MITIGATION OF LIQUEFACTION BENEATH EXISTING FACILITIES USING DENITRIFICATION

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ABSTRACT

Microbially mediated dissimilatory reduction of nitrate, or denitrification, offers the promise for non-disruptive mitigation of the potential for earthquake-induced liquefaction beneath existing facilities. Denitrification can mitigate liquefaction in two ways: by desaturation of the soil through generation of gas and by cementation of the soil through precipitation of calcium carbonate as calcite. Laboratory column tests demonstrate that desaturation via biogenic gas occurs almost immediately upon stimulation of the denitrifying microbes, providing short term mitigation while calcite is being precipitated. Once enough calcite is precipitated, denitrification provides long term mitigation. Laboratory simple shear testing demonstrates that a relatively small decrease in the degree of saturation, as little as 5%, and a relatively small amount of calcite precipitation, as little as 0.4 percent of the dry weight of the soil, can both provide substantial mitigation of liquefaction potential. When there is sufficient normal stress on the ground surface (mitigating the potential for shallow crack development due to gas production), these processes are non-disruptive and thus provide a non-disruptive means of mitigating liquefaction beneath existing facilities.

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Mitigation of Liquefaction Beneath Existing Facilities Using Denitrification

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ABSTRACT

Microbially mediated dissimilatory reduction of nitrate, or denitrification, offers the promise for non-disruptive mitigation of the potential for earthquake-induced liquefaction beneath existing facilities. Denitrification can mitigate liquefaction in two ways: by desaturation of the soil through generation of gas and by cementation of the soil through precipitation of calcium carbonate as calcite. Laboratory column tests demonstrate that desaturation via biogenic gas occurs almost immediately upon stimulation of the denitrifying microbes, providing short term mitigation while calcite is being precipitated. Once enough calcite is precipitated, denitrification provides long term mitigation. Laboratory simple shear testing demonstrates that a relatively small decrease in the degree of saturation, as little as 5%, and a relatively small amount of calcite precipitation, as little as 0.4 percent of the dry weight of the soil, can both provide substantial mitigation of liquefaction potential. When there is sufficient normal stress on the ground surface (mitigating the potential for shallow crack development due to gas production), these processes are non-disruptive and thus provide a non-disruptive means of mitigating liquefaction beneath existing facilities.

Introduction

Microbially mediated dissimilatory reduction of nitrate, or denitrification, offers the promise of non-disruptive mitigation of the potential for earthquake-induced liquefaction beneath existing facilities, a particularly intractable problem in earthquake hazard mitigation. Most available

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techniques for mitigating liquefaction potential are either intrusive, disruptive, or both. The few non-disruptive techniques that can be applied to this problem, e.g. compaction grouting or permeation grouting, are either limited with respect to the type of soil in which they are effective, prohibitively expensive, or both. Denitrification offers the potential for non-intrusive mitigation of liquefaction in two non-disruptive ways: by desaturation of the soil through generation of bio gas and by cementation of the soil through precipitation of calcium carbonate as calcite.

In denitrification, bacteria in the soil reduce nitrate to nitrite and then to nitrogen gas and oxidize organics to carbon dioxide. As nitrogen gas is relatively insoluble, the degree of saturation of the soil decreased relatively quickly as gas is generated, eventually reaching a limiting value that depends upon the size of the soil pores and depth below the ground water table (i.e., the steady state pore pressure). The relatively soluble carbon dioxide goes into solution in the pore water and speciates to bicarbonate which then can precipitate as calcium carbonate when calcium ions are present in the solution. Nitrogen and carbon dioxide gas production occur almost immediately upon stimulation of the denitrifying microbes, desaturating the soil relatively quickly and initiating the carbonate precipitation process. Desaturation provides mitigation as long as the denitrifying microbes are active and for some undetermined period after the microbial activity ceases. Calcium carbonate precipitation due to denitrification is a much slower process and may take months to years to precipitate enough calcium carbonate (as calcite) to provide a desired level of mitigation. However, once enough calcite is precipitated via this process, denitrification provides long term mitigation of liquefaction even after denitrifying microbial activity ceases due to the durability of the precipitated calcite. Furthermore, laboratory simple shear testing demonstrates that a relatively small amount of calcite, as little as 0.4 percent of the dry weight of the soil, provides substantial mitigation of liquefaction, limiting the time required for sufficient precipitation to occur.

Kavazanjian et al. [1] suggested that, based upon the combination of desaturation and carbonate precipitation, denitrification can be considered as a two-stage process for mitigation of earthquake-induced soil liquefaction. Stage 1 of this process was desaturation due to biogenic gas while Stage 2 of the process was calcite precipitation. Kavazanjian et al. [1] termed this two-stage process microbially induced desaturation and precipitation, or MIDP. One potentially disruptive aspect of MIDP is the potential for shallow crack development due to bio gas production. However, when there is sufficient normal stress on the ground surface crack development is suppressed. Thus, if there is sufficient non-liquefiable overburden from non-liquefiable soil or from a building slab, MIDP offers a non-disruptive means of mitigating liquefaction beneath existing facilities.

