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Undrained Behavior of Silty Soil Improved with Microbial Induced Cementation

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ABSTRACT

Microbial induced calcite precipitation (MICP) has been shown to be a natural and effective liquefaction mitigation technique for clean sands; however, MICP for liquefaction mitigation of silty soils has received limited attention. Presented herein are the experimental results of undrained simple shear testing of fine sand with varying amounts of silt treated with MICP to a moderate level of cementation (e.g., target increase in shear wave velocity of 300 to 400 m/s). The results indicate that MICP increases the shear strength of the silty sand, similar to the results of clean poorly-grade sand. In addition, MICP reduces the generation of excess pore pressures, thereby reducing its susceptibility to liquefaction. These results illustrate that MICP is a promising ground improvement method for liquefiable silty sands.

Introduction

Bio-mediated soil improvement is an emerging research field that meets societal needs for ground improvement in a more natural and sustainable manner. Bio-mediated soil improvement is a chemical reaction, mediated by bacterial activity, which improves the mechanical properties of the soil. Of the more studied methods to modify the mechanical properties of the soil with bio-geochemical reactions is microbial induced calcite precipitation (MICP). MICP uses urea hydrolysis as a chemical reaction to increase the alkalinity of the pore fluid and induce calcite precipitation, (Fujita et al. 2008, Stocks-Fischer et al. 1999). Sands cemented through the MICP process have been shown to exhibit an increase in shear strength, shear stiffness, and dilative properties (Montoya and DeJong 2015, Burbank et al. 2013, Montoya et al. 2013, Chou et al. 2011, van Paassen et al. 2010). The precipitated calcite influences the behavior of the soil by bonding the particles together and densifying the soil by decreasing the void ratio (Montoya and DeJong 2015). The majority of the MICP research to date has focused on treating clean sands; however, MICP also has the potential to improve silty sands (Mortensen et al. 2011). The research presented herein investigates the effectiveness of MICP on fine silty sands subjected to undrained loading.

Nevada sand mixed with different amounts of silt (0, 10, 25 and 35% by mass) is prepared to conduct constant volume monotonic direct simple shear (DSS) tests representing undrained conditions (Dyvic et al. 1987). Each silt-sand mixture is treated with MICP and compared to the behavior of the untreated soil. The MICP treatments are continued until a change in shear wave velocity (V_s) of 300 – 400 m/s is achieved. After treatment, the sample is transferred to the DSS

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device for consolidation and shearing. The amount of excess pore water pressure, peak shear stress ratio and maximum shear strength are evaluated and compared for the treated and untreated samples. Due to the MICP treatments, the shear strength increased and excess pore pressures decreased. In addition, the behavior of soil indicated a transition from a contractive state to more of a dilative state due to changes in the void ratio and the MICP bonds between particles.

Materials and Methods

Soil properties and sample preparation

The soils used for this study include a fine poorly graded sand, Nevada Sand, and a non-plastic silt, silica flour (Sil-Co-Sil 52). The grain size distributions of both soils were determined by sieve analysis and Hydrometer testing. The Nevada Sand was passed over the #200 sieve to eliminate all particles finer than 0.075 mm in order to ensure an accurate amount of silt in the specimen. The grain sizes of the sand and silt are compatible to prevent migration of the silt (e.g., Terzaghi's filter criteria, Holtz et al. 2011). Properties of the sand and silt used in the study are summarized in Table 1.

Table1. Sand and silt characteristics

Name	**Nevada Sand**	**Silica Flour**
Description	Uniformly graded (Gap graded)	Well graded
D_{50}	0.13 mm	0.01mm
Cu	1.7	n/a
Cc	1.24	n/a
Gs	2.65	2.65
Mineralogy	Quartz	Quartz
Shape	Angular*	Sub-angular

** - Shape based on evaluation by Mikola and Sitar (2013)*

To prepare specimens for tests, dry pluviation was used; however, as this method may lead to segregation of silt and sand, water was added to the silty sand specimens to reach a moisture content of 3-4% to prevent segregation. The specimens, which had a diameter of 66.8 mm and height of 13 to 16mm, were prepared to a target void ratio of 0.7. The goal is to have specimens with similar initial void ratios after applying 100kPa of vertical stress.

