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Application of microorganisms for improvement of liquefiable sand

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ABSTRACT: Liquefaction is an earthquake-induced phenomenon which can cause destructive damages. Liquefaction usually occurs in saturated loose sands because of excess pressure generation of incompressible pore water when subjected to cyclic shear stresses. Conventional strategies for liquefaction mitigation such as various grouting techniques using chemical additives (e.g. portland cement, lime, fly ash, bitumen) and mechanical methods (e.g. blending of soils and compaction) are usually costly, energy consuming and composed of environmentally unfriendly materials. Recently an innovative approach has been presented in which the microorganisms like soil bacteria are used to improve the mechanical properties of soils. This approach has resulted in a new discipline called Microbial Geotechnic which is considered as a very young branch of Geotechnical Engineering. Biocementation and biogas as methods in microbial geotechnic can be respectively used for liquefaction mitigation purpose by enhancing the binding forces and decreasing the excess pore water pressures. Biocementation is production of cementing materials forming as a bridge between particles through in situ microbial activity. Biogas is generation of gas bubbles in the pore water through microbial processes reducing the incompressibility of pore water. Although the real industrial applications of bio-techniques for reduction of liquefiability of sand have not yet been established, there are various laboratory-scale experiments and field tests promising the efficiency of the techniques in practice. This paper aims to present a concise review of the biological techniques and microbial processes which have potential for alteration of liquefiable sands.

1 INTRODUCTION

Saturated loose sands tend to contract when subjected to earthquake induced cyclic shear stresses, resulting in a sudden increase in excess pore water pressures. The development of high pore water pressures that results in reuction of effective stresses and the upward flow of water decrease the binding forces between the particles to zero and triggers liquefaction. Liquefaction is associated with sudden and catastrophic failures and often leads to life casualties and enormous financial consequences. There are two ways to prevent the liquefaction theoretically: enhancing the effective stress (binding force between particles) and/or lowering the pore water pressure.

In practice, grouting via cement, chemicals, compaction, fracture and jet, micro piles, jacked piers, driven piers, ground anchors, shoring, soil nailing, vibrocompaction, concrete columns and piers are conventional techniques used to improve the geotechnical properties of soils (Hayward Baker).The mechanical techniques are not usually energy-saving and cost-effective, and are often not suitable to be applied for large soil volumes or underneath existing structures. There are also many synthetic materials used for injecting into the soils. Cement and chemicals, as the most commonly used materials in soil improvement, can lead to permanent soil and water contamination, or air pollution (by emission of carbon dioxide) during manufacturing or usage. Chemicals are extensively used for grouting in geotechnical engineering (Indraratna and Chu 2005). The cement production is expensive and energy consuming as well. Worldwide, with over 40,000 yearly projects and approximately $6 billion in the industry, new environmentally friendly techniques for soil improvement have become necessary (DeJong et al. 2009). It is therefore a concern for geotechnical engineers to find alternative sustainable, clean and economical solutions.

About one thousand trillion microorganisms existing per cubic meter of soil encouraged the engineers to get these minute creatures to work for them. Hence, an innovative discipline called Microbial Geotechnic, in which the application of microorganisms for ground improvement is investigated, has recently been developed. Microbial Geotechnic can be considered as a multidisciplinary branch of Geotechnical Engineering (at the confluence of Microbiology, Geochemistry and Civil Engineering) aiming to employ microorganisms for improvement of mechanical properties of soil so that it will be more suitable for construction or environmental purposes (Indraratna and Chu, 2005).

Biocementation and biogas are two approaches in microbial geotechnic that can be applied for improvement of liquefaction potential of sandy soil by increasing the binding force (effective stress) and decreasing the excess pore water pressure respectively. Biocementation is generation of particle-binding materials (mineral precipitation) through microbial activity in situ in order that the shear strength of soil can be increased. Biogas is the production of gas bubble within the pore fluid which significantly reduces the pore fluid incompressibility.

