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REVIEW

Recent development in biogeotechnology and its engineering applications

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ABSTRACT Microbial geotechnology or biogeotechnology is a new branch of geotechnical engineering. It involves the use of microbiology for traditional geotechnical applications. Many new innovative soil improvement methods have been developed in recent years based on this approach. A proper understanding of the various approaches and the performances of different methods can help researchers and engineers to develop the most appropriate geotechnical solutions. At present, most of the methods can be categorized into three major types, biocementation, bioclogging, and biogas desaturation. Similarities and differences of different approaches and their potential applications are reviewed. Factors affecting the different processes are also discussed. Examples of up-scaled model tests and pilot trials are presented to show the emerging applications. The challenges and problems of biogeotechnology are also discussed.

KEYWORDS biogeotechnology, biocementation, bioclogging, biogas, strength enhancement, liquefaction mitigation, seepage control

1 Introduction

Microorganisms play an important role in the formation of soils and rocks. The activities of microorganisms can influence the compositions and engineering properties of the soil or rock. Unfortunately, they have been usually underestimated in the geotechnical engineering practices due to the lack of understanding of these activities and their influences. A proper understanding of biological principles would lead to improved soil characterization, enhanced understanding of soil behavior, and even alternative geotechnical engineering solutions [1]. Realizing the potential of integrating microbiological concepts with geotechnical practice is essential for advancing the state of knowledge in geotechnical engineering. A considerable amount of efforts have been made in the past decades on this emerging interdisciplinary research. The National Research Council [2] identified the application of biological processes in geotechnical engineering as one of the priority research areas in the new millennium. The use of microbial activities to improve soil properties provides a potential opportunity for sustainable development in geotechnical engineering [3].

In this paper, an emerging branch of geotechnical engineering—Biogeotechnology [4], is introduced. Biogeotechnology deals with the applications of biological methods to geotechnical engineering problems. Some microbial processes can change the engineering properties of soils and thus be potentially adopted in geotechnical engineering practices. To date, most research projects in this area focus mainly on the applications of biocementation, bioclogging, and biogas generation for the improvement of engineering behavior of soil or rock joints [5–9], seepage control in soil or joined rock [10,11] and soil liquefaction mitigation [12,13], etc. These microbial methods, and their potential applications and influence factors, are reviewed in this study. Examples of up-scaled model tests and pilot trials are also presented to show the efforts of pushing this innovative technique forward. The challenges for the application of biogeotechnology are also discussed in this paper.

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2 Biogeotechnology

2.1 Biocementation

Biocementation is to precipitate inorganic substances to form relatively stable and strong bindings by microbial activity, such as oxidation, reduction, dissolution, and precipitation. This phenomenon is widespread in nature with various microorganisms, such as fungi, actinomycetes, or bacteria. One of the most studied microbial-induced cementation processes in recent years is the Microbially Induced Carbonate Precipitation (MICP), which involves different processes, including urea hydrolysis [14], denitrification [15], sulfate reduction [16], and iron reduction [17,18]. Some alternative bonding substances for performing MICP are also reported, such as the barium hydrogen phosphate by microbial deposition [19]. Among them, the urea hydrolysis process is considered the most effective in MICP treatment. Urea hydrolysis is catalyzed by urease-producing bacteria (UPB) to produce ammonia and carbonic acid, as shown in Eq. (1). The released ammonia consequently increases the pH value, as displayed in Eq. (2). As the pH increases, the carbonic acid converts into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, as reported in Eq. (3). In the presence of free calcium ions (Ca^{2+}), as expressed in Eq. (4), the calcium carbonate ($CaCO_3$) would be precipitated [20–22] based on the nucleation sites served by the bacterial cells [14,23–26].

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{Bacteria}} 2NH_3 + H_2CO_3 \tag{1}$$

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \tag{2}$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+ \tag{3}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{4}$$

Bacillus pasteurii (American Type Culture Collection 6453), has recently been reclassified as Sporosarcina pasteurii (ATCC 11859), an alkalophilic bacterium with a highly active urease enzyme, which is the most used UPB in laboratory studies for the MICP. Some other microorganisms, such as Myxococcus xanthus [27], Thraustochytrium striatum [28], Escherichia coli HB101 [29], Bacillus sphaericus [30], and Sarcina ureae [31], also have been applied for the MICP treatment. The UPB also can be enriched or isolated from the local soil [25,32–43], groundwater [44] or waste-activated sludge [45,46], or in situ stimulated the natural indigenous bacteria [47–56].

Biocementation, utilizing the precipitated calcium carbonate with cementation through the MICP process, could bond the loose soil particles together as a whole and thus alter the engineering properties of soils. The biocementation has a great potential for the geotechnical applications related to strength enhancement, such as ground improvement [5,57–61], soil erosion mitigation [62–69], sediment stability [70], and dust suppression [71–75], etc. Besides, biocementation also can be applied for concrete crack remediation [76–78], historical building restoration [43,79], and ornamental stone protection [80–84], etc. However, it is worth mentioning that the durability of calcium carbonate may be influenced by some environmental factors, such as acid rain and freeze–thaw cycles [85,86].

2.2 Bioclogging

Bioclogging is the clogging of pore space in porous media by the microbial biomass [10], resulting in reducing its hydraulic conductivity. The microbial biomass could be the bacterial cells and their productions, such as the biofilms (composed of approximately 80%–85% extracellular polymeric substance) [11,87–89], and the precipitated calcium carbonate with MICP process shown in Eqs. (1)–(4). Besides, the nutrient that feeds the bacteria also can clog the pores [89]. For soil improvement, one major limitation or concern for the application of bioclogging in situ is the stability of the microbial biomass in soil [4]. It is known that both the bacterial cells, biofilm and the nutrient in the soil can be degraded, leading to the weakening or even failure of bioclogging effect [90]. By contrast, the stability or durability of the calcium carbonate in the soil is much better [90,91].

Bioclogging, based on the calcium carbonate precipitation with MICP process, could block the pores to reduce or avoid the seepage or isolate the material from contact with air. Thus, the bioclogging has a great potential applied in engineering practices related to the seepage control and materials protection, such as preventing the internal erosion of earth dams and levees [63,92,93], construction of aquaculture pond [74,94,95], sealing rock joints [96–100], CO_2 geological sequestration [23], corrosion protection of cement-based materials [101], enhancing the recovery of oil from oil reservoirs or controlling the flow of a spilled contaminant in a reservoir [102–104], etc.

2.3 Biogas

Biogas generally refers to the biogenic gases produced by the breakdown of organic or inorganic matter through microbial processes, such as the anaerobic digestion with anaerobic bacteria or fermentation with biodegradable materials. The most common biogenic gases found in subsurface soils are methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2), and nitrogen (N_2). Among these gases, nitrogen has shown several advantages over other gases, including 1) not a greenhouse gas, 2) neither explosive nor corrosive, 3) very low solubility in water, and 4) an inert gas that does not react with other gases or chemicals in the soil. Thus, nitrogen gas presents a great potential to serve the ground improvement purpose. Denitrification, a microbially facilitated process of nitrate reduction, is the most studied microbial process to produce nitrogen in recent years. As shown in Eqs. (5)–(8), denitrification is a multistep bacterial metabolism involving several enzymes that catalyze the stepwise reduction of nitrate to nitrogen [105,106].

$$\frac{1}{2}NO^-_{3(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \xrightarrow{\text{nitrate reductase}} \frac{1}{2}NO^-_{2(aq)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (5)$$

$$NO^-_{2(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{9}{8}H^+_{(aq)} \xrightarrow{\text{nitrate reductase}} NO_{(aq)} + \frac{3}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (6)$$

$$NO_{(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \xrightarrow{\text{nitric oxide reductase}} \frac{1}{2}N_2O_{(aq)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (7)$$

$$\frac{1}{2}N_2O_{(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \xrightarrow{\text{nitrous oxide reductase}} \frac{1}{2}N_{2(g)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \quad (8)$$