Biological Treatment Process

Sporosarcina pasteurii (ATCC 11589), a common alkalophilic soil bacterium with high urease activity, is used in the laboratory study to catalyze the biochemical reaction. *S. pasteurii* was grown at 30°C in an ammonium yeast extract (ATCC 1376). The ingredients were autoclaved individually and mixed together after sterilization. The growth medium was inoculated with the *S. pasteurii* stock culture and incubated aerobically at 30°C in a shaker for 40 h before harvesting at a final optical density (OD_{600}). Cultures were centrifuged at 4000g for 20 min in 15mL volumes. Harvested bacteria were stored in centrifuge vials at 4°C for maximum of 14 days.

Urea and calcium chloride based cementation media was used to induce ureolytic-driven calcite precipitation (Mortensen et al. 2011). Table 2 presents a summary of the cementation media components and their chemical concentrations. The cementation media is injected into the soil specimens under a low pressure. The initial treatment injection inoculates the soil with bacteria suspended in the cementation media without calcium chloride, to prevent cementation during this stage. The bacteria is retained for 3 to 6 hours. Subsequent injections of cementation media (including calcium chloride) are performed every 6 to 12 hours. The injections of cementation media are continued until the target V_s is reached, which is an increase of 300 to 400 m/s above the initial measured V_s value.

Table2. Chemical recipe for cementation media

Chemical	**Chemical concentration**
Urea	333 mM
NH_4CL	374 mM
$CaCL_2$	50 mM

The cementation process was monitored in real time with non-destructive V_s measurements. Bender elements prepared with specific techniques to operate in highly conductive environments are used to determine the V_s of soil specimens before and during treatment (Montoya et al. 2012). A 5-V, 100 Hz square wave is sent to the sending bender element and an oscilloscope is used to determine the travel time of the shear wave.

Specimen Shearing

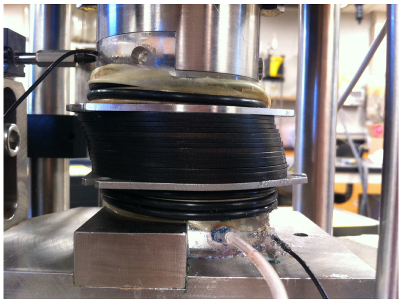

Figure 1. Nevada sand treated sample after shearing

The uncemented specimens were placed in the DSS device immediately after preparation and were saturated and consolidated under 100kPa stress while the bio-cemented specimens were treated in specially designed setups for the MICP treatments under 15kPa of overburden pressure and then placed in the DSS apparatus for saturation and consolidation. Once the specimens were consolidated to 100 kPa, all samples were sheared at a rate of 50%/per hour. The rate of shearing depends on samples height, which is calculated accordingly final specimen height after consolidation. The untreated void ratio of cemented samples is calculated by the calculating the volume of the specimen under 100 kPa pressure and weight of soil before treatment. Changes in void ratio were calculated as an indication of amount of calcite precipitated. A summary of the specimen conditions is presented in Table 3.

Table 3. Initial conditions of soil before shearing

Sample status	**Silt content**	**Untreated void ratio after consolidation under 100kPa**	**Treated void ratio after consolidation under 100kPa**	**Initial shear wave velocity (m/sec)**	**Final shear wave velocity (m/sec)**	**Calcite content (%)**
Uncemented	0	0.70	--	--	--	--
	10	0.69	--	--	--	--
	25	0.56	--	--	--	--
	35	0.65	--	--	--	--
Cemented	0	0.74	0.64	91.1	477.2	4.8
	10	0.71	0.67	101.0	407.94	2.35
	25	0.64	0.57	89.71	429.58	4.16
	35	0.69	0.65	67.07	465.65	1.66

Results

Uncemented Silty Soil Behavior

Silty sand specimens with fines contents of 0, 10, 25 and 35% were prepared, consolidated, and subjected to undrained shear loading. All specimens tested show contractive tendencies with decreasing normal stress and increasing pore pressure during shearing (Figure 2). The results also indicate the silt content influenced the undrained shear strength of the soil. Compared to the clean Nevada sand specimen, the 10% silt specimen exhibited slightly less shear strength. However, the specimens demonstrated an increase in shear strength with an increase in silt content at 25% and 35% silt. This behavior is likely due to the addition of fines filling the voids between particles leading to a more compact condition (Lade et al. 1998).

