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Strengthening the Soil Structure through Microbe-induced Calcium Carbonate Precipitation

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Abstract. Recently, microbe-induced calcium carbonate precipitation (MICP) has begun to be used to enhance the soil strata. This biomineralization method allows the microorganisms to multiply in the soil and to solidify the soil layers. Once completed, this process permanently strengthens the soil. This is an innovative, safe, and economic technology. The objective of the present study is to explore the feasibility of strengthening the soil structures using the MICP method. In the tests that have been conducted, we have simulated the soil structures using standard sand, producing test specimens with relative densities of Dr = 40%、60% and 80%. The MICP test results indicate that Bacillus pasteurii is quite efficient at releasing the calcium ions, which enables the growth of calcium carbonate crystals between the sand particles to perform infilling and cementation. After conducting the MICP treatment, the originally non-cohesive standard-sand specimens could be consolidated into the blocks, and the test specimens that are subjected to MICP treatment over longer durations exhibit better overall consolidation. The compressive strengths of the specimens increases from 0 kPa (the compressive strength of a loose sand specimen) to become approximately 3-12 kPa. This result indicates that the MICP method can result in cohesion using a standard-sand test specimen and will strengthen the structure. The resonant-column test results exhibits that the shear-wave speed depicts a significant increase, which further demonstrates that the specimen structure is considerably strengthened using the MICP treatment.

Keywords: microbial-induced calcium carbonate precipitation (MICP); bacillus pasteurii; compressive strength; resonant column test

1. Introduction

Earthquakes are frequently accompanied by serious disasters. One important factor that causes ground-structure damage is soil liquefaction. In case of a sandy-soil area where the groundwater level is high, soil liquefaction is likely to be triggered by various external causes such as seismic forces or other disturbances. Soil liquefaction can be majorly prevented by increasing the soil stiffness or ground-bearing capacity as well as by increasing the shear strength of the soil using stratum-improvement technologies.

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In the present study, we have investigated a novel cold-bonding technology that is currently under development in which the natural metabolism of microorganisms in the soil is used to vary the physical properties and to improve the mechanical properties of the soil. Thus, we have employed a microbial-mineralization technology to strengthen or cement the soil that can inhibit or prevent soil liquefaction (Bang *et al.* 2001, Hammes *et al.* 2003, Harkes *et al.* 2008, Dek uyer *et al.* 2012, Montoya *et al.* 2013, Waleed *et al.* 2014, Kim and Youn 2016, Atla *et al.* 2017, Zhang *et al.* 2017, Hsu *et al.* 2018).

In the early 1970s, biologists and geologists discovered that some harmless bacteria can cement loose sand into rock by mineralization as descried by Tiano (1995). For the present study, we selected Bacillus pasteurii as the biomineralization bacterium. These microbes are commonly observed in soil and have often been used to perform the microbe-induced calcium carbonate precipitation (MICP) tests as presented by Mitchell and Santamarina (2005) and Qian *et al.* (2009). Bacteria continuously metabolize nutrients, decomposing them into CO_3^{2-} and NH^{4+}. Meanwhile, the pH of the environment is increased, and the negatively charged water-soluble organic matter (SM) at the cell-membrane interfaces continuously chelate Ca_2^{+} until the crystal-ion concentration increases to a level that is sufficient to ensure nucleation. This results in the precipitation of $CaCO_3$, causing mineralization as showed by Qian (2009).

Globally, several studies have used biomineralization to enhance the mechanical properties of soils. For example, in Japan, Yasuhara *et al.* (2011) employed the effects of bioenzymes to precipitate calcium carbonate, which was used as a cementing material to improve the sand structures. Leon A. P. *et al.* (2010) used MICP to conduct large-scale sand-consolidation tests in their laboratories. Michael *et al.* (2015) have long applied biotechnology to strengthen sandy beaches and to prevent beach erosion of the Lakeshore Beach on the Key Lake in Canada. In the present study, we have conducted MICP tests by simulating the soil structures using standard sand to investigate the enhancement of soil structures and the feasibility of using MICP to prevent soil liquefaction.

2. Experimental details

2.1 Experimental program

To control the consistency of the soil specimens, we have used standard sand (ASTM C778) to make the remolded specimens in the form of simulated soil structures. This is because the nature of standard sand is very simple, which reduces the uncertainties that are observed during the tests. We planned the test items and variables as presented in Table 1. We manufactured the remolded specimens of standard sand with different relative densities, Dr, to be used to conduct the MICP tests. After performing the MICP tests, we performed compressive-strength and resonant-column tests (ASTM D 4015) to obtain information about the mechanical and dynamic properties of the specimens and to evaluate the effectiveness of soil reinforcement.

We performed the compressive-strength and resonant-column tests after indoor maintenance two days after the designated curing time. The objectives of these tests were to determine the strengthening effect of the MICP treatment on the remolded soil specimens that exhibited different initial porosity ratios.

The purpose of conducting the resonant-column tests was to measure the resonance frequencies of the test specimens under small strains to obtain the shear-wave velocities, Vs. The aim of