The complex reactions for denitrification can be simplified as follows:

$$NO^-_{3(aq)} + \frac{5}{8}CH_3COO^-_{(aq)} + \frac{3}{2}H^+_{(aq)} \rightarrow \frac{1}{2}N_{2(g)} + \frac{13}{8}H_2O_{(l)} + \frac{9}{8}CO_{2(aq)} + \frac{1}{8}HCO^-_{3(aq)} \quad (9)$$

Biogas, based on nitrogen production via the biological process of denitrification, is an effective way to desaturate the sand via introducing gas into it. Thus, the biogas has a great potential for the liquefaction mitigation of saturated sand [12,107,108]. The denitrifying bacteria can be isolated from various sources, such as wastewater, soils, and meadows. Most of them are heterotrophic bacteria, such as Paracoccus denitrificans and various pseudomonads [109,110]. Many researchers have adopted the enrichment culture method to cultivate denitrifying bacteria and applied them in the sand to generate nitrogen gas bubbles [12,13,15,111]. Similar to many other biological activities, denitrification is a high environment-interactive process. Environmental factors ineluctably affect the occurrence and effectiveness of the process. In general, complete denitrification is promoted by high soil moisture content, neutral to slightly alkali soil pH, high soil temperature, low rates of O_2 diffusion, and the presence of labile carbon source [112]. In dealing with the denitrification process, precautions should be taken as the concentration of nitrate, nitrite, and nutrient (electron donor) must be in a proper ratio [15]. Otherwise, undesired or even hazardous byproducts would accumulate and cause environmental contamination.

3 Strength enhancement of soil

Soils with poor engineering properties are often encountered in infrastructure constructions and must be improved to meet the requirements. Densification, replacement, geosynthetic or/and pile reinforcement, and cement or chemical grouting are the common soil improvement technologies. However, these approaches are usually energy-extensive consumption or not environmentally friendly. An alternative approach is to use the biogeotechnology of biocementation and bioclogging through the MICP process, which can become a low-cost, and environmentally friendly soil improvement technology. Numerous studies have demonstrated that the MICP process can significantly improve the engineering properties of soils, such as the strength [113–122] as shown in Fig. 1, stiffness [115,118,123–132], and thermal conductivity [133,134], etc. Some studies also proposed to further enhance the strength of bio-cemented soil by adding other materials, such as lime [42], fiber [54,125,135–143], hydrogel-assisted [144], the hydrophilic polymer [145,146], and alginate [147]. MICP based soil improvement involves a highly complex biological, physical and chemical process, which is mainly affected by the following four aspect factors: 1) soil properties, 2) urease producing bacteria (UPB) characteristics, 3) cementation solution (CS) parameters, and 4) treatment process. The effect of each is discussed in the following.

3.1 Effect of soil properties

I) Soil Type: To date, MICP treatment has been widely applied for different types of soils, including clay [52,53,148–150], silt [150,151], residual soil [42,129,152–155], coal ash [156,157], expansive soil [158], tabia [159], mixture of sand and clay [63,121,160–162] or silt [163–165], sandy soil [166,167], fine sand [85,168], coarse sand [85,168–173], calcareous sand [56,118,137,174–178], gravel [150,179,180] and

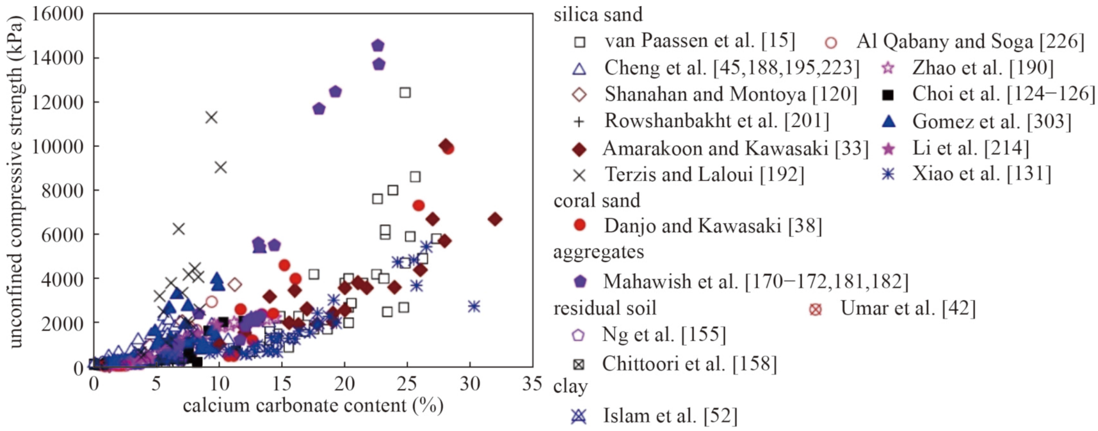

Fig. 1 Unconfined compressive strength of biocemented soil with calcium carbonate content.

aggregate [116,181–183], etc. Cardoso et al. [160] considered that the chemical interactions between the treatment solution and clay mineral must be considered when using MICP treatment for clay soil. On the contrary, Gomez and DeJong [184] claimed that the soil physical properties and calcite content were the two main governing factors on the soil improvement with MICP treatment, rather than the other biogeochemical differences. Soon et al. [154] also reported that MICP treatment was more effective in the strength enhancement of sandy silt than for the pure sand and attributed it to the insufficient interparticle contacts of sand caused by the contained coarser granular particles. However, Kim et al. [151] found that the MICP treatment was more active in the sand than in silt. So far, there is a lack of proper explanation at the fundamental level. More rigorous studies are required to establish the mechanisms behind it.

To date, most of the existing studies were carried out on soils with relatively coarse particles, although limited studies were reported for the use of MICP for fine-grained soils (e.g., clay). The major hindrance of using MICP to fine-grained soils is the geometric compatibility between soils and microbial communities. The soil with small particle sizes generally leads to a small pore-throat size. If the pore-throat sizes are comparable to or smaller than the sizes of bacterial cells, the bacterial cells would be retrained from penetrating the soil. Moreover, Phadnis and Santamarina [185] highlighted the importance of pore size for the viability of bacteria in soil, rather than the porosity. For instance, Rebata-Landa [150] found that the clay was uncemented due to the ignorable calcite content after 32 d of treatment. Kannan et al. [53] also reported that biostimulation is not effective in marine clay. Moreover, Sasaki and Kuwano [161] found that the improvement in liquefaction resistance was ignorable for the sand-clay mixture with MICP treatment and attributed it to the much small void ratio of the mixture causing the clogging of bacteria near the injection areas. However, Cardoso et al. [160] reported that the presence of clay minerals would increase the compressibility and reduce soil permeability, but do not significantly affect the MICP treatment. On the other hand, Ma et al. [186] also indicated that using a small amount of bentonite or kaolinite could help with the biocementation process for coarse sand.

For fine-grained soil with poor permeability (e.g., clay), the traditional MICP treatment with the percolation method is generally unsuitable. As an alternative, the mixing method has been widely adopted to apply MICP treatment with these types of soils [53,129,152,154,155]. Moreover, there are some novel applications of MICP treatment with fine-grained soils. For instance, Ivanov et al. [148] proposed to utilize the bio-encapsulation method to precipitate a calcite shell coated on the aggregates made of marine clay. Liu et al. [149] applied the MICP treatment to remidiate desiccation cracks in clayey soils. Islam et al. [52] proposed to utilize bio-stimulation to conduct the MICP treatment for clayey soil.

