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Liquefaction resistance of bio-cemented calcareous sand

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ABSTRACT

Coral reefs and other calcareous deposits may experience various types of significant dynamic loading, such as those from waves and earthquakes. When submerged and subjected to earthquake loading, the potential for liquefaction of calcareous deposits may cause a loss of human life and property; however, few studies have evaluated the liquefaction potential of calcareous sands relative to those conducted on silica sands. Accordingly, it is critical to study the cyclic resistance of calcareous sands as well as methods to mitigate their liquefaction potential. Microbial induced calcite precipitation (MICP) offers one such strategy that can be considered for improving the cyclic resistance of calcareous sands, particularly for those applications below existing infrastructure that would pose technical difficulties for traditional modes of ground improvement. This paper examines the effectiveness of MICP on the cyclic resistance of as a function of cementation solution (CS) content, effective confining pressure, and cyclic stress ratio (CSR) through a cyclic triaxial test program. The generation and accumulation of excess pore pressure and corresponding axial strains are compared across a range of treated and untreated sands. This study shows that the liquefaction resistance of clean calcareous sand may be significantly improved by the MICP treatment. Scanning electron microscope images are presented to help link the improvement in cyclic response to the microstructural features of the microbial-induced calcite and bio-cemented sand.

1. Introduction

Coral reefs and other calcareous soil deposits may experience various types of significant dynamic loading, such as those from waves and earthquakes. Additionally, significant coastal and ocean infrastructure are being constructed on these deposits [1,2]. Since 1960s, calcareous soil deposits have attracted increased attention for the exploitation of hydrocarbon resources [3]. In ocean engineering, calcareous sands are commonly used as the foundation materials for buildings and breakwaters and as the backfill material for road embankments or airport runways [4]. When submerged and subject to earthquake loading, the potential for liquefaction of calcareous deposits may cause a loss of human life and property, as observed during the 1993 Guam earthquake, which was characterized with a moment magnitude, M_w, of 7.7 [5]. This earthquake caused significant liquefaction and resulting damage to the commercial facilities and port areas on the deposits, which highlight the importance of understanding the liquefaction of calcareous sand. Calcareous sands are broadly-distributed along the coasts and coastal reefs of Australia, the Persian Gulf, the Gulf of Mexico, and the South China Sea for example [6], and these types of soils are the result of various physical, mechanical, chemical and biological depositional environments [7]. Calcareous sands consist of shells and corals, and as a result of their previous biological life, the sand include cavities and voids, which can be easily crushed [8–11]. Due to their low mineral strength, it is necessary to improve the cyclic resistance of loose to medium dense deposits of calcareous sand supporting structures. However, many traditional technologies used to improve liquefaction resistance, such as densification through vibro-compaction and vibro-replacement [12], driving of displacement piling [13,14], or compaction grouting [15], are inappropriate for improvement of calcareous sands as these methods induce significant forces that can crush the sand grains [16–18]. On the other hand, other grouting techniques with cement [19] or other cement agents [20], may be disqualified in certain marine settings due to environmental restrictions on such techniques and might pollute the marine environment [21].

Recently, a novel ground improvement technique [22–25] has gained interest due to its relatively green and sustainable advantages: microbial induced calcite precipitation (MICP). Ivanov and Chu [24] suggested that the raw materials for microbial grouting are significantly cheaper than chemical grout. The basic mechanisms of improvement

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using MICP technique includes: (1) synthesis of an enzyme through bacteria metabolic activities [26]; (2) microbial urease hydrolyses urea to produce ammonia and carbonate ions; (3) the carbonate ions bind with calcium to accumulate insoluble $CaCO_3$ in a calcium rich environment [27]. The chemical reactions governing the MICP process are given by:

$$CO(NH_2)_2 + 2H_2O \rightarrow\rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow\rightarrow CaCO_3 \quad (2)$$

Bio-cementation has been recognized for its broad application in treating various engineering challenges. For example, MICP has been used to reduce the permeability of soil [28,29], repair cracks in concrete [30,31], and improve the stiffness and strength of soil [32–36].

Additionally, several studies have shown that the bio-cementation technology has significant potential to efficiently mitigate liquefaction at developed sites in a passive, non-disruptive manner [37–40]. Burbank [38] et al. compared cyclic shear test results of sand treated with bio-cementation and Portland cement, and found the cyclic stress ratio (CSR) of the bio-treated soil was higher than the cement-treated soil for similar quantities of cementing agent. Han et al. [37] found that treating sand with MICP takes less time to improving liquefiable sand than colloidal silica grouting to achieve a similar liquefaction resistance. Montoya et al. [40] studied the dynamic response of MICP-treated siliceous sand of various strengths using centrifuge models and found that the pore pressure development, surface settlement, and the acceleration at the ground surface was lower than that of a comparable loose sand. On the other hand, Sasaki and Kuwano [41] found that siliceous sand with a 30% clay fraction showed no increase in liquefaction resistance following microbial precipitation of $CaCO_3$.

