwater flow is expected. Currently, a large scale sand specimen is being prepared with the aim of evaluating gas production within the soil matrix by simulating a potential in field application and by varying some boundary conditions to understand how they affect the considered process.
References