On the other hand, the MICP treatment may not be efficient for very coarse sand, gravel, and aggregate [150,173]. Rebata-Landa [150] reported that both the coarse sand and gravel were de-bonded with ignorable calcite content after 32 d of MICP treatment. Mahawish et al. [182] and Wu et al. [183] prepared well-bonded aggregates with a large amount of visible calcite cemented around the aggregates. Moreover, Pan et al. [173] and Wu and Chu [187] proposed to use the bioslurry [188] to improve the efficiency of MICP treatment for the soil with relatively larger particle sizes (e.g., aggregates, coarse sand). By using bioslurry, a unified grouting method has been proposed by Pan et al. [173] to be applied to the soil with a wide range of particle sizes.

II) Particle Size: Studies (e.g., Rebata-Landa [150], Pan et al. [173]) have shown that soils with too large or too small particle sizes are not conducive for the MICP treatment. For fine to medium coarse sand, the particle size may significantly affect the strength enhancement with the MICP treatment. Amarakoon and Kawasaki [33,189], Hoang et al. [168], Zhao et al. [190], Lin et al. [191], and Terzis and Laloui [192,193] reported that the strength enhancement of the bio-cemented soil was higher for relatively coarser soil under the same treatment conditions. Similarly, Jiang et al. [63] reported that bio-cementation of sand-clay mixture using coarse host sand was better than that with fine host sand. Amarakoon and Kawasaki [189] and Zhao et al. [190] attributed the effect of particle size on the bio-cementation to the soil permeability. The permeability would be greater for the soil with a larger particle size, which is beneficial for the treatment solution to be distributed into the soil, thus promoting the MICP process. Conversely, the soil with smaller particle sizes was more prone to clogging, preventing the penetration of treatment solution through the soil. Dhami et al. [194] also reported that the permeability reduction rate of the sand with large particle size was slower than that of small size during MICP treatment. On the other hand, Jiang et al. [63] considered that the inherent porosity would be greater for soil with larger particle size, which would host more carbonate precipitation.

On the contrary, Cheng et al. [85,195], Sharma and Ramkrishnan [121], Pan et al. [173], and Eryürük et al. [196] reported that the bio-cementation was more effective for the soil with small particle size. They considered that the soil with a smaller particle size could provide more interparticle contacts [85,121,173] and specific surface area [121] for the calcium carbonate precipitation and improve the homogeneity for the distribution of calcium carbonate [173].

III) Particle Gradation: In terms of the effect of particle gradation, Kim et al. [151] reported that the amount of the calcium carbonate precipitation in poorly-graded weathered soil was 5 times more than that of well-graded weathered soil and attributed it to the higher void ratio and greater void size in poorly-graded soil. On the contrary, Cardoso et al. [197] found that the soil with relatively good particle gradation has a large amount of calcium carbonate with the same treatment, but its unconfined compressive (UC) strength is relatively lower. On the other hand, Deng and Wang [175] reported that the UC strength of well-degraded soil is higher than that of poor-degraded soil with the same treatment. Cheng et al. [85] also found that the UC strength of well-graded sand was greater than that of uniform coarse sand while smaller than that of uniform fine sand and considered it might be related to the number of contact points. Moreover, Mahawish et al. [181], Gomez and DeJong [184], and Zamani et al. [198] reported that mixing a certain amount of fine-grain with a coarse grain soil could significantly improve the strength enhancement efficiency of MICP treatment. Mahawish et al. [181] attributed it to providing more contacts for calcium carbonate precipitation. Sasaki and Kuwano [161] considered that the presence of fine content might affect the morphology of the precipitated calcium carbonate.

IV) Soil Density or Relative Density (RD): Zamani and Montoya [165], Xiao et al. [176], Tsukamoto and Oda [199], Cheng et al. [200], Rowshanbakht et al. [201] and Lakshmi et al. [202] reported that a greater initial density or relative density (RD) generally leads to a higher strength of the bio-cemented soil with the same treatment or calcium carbonate content. Cheng et al. [200] and Rowshanbakht et al. [201] attributed it to the smaller spacing among particles with a greater initial density or RD, which is beneficial to form interparticle cementation. Soon et al. [154] also reported that the UC strength of the bio-cemented residual soil presented an increasing trend with its initial density but shown a reverse trend for the sand. They considered that both the denser residual soil and sand could provide more interparticle contacts, which is beneficial to improve the effectiveness of MICP treatment. However, the increase in density of sand would restrain the movements of bacteria and reagent solutions within the soil, and thus the MICP process would be retarded. Zamani and Montoya [165] found that more calcium carbonate would be obtained in soil with greater RD.

On the other hand, the studies of Kim et al. [151] and Mahawish et al. [170] implied that there is an optimum initial density or RD for the soil improvement with MICP treatment. Kim et al. [151] considered that the soil particles are not reasonably combined under either somewhat loose or dense conditions, resulting in less amount of calcium carbonate would be precipitated. However, Tsukamot and Oda [199] stated that the lower RD is beneficial to absorb more microbes and CS and thus precipitate more calcium carbonate. On the other hand, Mahawish et al. [170] claimed that more interparticle contacts with a greater RD are conducive to strength enhancement. Meanwhile, the size of the soil pore throat would be smaller with a greater RD, which in turn would result in the bacteria cannot infiltrate deeper into the soil, and as a result, a lower UC strength sample with heterogeneous distribution of $CaCO_3$ would be obtained.

V) Other Factors: Xiao et al. [131] and Song et al. [203] performed investigations on the effect of particle shape on bio-cementation. Song et al. [203] found that a greater amount and more homogeneous calcium carbonate would be precipitated with the spherical soil particles than angular particles. This is because the bacteria adhere more readily and forcefully to the smooth surface of spherical particles. On the other hand, Xiao et al. [131] reported that the UC strength of bio-cemented soil with angular particles is greater than that of rounded particles and considered this is due to the effective cementation area between angular particles is larger than that of rounded particles.

Cheng et al. [200] investigated the effect of initial pH of the soil on the soil improvement with MICP treatment and found that the soils under acidity and alkalinity conditions could precipitate more calcium carbonate than that of neutral soil, but their UC strength was lower than that of neutral soil. They considered this might be caused by the effect of pH value on the transport and adhesion of bacteria and the formation of calcium carbonate crystals.

3.2 Effect of UPB

I) Concentration (OD_{600}) of Bacteria: Amarakoon and Kawasaki [33], Liu et al. [66], Soon et al. [155], Zhao et al. [190], Eryürük et al. [196], Gat et al. [204], and Hataf and Baharifard [205] reported that the amount of the precipitated calcium carbonate and the bio-cemented soil strength tend to increase with the bacteria concentration (OD_{600}). Both Amarakoon and Kawasaki [33] and Zhao et al. [190] considered this because more bacteria could promote more enzymes and provide more nucleation sites for MICP. Wen et al. [206] reported that the increase in bacteria concentration could improve the precipitation rate of calcium carbonate, but the effect on the morphology of calcium carbonate was insignificant. Al-Thawadi and Cord-Ruwisch [32] reported that the size of the calcium carbonate crystal increased with the bacteria concentration. Wang et al. [207] found that a low bacterial density facilitated producing fewer crystals with larger average crystals volume. Zhao et al. [143,208] proposed to use the activated carbon and activated carbon-fiber felt to improve the bacterial retention ability and thus the yield of calcium carbonate. Moreover, Rowshanbakht et al. [201] reported that reducing the injected volume of bacteria solution to up to one-third of the pore volume did not significantly affect the performance improvement of the MICP treatment. On the other hand, percolating more bacterial cells into the soil may lead to clogging at the soil surface, resulting in the inhomogeneous distribution of the precipitated calcium carbonate [209].