Desaturation

Studies employing abiotic desaturation have shown that small reductions in the degree of saturation (e.g., less than 10% decrease) can lead to a significant increase in the liquefaction resistance of a soil. In cyclic triaxial tests on samples of Toyoura sand prepared by wet tamping, Okamura and Soga [2] found a roughly two-fold increase in the cyclic resistance upon decreasing the degree of saturation from 100% to 90%. However, a further decrease in the degree of saturation to 70% provided only minimal additional increase in cyclic shear resistance. Yegian et al. [3], using electrolysis, and Eseller-Bayat et al. [4], using sodium perborate mixed into the soil, also demonstrated a significant increase in liquefaction resistance by desaturation. Air injection has
also been suggested as an abiotic means of desaturating soil for liquefaction mitigation. In the tests conducted by Eseller-Bayat et al. [4], sand specimens remained unsaturated for sustained periods (up to 115 weeks) while subject to upward flow and horizontal cyclic excitation at the base.

Rebata-Landa and Santamarina [5], showed the biogenic gas generation via microbial denitrification could potentially serve as a liquefaction mitigation measure by desaturating the liquefiable. A potential benefit of microbially mediated desaturation for liquefaction mitigation compared to abiotic desaturation methods is that in a microbially mediated method the gas may be generated uniformly within the pores of the soil. Another benefit is that most of the gas produced by denitrification is relatively insoluble nitrogen. Fundamental aspects of the soil desaturation via microbial denitrification are discussed by van Paassen et al. [6]. The amount and rate of gas production via denitrification depends on the substrate availability, metabolic stoichiometry and conversion rate, and the ambient conditions (temperature and pressure) [7]. Pham [8] developed a model to predict the degree of desaturation as a function of these factors. Figure 1 illustrates the effect of substrate concentration and steady state pore pressure (i.e., depth below the water table) on the theoretical maximum degree of saturation.

Figure 1. Desaturation induced by denitrification as a function of pore pressure for maximal growth (dashed lines) and zero growth (continuous lines), for three different concentrations of consumed $\text{NO}_3^-$ (after Pham [8]).

The calculated gas saturations in Figure 1 are expected to be higher than the actual gas saturation based on the assumptions made and due to convective and diffusive transport mechanisms. Laboratory testing suggests that a degree of saturation of 70% may be a practical limit beyond which gas venting occurs. Furthermore, while Okamura et al. [9] and Eseller-Bayat et al. [3]
observed that the gas phase can remain stable for several years, Pham et al. [7] and O’Donnell et al. [10, 11] found that the gas volume in the soil pores slowly reduced over time.

Ishihara and Tsukamoto [12] and Okamura and Soga [2] showed that as little as 1 percent desaturation can increase the small strain stiffness cyclic resistance of a soil during undrained loading. Monotonic loading consolidated undrained triaxial compression tests conducted by He and Chu [13] on sand desaturated by denitrification showed a dampened pore pressure response and increase shear strength and strain stiffness. O’Donnell et al. [11] performed undrained cyclic simple shear tests on sand which was saturated and abiotically desaturated. Figure 2 shows the results of the tests reported O’Donnell et al. [11]. In these tests, a reduction in the degree of saturation to 97% increased the cyclic shear resistance of the soil by approximately 40 percent.

![Graph showing the response of saturated and unsaturated Ottawa 20/30 sand under undrained cyclic simple shear loading](image-url)
In centrifuge testing at the University of California at Davis Natural Hazard Engineering Research Infrastructure (NHERI) testing facility on Ottawa F-65 sand prepared to an initial relative density of approximately 40%, soil desaturation to a degree of saturation of 90 – 95% via biogenic gas production did not prevent the soil from liquefying when 15 uniform cycles of loading with an amplitude of 0.35 g was applied to the model. However, when soil desaturation resulting from biogenic gas production approached a degree of saturation of 70% liquefaction was not triggered by 45 cycles of loading with an amplitude of 0.7 g [14].

**Carbonate Precipitation**

Interest is soil improvement via microbially induced carbonate precipitation (MICP) has steadily increased over the past 15 years. MICP has been shown capable of improving soil properties and mitigating liquefaction potential through interparticle cementation, roughening of soil particles, and void ratio reduction [15, 16, 17, 18, 19, 20]. In MICP, microbes alter the geochemistry of pore water to induce the precipitation of carbonate minerals, usually in the form of calcium carbonate (CaCO₃) and most often as calcite. MICP can be induced by a number of different mechanisms, including hydrolysis of urea, sulfate reduction, photosynthesis, and microbial denitrification [16]. Hydrolysis of urea, or ureolysis, is the MICP mechanism that has attracted the most attention due to its ability to quickly precipitate relatively substantial amounts of carbonate minerals and induce interparticle cementation [15]. Cyclic triaxial testing conducted by Burbank et al. [21] showed increase that the cyclic resistance of liquefiable soils increased by anywhere from two to four times when soil was treated with MICP via ureolysis to CaCO₃ contents of 2.2 – 7.4%. Montoya et al. [22] conducted centrifuge model testing that showed that MICP via ureolysis can suppress pore pressure generation and settlement in cyclically loaded soil treated to CaCO₃ contents of 2.6 – 8.0%.