Cemented Silty Soil Behavior

The MICP treatment method was applied on soil specimens containing 0, 10, 25 and 35% silt. All specimens were treated for an equal time and number of injections to reach a target increase in V_s=300 to 400 m/s. Constant volume direct simple shear tests were the performed on the specimens.

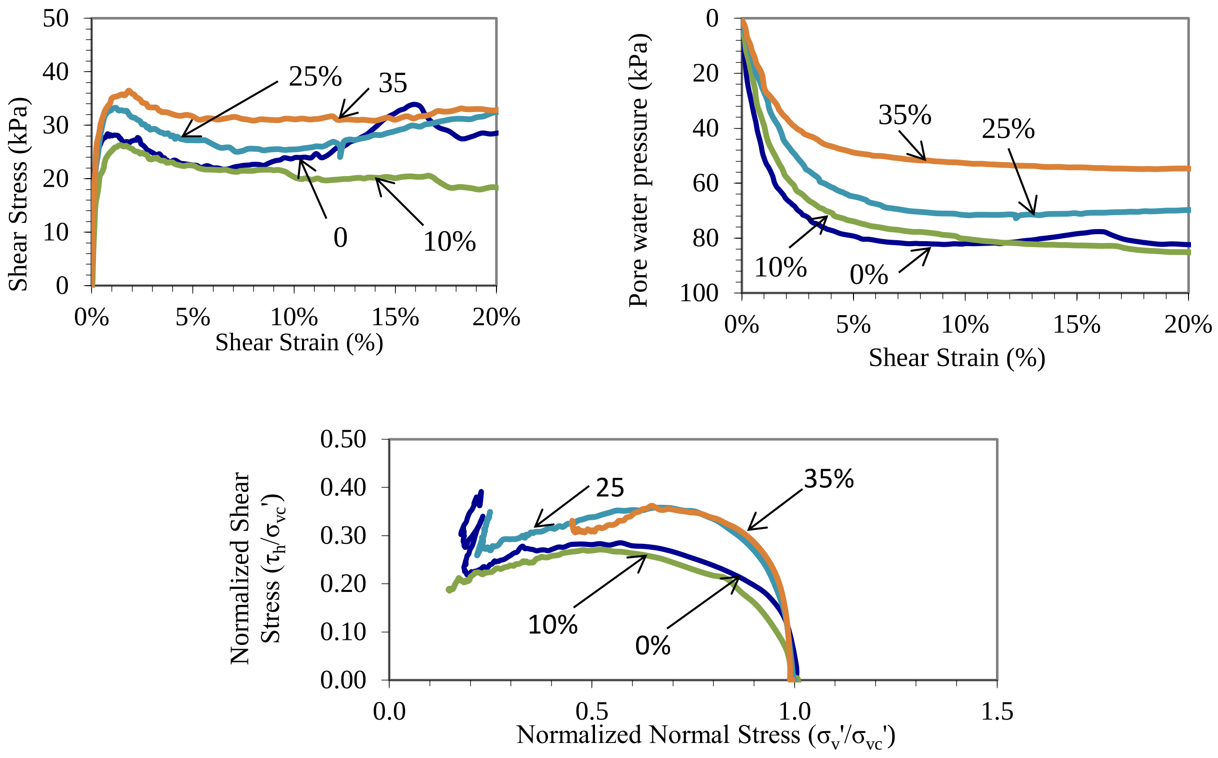

Figure 2. Uncemented silty soil behavior in undrained direct simple shear test

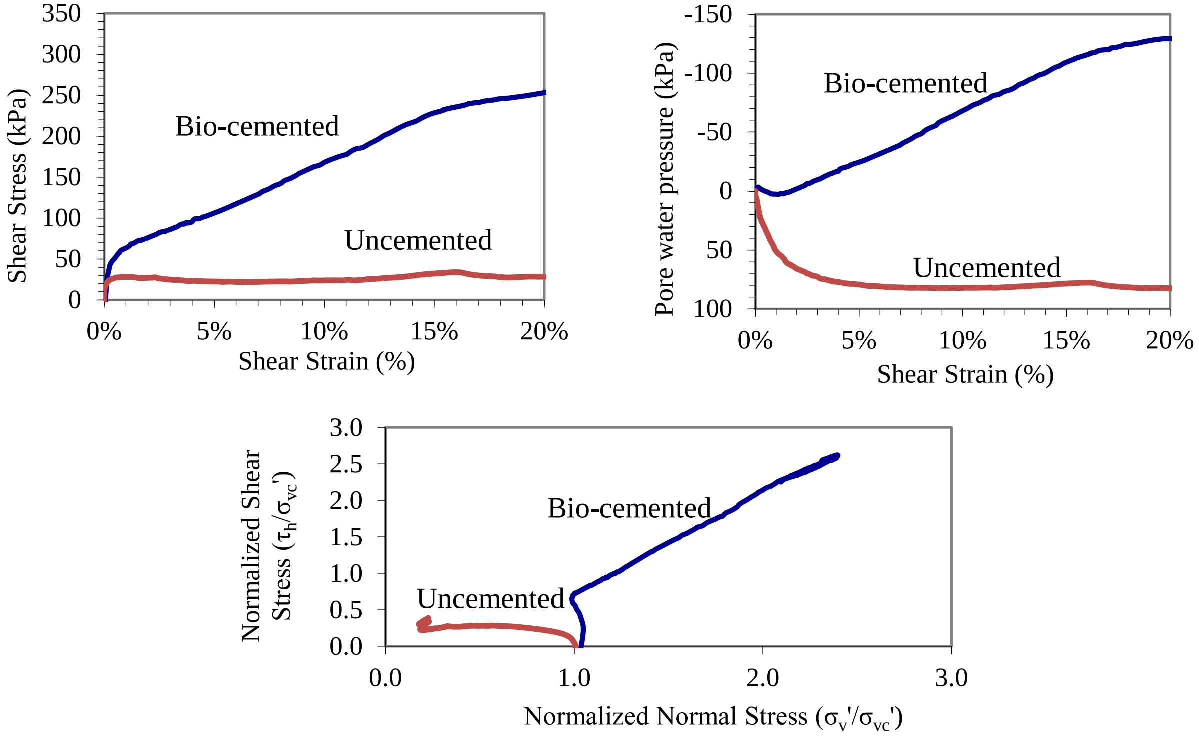

Figure 3. Undrained direct simple shear results of bio-cemented clean Nevada sand

Changes in shearing behavior of Nevada sand with 0% of silt is presented in Figure 3. The results indicate that the cemented soil behavior has transitioned to that of a dense sand. The shear strength has increased from 28 to 72 kPa and negative excess pore pressure is generated during shearing in the bio-cemented specimen. In addition, the normalized behavior has changed from contractive to dilative tendencies.

Changes in the shearing behavior of Nevada sand with 10% of silt are presented in Figure 4 as an example of bio-cemented silty soil behavior. The maximum shear strength of bio-cemented soil increased compared to the uncemented sample. The amount of excess pore pressure generated during shearing also decreased due to the bio-cementation. It is also important to note that the improvements in shear strength properties due to bio-cementation for the 10% silt specimen is not as significant as the clean Nevada sand specimen, since it does not exhibit the dilative tendencies the bio-cemented clean Nevada sand exhibited. In comparison, the bio-cemented silty sand specimens with 25% and 35% silt illustrated improved behavior, with similar or higher shear strengths and more dilative tendencies (Figure 5).