II) Urease Activity (UA) of Bacteria: Zhao et al. [210] considered that using the bacteria solution with a higher UA could yield more calcium carbonate and, in turn, a greater UC strength for the bio-cemented soil. Achal et al. [211] proposed to cultivate new bacteria via UV irradiation to improve the urease activity of bacteria. However, Cheng et al. [85] reported that a lower UA of the bacteria generally led to a greater UC strength of the bio-cemented sand under the same calcium carbonate content and considered that a slower precipitation rate of calcium carbonate caused by a lower UA is more effective to bond sand grains.

3.3 Cementation solution parameters

Cementation solution (CS) is usually a mixture of calcium and urea. Some other substances may also be added to the CS in some studies, such as nutrient broth, NH_4Cl and $NaHCO_3$ [14,38,123,146,152,155,157,199,206,212–217], yeast extract [31,184], Tris base [31], sodium malate [38], sodium acetate [48,184], and polyvinyl alcohol [146]. Chen et al. [218] also proposed to use urine as the urea source for MICP treatment.

I) Calcium Source: $CaCl_2$ is the most commonly used calcium source for MICP treatment. Some researchers demonstrated that the efficiency in calcium carbonate precipitation [219,220] and strength enhancement [76] using $CaCl_2$ as the calcium source were higher than others, such as $Ca(NO_3)_2$, $Ca(CH_3COO)_2$, and $Ca(Ac)_2$. Abo-El-Enein et al. [76] attributed it to that more rhombohedral calcite could be precipitated using $CaCl_2$ as a calcium source, which is more conducive for the bonding among interparticle. However, Zhang et al. [221,222] reported that the UC strength of the bio-cemented sample using $CaCl_2$ was lower than that of $Ca(CH_3COO)_2$, while higher than that of $Ca(NO_3)_2$ under the same dry density.

Moreover, Cheng et al. [200,223] proposed to use seawater as the calcium source to prepare the CS by adding the urea into the seawater for MICP treatment. Some researchers [124,126,224] also proposed to dissolve the eggshell, limestone powder, oyster shell, and scallop shell, et al., by acid to provide the calcium source for MICP treatment. The MICP treatment is particularly suitable for calcareous sand, which contains a high percentage of calcium carbonate [225].

II) Concentration of Cementation Solution (CCS): To date, numerous studies have been conducted to investigate the effect of CCS on the biocementation of MICP. Cheng et al. [223], Al Qabany and Soga [226], Lai et al. [227], and Mujah et al. [228] reported that a lower CCS generally results in a greater strength enhancement of the biocemented sand under the similar calcite content. Both Al Qabany and Soga [226] and Mujah et al. [228] believed it was caused by the difference in the sizes of the precipitated calcite crystals. Al Qabany and Soga [226] found that the calcite crystals precipitated using high CCS had large size and inhomogeneity distributed spatially, which would cause the samples to deform locally during loading, resulting in smaller strength enhancement of the biocemented sample as a whole. Namely, the low strength enhancement of the biocemented sample using high CCS is due to the inhomogeneous cementation caused by the large size of the precipitated calcite crystals. Velpuri et al. [229] also considered that a higher CCS would lead to a more severe clogging at the injection point, and thus a more non-uniformly cemented specimen. Mori et al. [230] stated that low CCS could result in a more homogeneous pattern of calcite precipitation due to more nucleation sites than that of high CCS. Al-Thawadi and Cord-Ruwisch [32] also reported that the size of the crystal increased with the CCS. On the contrary, Mujah et al. [228] concluded that the sizes of the calcite crystals precipitated using low CCS were comparatively larger than that of high CCS and considered that larger crystals were more effective in enhancing the UC strength of soil. However, Lai et al. [227] considered that the effect of CCS on the biocementation of MICP might be mainly caused by the difference in bonding strength of precipitated calcium carbonate rather than other factors, such as calcium carbonate distribution.

On the other hand, Amarakoon and Kawasaki [33], Danjo and Kawasaki [38], Jiang and Soga [92], Wang and Tao [146], Lee et al. [152], Soon et al. [155], Deng and Wang [175], Zhao et al. [190], and Wen et al. [231] reported that the strength of the sample using high CCS was greater than that of low CCS under the same treatment conditions (e.g., number of treatments, total treatment duration), as more calcium carbonate would precipitate when using higher CCS. Meanwhile, Zhao et al. [190] stated that the increase rate for the UC strength of bio-cemented sand tends to decrease with the increase in CCS and attributed this to the process that the calcium cannot be fully utilized when the CCS is higher than 1.0 mol/L, which might be caused by the limitation of the enzyme quantities or the reduction in the urease activity of bacteria. Al Qabany and Soga [226] also reported that the chemical efficiency of the 1.0 mol/L case (about 20%) was much lower than that of 0.25 and 0.5 mol/L (varying from 70% to 100%) cases. However, they believed it was due to the less stable calcium carbonates (i.e., vaterite) would be precipitated using 1.0 mol/L and higher CCS, which may be flushed out at the subsequent injections. On the contrary, Li et al. [232] considered the lower CCS favored to form vaterite and the higher CCS favored to form calcite. Meanwhile, Li et al. [232] and Velpuri et al. [229] also claimed that the precipitation rate of calcite would increase with the calcium concentration (from 0.0125 to 0.1 mol/L). Okwadha and Li [233] suggested that the optimum MICP treatment were 666 mmol/L urea and 250 mmol/L calcium at 2.3E8 cells/mL bacterial cell concentration.

In terms of the upper limit of CCS for MICP, Lee et al. [152] and Soon et al. [155] found that shear strength and calcite content of the residual soil treated with 1.0 mol/L CCS were identical to those of the control specimen (supplied with cementation reagent without bacteria). They considered that, at high salinity (i.e., 1.0 mol/L), the bacterial activity would be inhibited and thus retarded the calcite precipitation. Al Qabany and Soga [226] also reported that most of the null UC strength samples were 1.0 mol/L samples. However, some other researchers [190,234–236] have claimed to obtain high-strength biocemented sand columns with CCS higher than 1.0 mol/L. For instance, Rong et al. [237] reported achieving a UC strength of 6.1 MPa for a sand column treated using a CCS of 2.0 mol/L.

III) Other Factors: Ghasemi et al. [238] performed an investigation on the effect of the ratio of calcium and urea on the bio-cementation and found that more treatments were required to reach the target cementation level if using the CS with a lower ratio of calcium and urea. Keykha et al. [239], Li et al. [240], Seifan et al. [241] reported that the treatment solution (containing bacteria, urea, and $CaCl_2$) with a higher pH (up to 12) is favored to yield more calcium carbonate.