There are far fewer studies that have evaluated how the magnitude of MICP improvement and confining pressure has impacted liquefaction resistance. In addition, the few studies that have focused on the cyclic response of marine soils like calcareous sand [42,43] have evaluated natural sands without MICP treatment. Calcareous sand is a biogenic material that shares many physico-chemical characteristics with calcium-based bio-cementation; accordingly, the potential for natural efficiencies between the carbonate crystal-particle interface strength may be significant. For example, Khan et al. [44,45] conducted some initial investigations on the coral sand using different bacteria and observed that unconfined compressive strengths in the range of 13–20 MPa were achievable.

The objective of this experimental laboratory investigation is to determine the efficacy of MICP-treatment to improve the cyclic resistance of calcareous sand. In order to make sufficient comparison against various treatments, the cyclic response of the untreated calcareous sand is studied using a series of cyclic triaxial compression tests (CTCs). Then, a series of CTCs are conducted to compare the liquefaction mitigation of different cementation solution (CS) contents, effective confining pressures, and cyclic stress ratios and to analyze the factors affecting mitigation. Scanning electron microscope (SEM) images are presented to help link the improvement in cyclic response to the microstructural features of the microbial-induced calcite and bio-cemented sand.

2. Experimental materials

2.1. Characteristics of Yongxing Sand

The calcareous sands in this study were sourced from Yongxing Island of the Xisha archipelago located in the South China Sea. The particle size distribution (PSD) and a microscopic image of the Yongxing Island sands are presented in Fig. 1. The medium to coarse, shelly sand is characterized with widely varying grain shapes ranging from platy to rod-like to ellipsoidal; these grain shapes can facilitate significant interlock while exhibiting remarkably large void space like other carbonate sands [7,42,43,46]. Based on the Unified Soil Classification System [47], the sand is classified as poorly-graded, other properties such as the specific gravity, and maximum and minimum void ratios are shown in Table 1. The $CaCO_3$ content in Yongxing Island sand was more than 90% prior to MICP treatment. Two sets of particle size curves including the ranges in PSDs for most liquefiable and potentially liquefiable soils [48] are compared to Yongxing Island sand in Fig. 1. Based on the PSD, the potential for liquefaction of loose deposits of this sand is high.

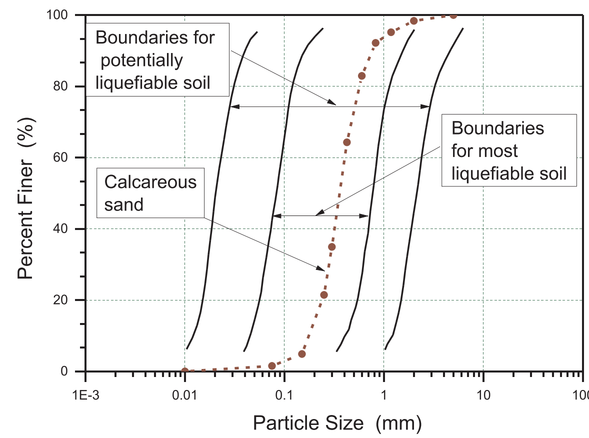

Fig. 1. Particle size distribution curve superimposed with liquefiable boundary (modified from Diaz-Rodriguez et al., 2008).

Table 1
Index properties for the original calcareous sand.

Sand property	Values
Specific Gravity (G_s)	2.79
Minimun Void Ratio (e_{min})	1.22
Maximum Void Ratio (e_{max})	1.69
D_{10}	0.18
D_{30}	0.28
D_{50}	0.36
D_{60}	0.40
Coefficient of Uniformity (C_u)	2.22
Coefficient of Curvature (C_c)	1.09

2.2. Bacterial suspension and cementation solution (CS)

The urease strain of Sporosarcina pasteurii was used as the active microbe for production of the calcite in the experiments conducted in this study. The previously frozen strain was activated in a plate medium, and then cultivated in sterilized growth media which consisted of the following per-liter deionized water concentrations of:(1) 20 g yeast extract, (2) 10 g NH_4Cl, (3) 12 mg $MnCl_2{\cdot}H_20$, (4) 24 mg $NiCl_2{\cdot}6H_20$ with a pH of 9.0, achieved using sodium hydroxide. Bacteria were grown in incubator shaker in 30 °C with about 36 h to reach an optical density of 600 nm (OD_{600}) of 0.8–1.0 (10^7 cells/mL). To remove the abundant metabolic waste and odor, the harvested bacteria were centrifuged at 4 °C at a speed of 4000 rpm for 15 min. Following concentration in the centrifuge, the resulting supernatant was removed and replaced with 0.9% sodium chloride solution before the bacteria were resuspended. The enzymatic activity of the final bacterial media was about 1.4–2.0 mM urea/min. The cementation solution (CS) used in the experiments was a mixture of 0.5 mol/L urea and 0.5 mol/L $CaCl_2$.