A summary plot of normalized shear stress versus silt content is presented in Figure 6 for both bio-cemented and uncemented silty sand. As illustrated in the plot, the normalized shear stress of the uncemented specimens slightly decreased up to 10 % of silt and then increased. The bio-cemented samples show a significant increase in normalized shear stress compared to the uncemented specimen at every level of silt content.

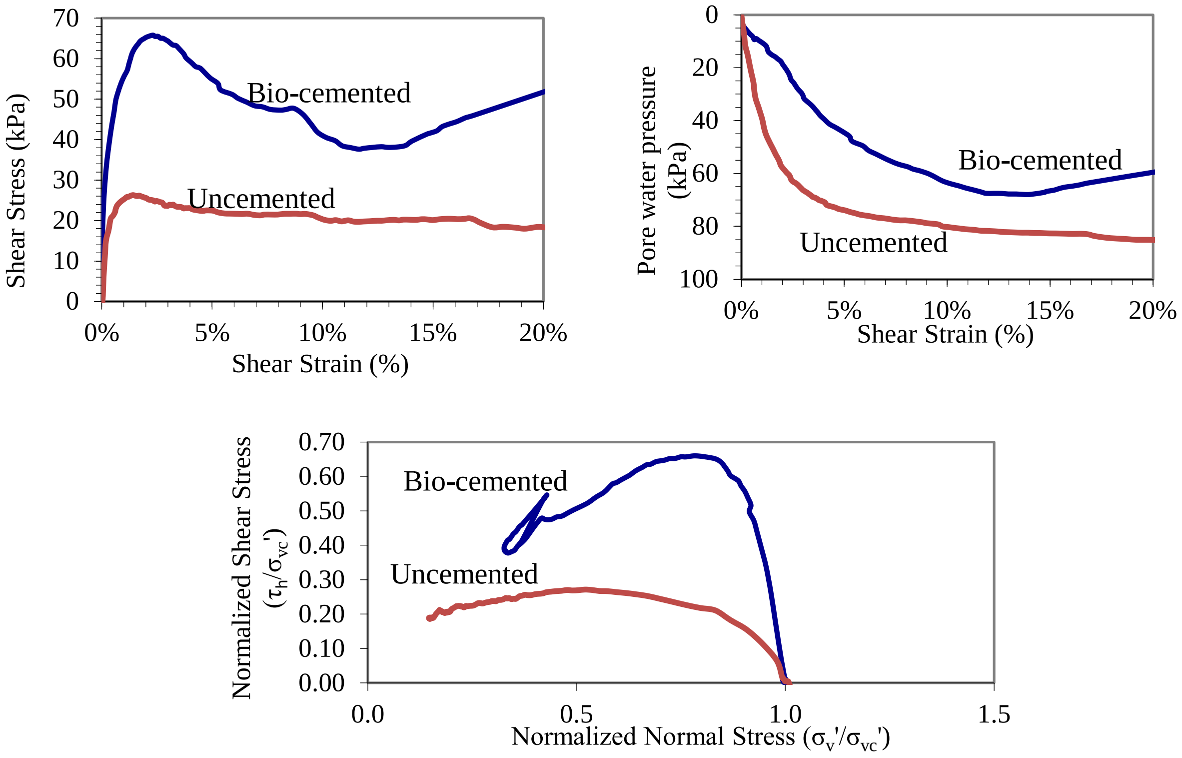

Figure 4. Undrained direct simple shear results of bio-cemented Nevada sand with 10% silt