3.4 Treatment process

I) Grouting technology: The grouting technology involves the parameters of a) grouting mode, b) grouting method, c) grouting rate, and d) grouting pressure.

a) Grouting mode: There are mainly three grouting modes: 1) Intermittent mode [85,242,243], 2) Continuous mode [242,243], and 3) Recycle mode [126,163,168]. The intermittent mode is conducted by injecting the treatment solution into the sample and then curing it for a period of time until the next treatment, the continuous mode is to inject the treatment solution into the sample continuously during the whole treatment duration, and the recycle mode is to inject a certain volume of treatment solution into the sample circularly. The intermittent mode is the most common grouting mode. Moreover, Martinez et al. [242] reported that the distribution of the precipitated calcite within 0.5 m sand column prepared with the intermittent grouting mode was more uniform than the continuous mode. Rong et al. [243] also reported that the UC strength of the sample prepared with intermittent mode was higher than that using continuous mode.

b) Grouting method: There are mainly three grouting methods: 1) Two-phase method [159,236,244–248], 2) One-phase method [26,132,234,249], and 3) Mixing method [152,154,155,190]. The two-phase method is a traditional grouting method done by: injecting the bacteria solution and the CS into soil separately with the percolation method. This method generally leads to uneven distribution of the bacteria attached in soil [250], thus distributing the precipitated calcium carbonate [243]. Moreover, a large amount of injected bacteria (more than 85%) was found to be flushed out of the sample during the injection of CS [247,208]. To assist the adsorption of bacteria in soil, Whiffin et al. [236] proposed injecting one pore volume of 50 mmol/L $CaCl_2$ solution into the sample immediately after injecting the bacteria solution. Harkes et al. [247] further improved this method by reducing the injected volume of bacterial solution to one-sixth of pore volume and increasing the injected volume of $CaCl_2$ solution to 1.5 times of pore volume. Cui et al. [246,251] proposed to use the two-step biological injection (i.e., injecting 0.4 pore volume of pure bacteria solution first and then injecting 0.6 pore volume of mixed bacteria solution) to improve the two-phase method. Zhao et al. [208] proposed to use the activated carbon to improve the bacterial retention ability.

The one-phase method is to inject the mixture of bacteria solution and CS into the soil at one time. In general, an instant and intensive ex-situ bio-flocculation would occur immediately after the mixing, leading to severe clogging at the injecting point. Kalantary and Kahani [249], Xiao et al. [132] proposed reducing the temperature of bacteria solution and CS to 3°C−4°C before the mixing, and Cheng et al. [234] proposed using a low pH bacteria solution (pH ≤ 6.0) to prevent the clogging.

The mixing method introduces the bacteria into the soil by mixing the soil with a bacteria solution. This method is usually adopted for the soil with poor permeability, and the sample prepared with this method would be cured without repeated treatment [152,154,155] or immersed in a batch reactor filled with CS [157,160,190,206,212,231] until the pre-set curing time. The salt-solution fixing method injects the $CaCl_2$ solution into the soil immediately after the injection of bacteria solution to assist the adsorption of bacteria.

c) Grouting rate: Al Qabany et al. [252] reported that the chemical efficiency was maintaining at > 90% as the grouting rate of CS was lower than 0.042 $mol\cdot L^{-1}\cdot h^{-1}$ and would decrease to an average of 50% for a grouting rate of 0.084 $mol\cdot L^{-1}\cdot h^{-1}$. They considered that the difference in chemical efficiency with various grouting rates could be related to the bacteria-related process or experimental inconsistencies (e.g., variations in sand packing).

d) Grouting pressure: Most of the existing studies used granular materials with good permeability and thus generally used the grouting method without pressure (i.e., percolation method). The grouting with pressure is generally used for the soil with relatively poor permeability (e.g., residual soil). For instance, Soon et al. [155] adopt a pressure grouting method with a grouting pressure of up to 2 bar to inject the CS into the residual soil. However, when a high grouting pressure is used, the grouting can become a different category, such as fracture grouting rather than permeation grouting. For this reason, the injection pressure affects the results of biogrouting in the study reported by Lee et al. [129]. The UC strength of a residual soil treated using different injection pressures was affected by the injection pressure applied. The higher the pressure, the lower the UC strength, and the UC strength of the specimen treated using 0.2 bar injection pressure is 2.3 times higher than that using 2 bar. The permeability for the specimen treated under a 2 bar injection pressure is also 3.5 times higher, indicating the effect of possible fracture induced in the soil.

II) Number of Treatments or Cementation Level: It has been widely reported in the literature that the strength enhancement of the bio-cemented soil generally increases with the number of treatments [123,130,134,170,181,213,246] or the cementation level [115,117,131,244,248,253–256].

III) Treatment Duration or Interval: Several studies [33,42,121,123,130,155,190,202,239] have reported that the strength enhancement of the bio-cemented sample would be greater with longer treatment duration. On the contrary, Danjo and Kawasaki [38] found that the UC strength of the bio-cemented sample decreased with the increase of injection interval (0.5, 1, and 2 d), although the calcium concentration in the drainage with greater interval was lower than that of smaller interval. They considered that the calcites were more preferentially precipitated around the interparticle contact with smaller intervals. A similar result was also reported by Amarakoon and Kawasaki [33]. However, it should be noted that the UC strength is affected by other factors such as the uniformity of the treatment.

IV) Curing Temperature: Cheng et al. [200] and De Muynck et al. [83] reported that the sample curing at a higher temperature could produce more calcium carbonate, but its UC strength was smaller. Cheng et al. [200] claimed that the smaller UC strength at a higher temperature was due to the relatively smaller size of the precipitated calcite crystals that mainly cover the grain surface rather than fill the gaps between adjacent grains. On the other hand, De Muynck et al. [83] attributed it to the high precipitation rate of the calcium carbonate at a higher temperature, resulting in poor adherence and lower consolidative effect of the precipitated calcite.

On the contrary, Danjo and Kawasaki [38] reported that the UC strength of the bio-cemented sand increased by approximately 0.5 MPa with every 5°C increase in the curing temperature (20°C–35°C) and attributed it to more calcium carbonate would be precipitated at a higher temperature. Some studies also suggested that there is an optimal curing temperature for the soil improvement with MICP treatment. For instance, Mujah et al. [257], Cheng et al. [85] reported that the UC strength of the biocemented sand curing at 25°C was higher than that at 4°C and 50°C. Amarakoon and Kawasaki [33] found that the bio-cemented sand curing at 30°C had higher UC strength than that at 25°C and 35°C. Keykha et al. [239] suggested that 40°C was the optimum temperature for MICP treatment.

V) Saturation State during Curing: Cheng et al. [195] performed an investigation on the effect of saturation degrees of the sample during curing on the geotechnical properties of bio-cemented sand. Results showed that higher UC strength could be obtained for the bio-cemented soil with treatment under a lower saturation degree at similar calcium carbonate content. The microscopy images demonstrated that a strong coating effect of the MICP process was predominant for the sample at 20% saturation and the gaps between the host grains were almost filled with crystals. In comparison, for the sample at 100% saturation, the crystals precipitated not only at the interparticle contacts but also on the grain surface or suspended in the pore spaces. Cheng et al. [195] considered that, for a partially saturated condition, the MICP solution is predominantly concentrated at the interparticle contacts and thus the calcium carbonate precipitation, while in the case of full saturation, the MICP solution occupies the whole pore space and thus the calcite can be precipitated on both the grain surface and gain gaps. Shanahan and Montoya [120] also reported that the UC strength of the sample prepared with unsaturated treatment was greater than that with saturated treatment with similar calcite content.

VI) Oxygen Availability: Li et al. [214] studied the effect of oxygen supply on MICP treatment and reported that oxygen availability has a significant effect on the soil improvement with MICP process, and the UC strength of the sample curing with sufficient air supply could be 100 times that of air restricted. Seifan et al. [241] found that a higher aeration rate favored calcium carbonate precipitation. Jiang et al. [258] also reported that the ureolytic activity of B. megaterium in anoxic conditions was greater than that in oxic conditions. Mortensen et al. [259] considered that the MICP would not be diminished by the absence of oxygen or lysis of cells containing the urease enzyme on the time scale of an hour. The effect of oxygen depends on whether bacteria need to be cultivated in the soil. The function of oxygen is for the cultivation of bacteria, not the urologic process.