Although the real size applications of bio-techniques for liquefaction mitigation have yet to be presented, there are several laboratory-scale experiments and field tests promising the efficiency of the techniques in practice. This review paper is aiming to summarize the existing applications of biothecnology for amendment of liquefiable sands, to investigate the advantages and disadvantages of bio-techniques in comparison with the current conventional methods.

2 BIO-TECHNIQUES FOR LIQUEFACTION MITIGATION

2.1 Biogas

There are many studies which have demonstrated that a small reduction in degree of saturation of fully saturated sand can lead to a considerable increase in liquefaction resistance. Martin et al. (1978) performed a series of cyclic shear tests on fully and partially saturated sand specimens with 40% porosity. They explained that a 1% reduction in the degree of saturation of a saturated specimen can reduce 28% of pore water pressure per cycle. Chaney (1978) and Yoshimi et al. (1989) have expressed that the liquefiability of fully saturated sand decreased by two-fold with 10% reduction in degree of saturation. Xia and Hu (1991) have shown that the liquefaction strength increased more than 30% when the degree of saturation was lowered only to 97.8%. Yang et al. (2003) subjected the specimens under merely horizontal excitation and achieved four-fold decline in the excess pore pressure ratio with 1% reduction in saturation.

Gas generation within the pore fluid that desaturate the soil can be considered as a countermeasure against liquefaction. Eseller (2004) investigated the various techniques inducing partial saturation in soil and evaluated their advantages and disadvantages. Micro bubbles method is a newly developed soil improvement technology entrapping gas/air bubbles of 10-100μm in diameter into pore fluid. Air injection into sand layers (Okamura and Teraoka 2005; Okamura et al. 2006), application of a discharge-recharge cycle of groundwater (Takemura et al. 2009) and electrolysis (Yegian et al. 2007; Eseller 2009) are typical techniques among those reported in the literature. Biogas which is the most innovative technique producing gas bubbles through microbial activity has been recently presented for the liquefaction mitigation purpose (Chu et al. 2009). Using of biogas generation technique for this purpose has not yet been reported as an independent main technique but applied as a side-technique along with biocementation. Actually, such biocementation processes in which gas byproducts can be used for gas bubble generation in pore fluid have been investigated in the other studies (e.g. denitrification process).

2.2 Biocementation

Preventing the movement of particles and providing shear strength between them decrease the liquefaction potential of soils. Evaluation of sites improved by the techniques which increase contact force prior to earthquake, shows no damages owing to liquefaction to either the improved ground or the structures built upon them (Mitchel and Wentz, 1991). Chemical grouting is a technique which is widely used for this purpose in geotechnical engineering (Indraranta and Chu, 2005).

Biocementation is production of microbially induced cementing materials (mineral precipitates) as a bridge between particles in order to enhance the shear strength of soil. As a result of microbial activity, various minerals may be precipitated in situ, including iron sulfides, iron oxides, manganese oxides, silica, and calcium carbonates (Ehrlich, 2002). It should be mentioned that the biocementation is different from biobinding which is formation of particle-binding cellular chains. Since biological bindings are unstable and can be degraded by other microorganisms, they may not be suitable for large scale applications such as increasing the liquefaction resistance (Ivanov and Chu, 2008).

Three patents are found for biocementation process of soil improvement. Kucharski et al. (2005) registered a patent titled “Formation of high strength cement in permeable starting material for structural applications, and for pavements, roads, and runways, comprises combining starting material with urease producing micro-organism, urea and calcium ions”. Paassen et al. (2007 and 2009) registered two separate patents titled “Immobilization of bacteria to a geological material” and “Microbially induced carbonate precipitation as ground improvement technique”.