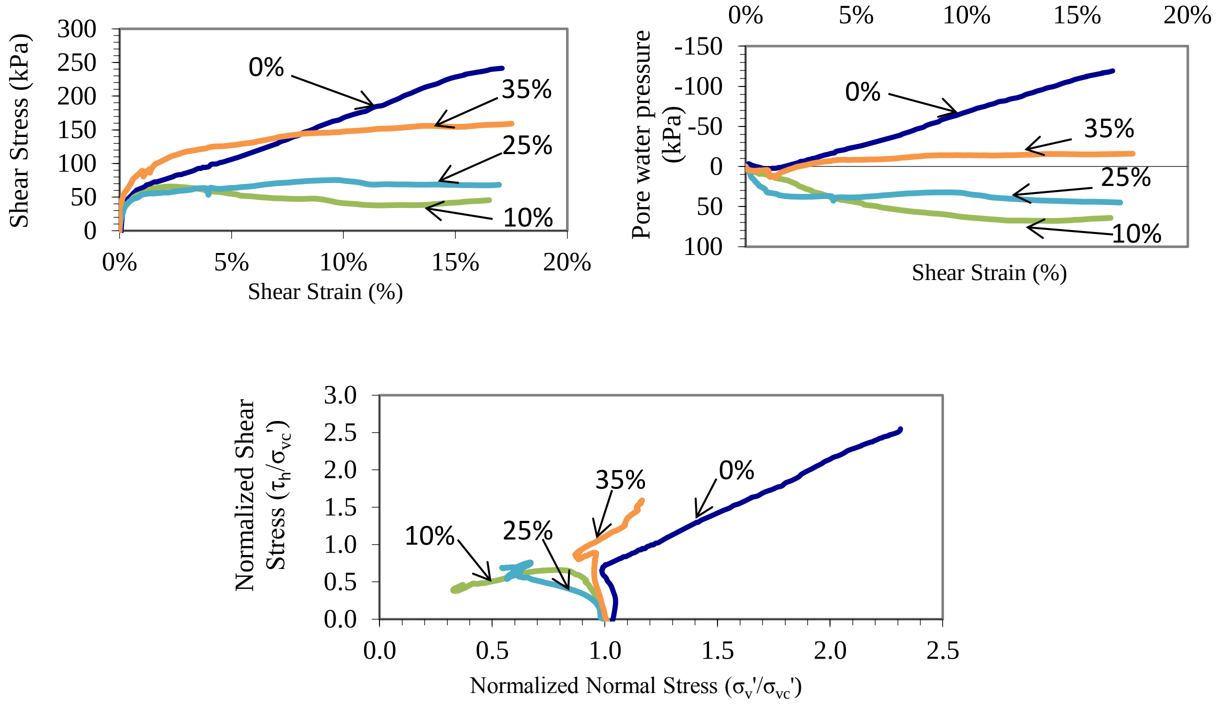

Figure 5. Bio-cemented silty soil behavior in undrained direct simple shear test

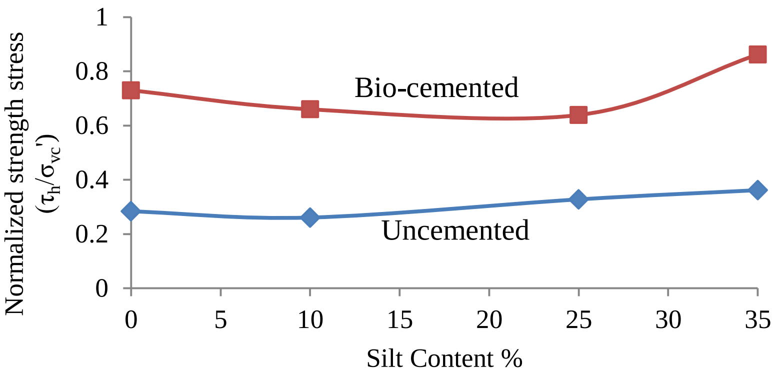

Figure 6. Changes in normalized shear strength with increase in silt content

Conclusions

The results obtained in this study show that MICP treatment method has a significant influence in increasing the shear strength properties of silty soil. MICP increases the shear strength of silty sand to similar strengths as the clean Nevada Sand. The excess pore pressures generated during shearing decrease due to the bio-cementation; however, the change in excess pore pressure generation for the bio-cemented silty soil is not as significant as seen with the clean Nevada sand where significant negative excess pore pressures were generated. Based on the results presented herein, bio-cemented silty sand with silt contents up to 35% and treated to shear wave velocities ranging from 400 – 500 m/s exhibit improved behavior with respect to liquefaction. In general, the improvement in undrained behavior of the bio-cemented silty soil illustrates that MICP is a promising ground improvement method for liquefiable silty sands.

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