4 Seepage control of soil

Seepage control is a standard construction process for many infrastructure projects such as urban excavations, earth dams, tunnels, and other underground constructions. Excessive or uncontrolled seepage would impose a significant risk on the stability and safety of those constructions. The conventional countermeasure is to use cement or chemical grout to cope with the risk of undesired seepage and increase the work safety level. However, the particle size and viscosity of the cement and chemical grouting limit their application ranges. The effectiveness of standard seepage confinement is largely compromised when the soil pore size is extremely small. As an alternative, the bioclogging with MICP process has much lower viscosity than typical cement suspension, and it can flow like water inside the tiny pore in soil to induce calcium carbonate.

As shown in Fig. 2, numerous studies have shown that the permeability of soils can be significantly reduced through the MICP process [4,35,46,108,127,224,250, 257,260–262] due to the pore-clogging caused by the precipitated calcium carbonate. In general, the permeability of biocemented soil depends on the initial pore-throat size of the soil and the amount of precipitated calcium carbonate. Several studies have implied that the reduction in permeability for the biocemented soil with greater density [205] or relative density [201,226], larger content of fine [163], smaller particle size [173,195,196], well-graded soil [175] are more significant with same treatment conditions due to the smaller pore space or pore-throat size in soil. Song et al. [203] also found that the permeability reduction for the soil with angular particles was greater than that with near-spherical particles and attributed it to the slot-shaped pores formed by the angular particles, which was more likely to be clogged by the precipitated calcium carbonate.

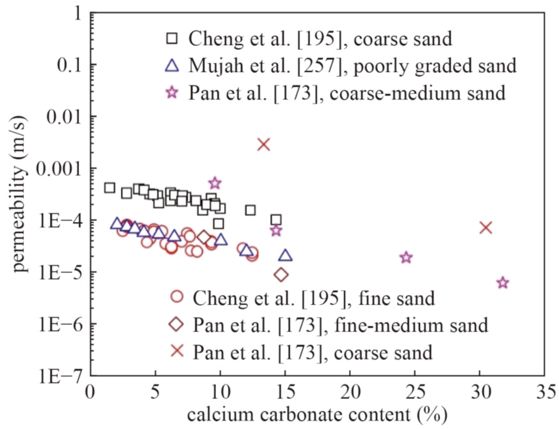

Fig. 2 Permeability of biocemented soil with calcium carbonate content.

Moreover, the MICP treatment using a longer curing time [205,218], more number of treatments [37,40,74, 94,163,170,175,263], higher CS concentration [40,175, 205,223,231], greater bacterial density [205], or larger amount of injected bacteria [201] generally leads to a greater reduction in the permeability of the biocemented soil as more calcium carbonate would be precipitated with these conditions. On the other hand, Cheng et al. [85,195] found that, for the same amount of calcium carbonate, UA of bacteria has a minor impact on the permeability of biocemented soil [85], while a lower saturation condition could maintain a relatively high residual permeability [195]. Moreover, Pan et al. [173] and Yang et al. [264] proposed using bioslurry, a new type of biocement [188], for the seepage control of sand, which was proven to be more effective and efficient in the reduction of permeability. Cheng et al. [147] proposed a novel approach of using in situ microbially induced Ca^{2+}-alginate polymeric sealant for seepage control.

5 Liquefaction mitigation of soil

Saturated, loose, and cohesionless soils with insufficient cyclic shear strength have a greater potential for liquefaction when suffering cyclic loading, such as earthquakes, resulting in severe damage to engineering structures. Liquefiable soils are conventionally improved through dynamic compaction, chemical grouting, and deep mixing, which are typically energy-intensive and can negatively impact the environment. As an alternative, biogeotechnology presents promising approaches for liquefaction mitigation through improving soil's shear strength with biocementation or reducing the saturation degree of soil with biogas.

5.1 Soil strengthening with Biocementation

Several studies, conducted with the cyclic triaxial tests [48,161,176,177,265,266], centrifuge tests [255,267–269], cyclic direct simple shear test [270], and shake table test [178], have demonstrated that the liquefaction resistance of soil could be significantly enhanced through the MICP treatment, showing a reduction in the excess pore pressure (as shown in Fig. 3). Moreover, a higher cementation level for the biocemented soil generally leads to a greater enhancement of liquefaction resistance [48,176,177,255,268]. On the other hand, Montoya et al. [255] and Zhang et al. [178] found the surface accelerations were amplified for the biocemented soil, which is undesirable, and a trade-off between improving the liquefaction resistance and minimizing the surface acceleration should be considered for the design of cementation level.

Besides the cementation level, the distribution pattern of the calcium carbonate [265], saturation degree during curing [266], confining pressure [177], and fine content [161] were also reported to have effects on the liquefaction resistance of the biocemented soil. Feng and Montoya [265] found that the improvement of liquefaction resistance for the specimen with higher shear-wave velocity was more significant than that with lower shear-wave velocity under the same mass of calcium carbonate, and attributed it to the difference in the distribution pattern of the calcium carbonate. Simatupang and Okamura [266] reported that the lower the degree of saturation during curing, the greater the liquefaction resistance of the biocemented soil. This is due to the preferential precipitation of the calcium carbonate at the particle contacts under a lower saturation degree, which also has been reported by Cheng et al. [195]. In essence, it was caused by the difference in the distribution pattern of the calcium carbonate. Xiao et al. [177] found that an increase in confining pressure would lead to a decrease in the liquefaction resistance both for untreated and biotreated calcareous sand. Moreover, Sasaki and Kuwano [161] reported that the inclusion of fines would hinder the liquefaction resistance improvement of the biocemented soil and considered it was caused by the fines curtailing the efficiency of calcium carbonate precipitation at the interparticle contacts.

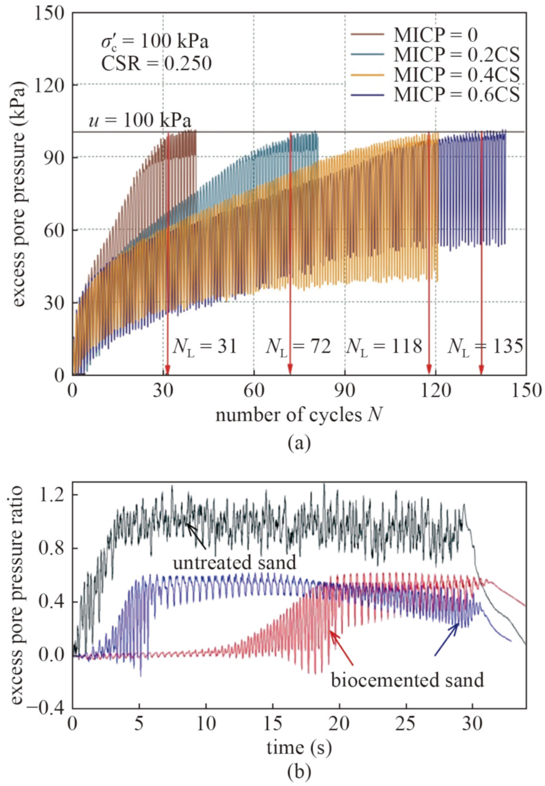

Fig. 3 Development of excess pore pressure for biocemented sand: (a) Cyclic triaxial tests of Xiao et al. [177] (Reprinted from Soil Dynamics and Earthquake Engineering, 107, Xiao P, Liu H, Xiao Y, Stuedlein A W, Evans T M, Liquefaction resistance of bio-cemented calcareous sand, 9–19, Copyright 2018, with permission from Elsevier); (b) shake table test of Zhang et al. [178] (Reprinted from Soil Dynamics and Earthquake Engineering, 129, Zhang X, Chen Y, Liu H, Zhang Z, Ding X, Performance evaluation of a MICP-treated calcareous sandy foundation using shake table tests, 105959, Copyright 2020, with permission from Elsevier).