3 MICROBIAL PROCESSES

Formation of sandstone in the various places of earth's crust and methane gas generation in soils are two examples of cementation and gas production processes in the natural environment. A number of factors, such as pore-fluid chemistry, composition, permeability, etc. influence these natural processes (Hall et al. 2004, Mozley and Davis 2005). In addition, there is increasing evidence that microorganisms have important role in the natural processes (Douglas and Beveridge 1998; Mozley and Davis 2005). They can act as agents altering the geochemistry of pore fluid. Exploring the natural processes of mineral precipitation and/or gas generation in soils is one of the biological aspects of the interdisciplinary field of microbial geotechnic.

Different microbial processes which can lead to biocementation and/or biogas generation to solve geotechnical engineering problems have already been recognized. Ivanov and Chu (2008) reviewed and assessed the processes in detail. Some of them that are considered the most in literature are listed below:

- Ureahydrolysis: precipitation of carbonates of metals in the presence of urea and dissolved metal salts by ammonifying bacteria
- Sulfate reduction: formation of sulfides precipitates of metals in the presence of sulfate salts and carbon source by sulfate-reducing bacteria under anaerobic condition
- Iron/Manganese reduction: production of insoluble carbonate or hydroxide of Fe/Mn in the presence of iron/manganese minerals in soil by iron/manganese-reducing bacteria under anaerobic condition

- Denitrification: nitrogen gas formation by reduction of nitrate and nitrite by denitrifying bacteria under anaerobic condition

Among all biocementation processes, Microbially Induced Calcite Precipitation (MICP) by urea hydrolysis has mostly been studied. In this process, aerobic bacteria producing the enzyme urease (usually *Sporosarcina pasteurri*) along with urea and dissolved calcium source is introduced into the soil. The hydrolysis of urea into ammonium and carbonate ions is catalyzed by microbial urease. The produced carbonate ions precipitate in the presence of calcium ions as calcite crystals, which make cementing bridges between the sand particles. The detailed process depicted by DeJong et al. (2009) in Figure 1. The general equilibrium reaction is:

$$Ca^{2+} + CO_3^{\,2-} \longleftrightarrow CaCO_3 \downarrow \qquad (1)$$

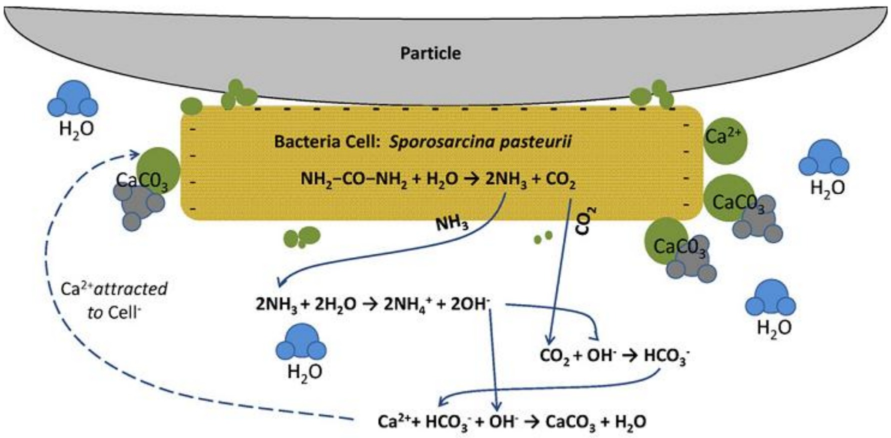

Figure 1. Microbially induced calcite precipitation process (DeJong et al., 2009)

The carbon dioxide gas produced during the reactions has no positive effect on lowering the degree of saturation, because of its high solubility in water. Ammonium chloride ([NH_4^+] [Cl^-]) is toxic side-product of the process that should be washed and extracted.

The pH value induced by microbial activity (OH^- generated from NH^{4+} production) is an important factor in controlling the amount of calcite precipitation. Extra amounts of cementation lead to clogging the pores and reducing the hydraulic conductivity that disturb groundwater flow. On the other hand, a minimum amount of calcite is required to precipitate in order that desirable binds can be formed between sand particles. Controlling the amount of calcite precipitation is therefore one of the important challenges.