A potential problem with using MICP via ureolysis for soil improvement is that it produces ammonium chloride as a byproduct. Ammonium chloride is recognized as a groundwater contaminant and thus may need to be flushed from the soil after treatment [23]. Another potential problem with ureolysis for soil improvement is that it is an anaerobic process that relies upon dissolved oxygen in the pore water, possibly limiting its use at depth where the supply of dissolved oxygen in the pore water may be limited. In part to avoid dealing with the potential shortcomings of ureolysis, denitrification was proposed by some investigators as an alternative to ureolysis for MICP [16, 22].

Denitrification is a slower process for CaCO₃ precipitation than ureolysis. While treatment of soil to carbonate contents greater than 3%, proposed by some investigators as a threshold value for soil improvement (e.g., Whiffin et al. [15]), make take only days to weeks via ureolysis, it would likely take months to even years to achieve this amount of carbonate precipitation via denitrification. However, denitrification is performed by many common soil microbes and is an anaerobic process (i.e., does not require dissolved oxygen in the pore water) and produces nontoxic byproducts (nitrogen and carbon dioxide gas. Scanning electron microscopy (SEM) images presented by O’Donnell et al. [25] from Ottawa 20/30 sand columns treated via denitrification indicated that the precipitated calcium carbonate was primarily calcite (the preferred form of CaCO₃ due to its thermodynamic stability) and that interaction between the gas phase and the pore water forced precipitation into the contact zone between particles. The SEM image in Figure 3,
from O’Donnell et al. [25], appears to show carbonate precipitation at an inter-particle contact and the circular remnant of a bubble in the pore space. It is hypothesized that the bubble forced precipitation into the contact zone. O’Donnell et al. [25] also hypothesize that the slow rate of precipitation via denitrification tends to produce larger calcite crystals than ureolysis and that these larger crystals lead to a greater degree of soil improvement for a given calcite content than ureolysis.

Figure 3  SEM image of Ottawa 20/30 sand treated by denitrification showing calcite crystals in the inter-particle contact zone and the circular remnant of a gas bubble [25]

O’Donnell et al. [25] showed that a carbonate content as low as 0.4 % can improve the cyclic shear resistance of a soil. Figure 4 presents the results of cyclic simple shear tests on saturated specimens of untreated Ottawa 20/30 sand and on sand treated via denitrification to induce carbonate precipitation. At a carbonate content of 0.4% the cyclic shear strength of the sand has increased by 25% compared to the cyclic strength of untreated sand at the same initial relative density (40%). At a carbonate content of 0.9% the cyclic shear strength of the sand has increased by 25% compared to the cyclic strength of untreated sand at the same initial relative density.

Conclusions

Through the combination of gas generation and CaCO₃ precipitation, denitrification can be considered a two-stage process for mitigation of liquefaction potential. Kavazanjian et al. [1] termed this two-stage process microbially induced desaturation and precipitation, or MIDP. Because this process is non-disruptive when there is sufficient overburden pressure to inhibit cracking, it offers the potential for mitigation of liquefaction beneath existing facilities.
Desaturation due to gas generation provides initial (short term) mitigation. Carbonate precipitation in the form of calcite provides long term mitigation. A foundation slab or an overlying non-liquefiable soil layer can provide the necessary overburden pressure to inhibit cracking. Desaturation due to generation of nitrogen gas begins almost immediately upon stimulation of denitrifying organisms. Laboratory cyclic simple shear testing shows that even small amounts of desaturation (e.g., reduction to 97% saturation) can increase the cyclic resistance of a soil by 25%. Theoretically (based upon stoichiometry), complete desaturation of granular soil at a shallow depth below the water table is possible. However, practical considerations show that a degree of saturation of 70% may be the practical limit. Carbonate precipitation via denitrification occurs at a relatively slower rate than desaturation and at a slower rate than by ureolysis (another microbial carbonate precipitation process). However, laboratory simple shear testing shows carbonate precipitation as small as 0.4% by weight can increase the cyclic shear resistance of a saturated soil by 25% and precipitation of 0.9% carbonate can increase cyclic shear resistance by as much as 50%. Further work is needed to study the combined effect of desaturation and carbonate precipitation and to move the development of MIDP as a liquefaction mitigation technique from the laboratory to the field.

Figure 4 Cyclic simple shear test results on untreated and treated Ottawa 20/30 sand [25]
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