5.2 Desaturation with Biogas

Studies [271–276] have shown that the mechanical behavior of soil is significantly affected by the presence of gas in either dissolved or free form. In particular, the liquefaction resistance of saturated sand can be largely enhanced by reducing its degree of saturation via introducing gas into it [274,277–282]. However, there is no effective way to inject gas bubbles uniformly into the soil and keep the bubbles in the soil for a long time. Meanwhile, the injection method is not a cost-effective approach. A biologically mediated process is a promising alternative for this purpose. The bacterial suspension could be easily introduced into the soil due to its low viscosity, leading to relatively uniformly distributed bacterial cells in the soil. Thus, the tiny gas bubbles generated in this way tend to be more uniform than that of injection method [12,275].

As shown in Fig. 4, a series of shaking table tests [12,107,110,283,284], cyclic triaxial tests [13,111,285–287], and centrifuge model test [288] have demonstrated that the bio-desaturation method, introducing the nitrogen into the sand with denitrification process, can significantly reduce the excess pore water pressure, mitigating the liquefaction potential of sand. He et al. [12] reported that the pore water pressure ratios could be smaller than 0.5 when the saturation degree of sand was lower than 95%. Meanwhile, a lower saturation degree of sand generally leads to a greater reduction in pore water

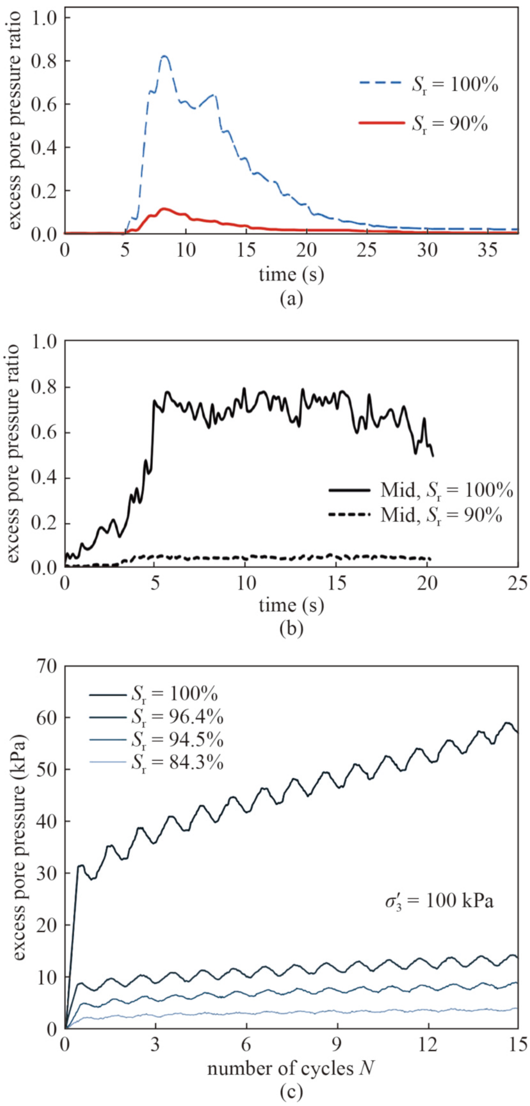

Fig. 4 Development of excess pore pressure for desaturated sand: (a) shaking table test of He et al. [107] (Reprinted from Journal of Zhejiang University. Science A, 17(7), He J, Chu J, Wu S, Peng J, Mitigation of soil liquefaction using microbially induced desaturation, 577–588, Copyright 2016, with permission from Elsevier); (b) shaking table test of Wu [284]; (c) triaxial tests of Wang et al. [287].

pressure ratio, and the saturation degree could be controlled by the initial nitrate concentration added to the soil [12,107]. On the other hand, Rebata-Landa and Santamarina [275] considered that the soil grain size affects the entrapment of biogas in soil. The sand with a small percentage of fines may fail to trap the generated bubbles. To preserve the biogas in the sand, Wu [284] developed a method to combine the bio-desaturation (denitrification process) and bioclogging (MICP process) for mitigation of soil liquefaction through microbial processes. Flow tests for sand columns treated using the combined bio-desaturation and bioclogging method under a hydraulic gradient of 0.1 with either upward or downward flow indicate that the combined method effectively enhances the stability of the bubbles. Other studies performed by O'Donnell et al. [13,105,106,111], Wang et al. [276], Kavazanjian and O'Donnell [285], and Hall et al. [288] employed the denitrification process to induce calcium carbonate precipitation and generate nitrogen gas at the same time. The advantage of this process is that it provides an additional benefit for mitigating soil liquefaction through biogas (N_2) desaturation besides associated carbonate precipitation. The disadvantage is that the calcium carbonate precipitation induced via denitrification process is not as efficient as the precipitation caused by ureolytic bacteria [286,289].

6 Examples of up-scaled and field trial of biogeotechnology

In the laboratory, biogeotechnologies have shown excellent efficiency in improving or modifying soil engineering properties. To realize such potential of biogeotechnologies in future engineering practices, conducting up-scaled tests or field trial are necessary. Based on laboratory bench-scale column test or small model test, several up-scaled experiments and field trials have been carried out worldwide. Those trials mainly focused on the feasibility of application of biogeotechnologies in the field, proper deploying measures, monitoring techniques, and the post-improvement evaluating means. All of which contribute to the efficient and reproducible soil improvement process based on biogeotechnology.

6.1 Up-scaled experiments

Several up-scaled model tests have been reported regarding the feasibility of biocementation as a soil improvement technique at a large experimental scale [68,235,290–293]. van Paassen et al. [291,292], first applied the MICP technique to a 1 m^3 sand deposit and turned it into a sand block with substantial UC strength values. Based on the experience gained, two 100 m^3 fine sand pilot tests were performed by Deltares (NL) [235,291] and Soletanche Bachy [290], respectively. A total volume of 100 m^3 of cementation solution was circulated through the 100 m^3 sand deposit during 12 d using injection and extraction wells. The time-lapse shear-wave seismic measurements were also conducted to monitor the biogrouting process during treatment. UC strength tests on cored samples showed peak strength up to 12 MPa. The Young's modulus reached 8500 MPa. However, the amount of precipitated calcium carbonate was spatially dispersed. It could be due to the heterogeneity of bacteria and cementation solution distribution and preferential flow paths, leading to higher calcium carbonate crystal settlement than other non-preferential flow areas. Recently, Wu et al. [293] first carried out a large-scale biogrouting test on sand and rock mixture material, extending the biocementation to a broader scope of application. As shown in Fig. 5, a 1-m^3 container filled with sand and rock was turned into a hard piece of block after two weeks of two-phase biogrouting treatment.

6.2 Field applications

Employing microbiological activity in water flow control was one of the earliest field applications of biogeotechnology. Johnston et al. [294] pumping nutrient and amendment solution for the biostimulation in a site located in South Australia that was contaminated with diesel and gasoline. The 2.25-d biostimulation led to a significant increase in biomass concentration and EPS concentration, translating to a 5-fold decrease in permeability. A similar biobarrier was established to measure the extent of bioclogging and stability in a well-characterized fracture bedrock site located in Southern Ontario, Canada [295]. After 43-d biostimulation of the biofilm growth and 179-d starvation on biofilm persistence, an overall 3.3-logs of hydraulic conductivity reduction were observed for the 222-d experiment [296].

Fig. 5 Up-scaled model tests: 1 m^3 sand model of Wu et al. [293].