Application of this MICP process for liquefaction mitigation has first been proposed by DeJong et al. (2006). After that, some experimental studies have been done to reduce the liquefaction potential of sand by using this technique (Whiffin et al. 2007; Paassen et al. 2009). The largest scale of experiments which has been reported up to now was in one hundred cubic meters tank scale by Paassen et al. (2009).

Although the technical possibility of Microbially induced Calcite Precipitation (MICP) by urea hydrolysis has been successfully approved at large scale, its applicability for real projects in comparison with chemical grouting methods is so far limited by the axenic and aerobic conditions which is required for cultivation of highly urealytic bacteria, its unpredictable and inhomogeneous improvement pattern, cost for substrates, cultivation of particular bacteria and elimination of side products. Therefore, the main focus of studies is overcoming challenges preventing real scale application.

Stimulation of indigenous bacteria instead of augmentation of exogenous bacteria has been applied as an effective way to overcoming the challenges to a rather high extent. By this method suitable nutrients should be added to soil to activate desired bacteria. It increases the predictability of treatment pattern, reduces the cost and makes the using of multiple techniques possible. Another step forward made in order to reduce the restrictions of the technique is pretreatment of industrial wastes for using as substrate for indigenous microorganisms. These two procedures are not only applicable for hydrolysis process but also are general and can be used in other microbial processes (Paassen 2009; Paassen et al. 2009; Burbank et al. 2010; Weaver et al. 2011; Hata et al. 2011).

Denitrification is another microbial process producing nitrogen gas which has been presented for liquefaction mitigation. This respiratory process reduces oxidized form of nitrogen (nitrate and nitrite) in reaction to the oxidation of organic matter as an electron donor. Dinitrogen gas produced in this process is stable and little soluble in water. It is neither greenhouse gas nor combustible in comparison with the other common gases produced in microbial processes (i.e. methane, carbon dioxide and hydrogen). One of the reasons that make this microbial process unaffordable for large scale application problems is the cost of nitrate as electron acceptor (Ivanov and Chu 2008). Using cheap waste materials rich in nitrogen can solve this problem. Some experiments have shown that pretreated organic waste streams (e.g. molasses from sugar factory) for production of calcium salts of fatty acids as well as pretreated waste streams rich in nitrogen (e.g. digestate of pig manure) for nitrate production can together be used for calcium carbonate precipitation and nitrogen gas generation (Paassen 2009; Paassen et al. 2009).

Although the nitrogen gas bubbles formation through the denitrification process can reduce the liquefaction potential of sand, it has two disadvantages: 1- flow and distribution of substrates, which are main factors in homogenous cementation within the sand, and are affected by gas bubbles formation 2- a sudden release of bubbles at shallow depth can lead to sand boiling (Paassen et al. 2010). However, ubiquity of nitrate-reducing bacteria in soil, having no toxic by-products, injection of highly concentrated substrate solution, easily occurring in oxygen-less medium, greater amount of carbonate yield than ureolysis, being cheaper because of full consumption of electron donor, needless to use harmful exogenous organic material and being thermodynamically more favorable than ureolysis, all made this process more desirable than the other common methods (Hamdan et al. 2011).

4 CONCLUSIONS

Although industrial application of biological techniques for soil improvement problem has not already been reported, the results of recent studies promisingly imply that the bio-techniques can be a suitable alternative for conventionally expensive and/or environmentally unfriendly techniques. Of course this interdisciplinary field is very young and there are many investigable unknowns ahead of researchers that should be understood.

There are various microbial processes that have the potential of liquefaction mitigation in loose saturated sand by making cement bridge between sand grains (increasing the binding forces) and/or forming gas bubbles within the pore fluid (lowering the degree of saturation). Among all, biocementation through the ureolysis process and biocementation and biogas generation through the denitrification process are considered more by researchers. Although the large scale experimental studies of treated sand through the denitrification process has not yet been reported, the theoretical studies and small scale laboratory tests show some preferences than ureolysis process.

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