Other successful field trials of bioclogging were also reported in the Netherlands and Austria to reduce leakage through water-retaining constructions [297,298]. Besides biofilm, the precipitation of calcium carbonate through the MICP process was also employed in situ for fractured rock sealing and permeability reduction [299,300]. In the study, MICP was promoted in a fractured sandstone layer within the Fayette Sandstone Formation 340.8 m below ground surface. After 24 cementation solutions and 6 microbial suspension injections, the injectivity was decreased more than 3 times and a significant reduction in the in-well pressure falloff was observed [300]. They also presented results of enhancing wellbore cement integrity with MICP in a field-scale demonstration [301].

Another field trial highlighted the use of biocementation to biologically cement and stabilize the gravels around a gas pipeline in the south of the Netherlands [292]. A soil volume of 1000 m^3 was treated using the biogrouting procedure at a depth varying between 3 and 29 m below the surface. There were 200 m^3 of bacterial suspension and 300 to 600 m^3 of cementation solution injected to cement the gravel layer. After treatment, the gravel appeared to be heterogeneously packed, and the shear strength increased with the number of flushes. Besides the traditional injection approach, Gomez et al. [302] performed a field-scale MICP via surface percolation at a mine site location in Saskatchewan, Canada. Results show that a thickness of 2.5 cm stiff crust was formed after 20 d of treatment. Improvement was assessed to a depth of 40 cm using dynamic cone penetration (DCP) testing and calcium carbonate content measurements. A water-jet impingement erosion test was performed, and the result verified the effectiveness of the MICP as a dust control measure.

Stimulation of selective native microorganisms (biostimulation) instead of introducing foreign strains (bioaugmentation) for biocementation in the field would be able to alleviate the concerns of ecological and environmental impact. Gomez et al. [303] conducted a large-scale comparison of biostimulation and bioaugmentation approaches for biocementation in sands. Two identical sand specimens were made with the same dimension of 0.5 m high, 1.7 m diameter, and 0.3 m thickness. MICP treatment was applied in two treatment phases over 12 d. The results suggest that native ureolytic microorganisms may be biostimulated to induce biocementation and significantly improve loose sands at the meter scale. The post-treatment strength was evaluated by cone penetrometer and geophysical measurements. The shear wave velocity of biocemented sand reaches between 131 and 967 m/s, and mid-depth cone penetration resistances range between 3.6 and 32.1 MPa [304]. At highly cemented locations near injection points in both tanks, soil shear wave velocities and cone penetration resistances improved by over 600% and 500%, respectively [305]. In another study, microbes cultivated at depth from field samples have shown their ureolytic ability to induce calcium carbonate precipitation at treatment depths up to 12 m for geotechnical ground improvement [51]. These large-scale experiments and pilot trials all indicate the great potential of biogeotechnologies in various engineering applications. At the same time, challenges are also revealed in the implementation of biogeotechnologies in-field.

7 Challenges and strategies for biogeotechnology

As an emerging and promising technique, biogeotechnology has already attracted vast initiatives from both scientific researchers and industrial professionals. Experiments and trials mentioned before really promise an exciting future for this technique. However, all new solutions to tackle traditional problems always come with challenges.

The first challenge is the uniformity of treatment effect. For field application, the uniformity of the treatment is governed by many factors which are not easy to control as those in the laboratory. The microbial members, cementation material, and environmental factors interact simultaneously and affect the treatment process. Although the materials used in biogeotechnologies, such as biocement, are usually in a liquid form with very low viscosity and their implementation does not cause a significant ground disturbance, the introduction of biocement into fine-grade soils is still not effective without soil mixing [3]. Real-time quality control in the treatment process is another challenge for any project to adopt microbial methods. Geophysical methods could be an effective monitoring technique in the treatment process to detect the presence of biogrout in soil. The selection of proper sensors and their deployment mainly rely on the understanding of the biogeochemical process introduced by microorganisms. When the proper monitoring techniques become mature, we can confidently apply biogeotechnologies in the field and alter the operation in time for optimization of the treatment process.

In most of the studies, the cultivation of microorganisms and source for cementation solution (such as calcium for MICP or nitrate for denitrification) are from high-grade chemical reagents which are too expensive for field applications and not sustainable. Organic waste can be a nutrient source for both bacteria growth and fermenting microorganisms in large-scale applications to diminish the cost. Some studies proposed to cultivate the bacteria in non-sterile conditions [45,209] or using inexpensive technical-grade reagents [306], food-grade yeast medium [307], and sanitized media with inexpensive nutrients and water resources [308] to reduce the cost for the in situ application. Using limestone powder derived from aggregate quarries and disposed of industrial biofuel acid to produce calcium source for biocementation can be a cost-effective and sustainable method [126]. Some laboratory tests have been carried out to establish the procedure for using the by-product of limestone mines and corn cobs as the source of biocement. Through a fermentation process, biocementation solutions were produced and applied directly on top of soil or a crushed stone layer. As a result, once this layer dries, a biocemented slab is formed. Eggshells [124], oyster shells [224], and calcareous sand [225] are also reportedly been used as calcium sources. A direct cost comparison of using biocement and normal cement or chemical for treating soils may not be made at this stage due to the production procedures of the biocement. Because the biocement at the current stage is mostly produced in laboratory conditions and may be produced in a factory setting in the future. When a large quantity of biocement is required for the actual construction work, a factory-scale production line must be established. Until then, the cost of biocement can be evaluated realistically. Continuously finding effective and economic measures to produce microorganisms and cementation sources is a critical step in pushing the biogeotechnologies into engineering practices.

Another major concern of biogeotechnologies stems from their environmental impact. The biosafety of in situ biogeotechnology approaches needs to be addressed. The employed microorganisms must be non-pathogenic and non-hazardous. Before any foreign strains or cultures are introduced into the local environment, their genetic information must be identified to ensure their biosafety. Information on the microorganisms, their fate in the environment, and their ecological effects must be available to designers and workers. As an alternative, using the urease for the urea hydrolysis to precipitate the calcium carbonate, so-called Enzyme Induced Calcite Precipitation (EICP) [309–312], could reduce or even avoid the issue of bio-safety. The urease can be extracted from UPB [163,168] or some plant seeds, such as soybean [313], jack bean [314,315], and watermelon seeds [309,316]. Moreover, the production of any potential hazardous and harmful byproduct during the treatment process must be properly collected and treated. Alternatively, different processes should be adopted to avoid the harmful byproduct. For example, to avoid the production of ammonia, denitrification-based biocementation can be employed [15,289,317], although the process is not as effective as MICP at the moment. Overall, the environmental assessment would ensure the sustainability of the biogeotechnology concept.

8 Concluding remarks

Although much attention and resources have been devoted to the use of biotechnologies in geotechnical engineering in the past decades; we are yet to fully understand the mechanisms of different microbial processes and the methods to control the engineering properties of treated soil reliably. In this paper, three major microbial processes, biocementation, bioclogging, biogas desaturation, and their potential applications and influence factors, are reviewed. Examples of up-scaled model tests and pilot trials are introduced. Difficulties and challenges in field implementation, monitoring, cost efficiency, and environmental impacts are also discussed. The microbial processes involved in biogeotechnology usually comes with complicated physical and chemical processes, leading to many uncertainties and difficulties in the research and application of biogeotechnology. To better understand the fundamentals of biogeotechnology and its applications to engineering practices, it is essential to encourage cross-disciplinary collaboration between researchers and industry practitioners. There are still many challenges to overcome before biogeotechnology can be fully adopted in field applications. By integrating experts from different disciplines, a breakthrough would emerge to push the frontier of biogeotechnology and its applications in the future.

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