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Development of Model Preparation Procedure for MICP-treated Sand in Centrifuge Tests

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ABSTRACT: Microbially-induced calcium carbonate precipitation (MICP) has been proven to be an effective method for mitigating soil liquefaction in laboratory tests and physical models. However, previous physical modeling where the entirety of soil within a model container is treated has limitations as it does not reflect field applications where treatment will have a limited spatial extent. A new modeling protocol was therefore developed to more accurately represent MICP treatment as it will occur in the field. This paper describes the protocol developed for constructing a centrifuge model using precast discrete MICP treated blocks placed within an uncemented stratigraphy. For this research, MICP blocks were precast using a PVC mold with embedded treatment ports. Ottawa F-65 sand was pluviated into the centrifuge model container to the desired elevation, the precast block was carefully lifted, inverted, and placed on top of the soil surface, and then model construction was completed by pluviating the remaining sand and saturating the model with a viscous fluid under a vacuum. Special handling techniques were developed and employed to place blocks with minimal disturbance for both the 1m and 9m radius centrifuge model containers. Shear wave velocity measurements were used throughout the process to track the improvement realized by MICP during the treatment process and then to evaluate the performance during earthquake shaking.

1 INTRODUCTION

Microbially-induced calcium carbonate precipitation (MICP) is a nature-based method for soil improvement. MICP treatment is enabled by ureolytic bacteria and precipitates calcium carbonate in the presence of calcium (Whiffin et al., 2007; DeJong et al., 2010; Al Qabany and Soga, 2014). The precipitated calcium carbonate modifies the soil properties through cementing particle-particle contacts to create shear strength, coating grains to increase density, and roughening grains to increase dilatancy. These changes in soil properties are generally known to increase resistance to liquefaction and reduce the consequences of liquefaction.

Centrifuge studies with MICP treated soils have shown increased liquefaction resistance and reduced vertical settlements compared to untreated soils (e.g., Montoya et al., 2013; Darby et al., 2019; Zamani et al., 2021; San Pablo et al., 2023). Montoya et al. (2013) and Darby et al. (2019) performed centrifuge tests using the 1m centrifuge at UC Davis by treating an entire soil profile with different levels of MICP and comparing the results with an untreated profile. The findings from these centrifuge test programs advanced fundamental knowledge, but were limited in that they did not realistically represent expected field conditions where a finite zone of soil at a project site would be treated within the broader subsurface. In addition, MICP cementation of the entire soil profile limited the strain levels that could be generated by earthquake shaking.

In practice, ground improvement performed to mitigate hazards due to liquefaction of the underlying soil will necessarily be limited in depth and lateral extent. Therefore, research was needed to investigate the performance of an MICP treated zone surrounded by untreated soils when subjected to seismic loading. Creating a finite treatment zone within a centrifuge model container presents challenges with respect to controlling the zone where the MICP treatment is applied. Accordingly, a method was developed to create precast finite MICP blocks where the dimensions of the block and magnitude of cementation could be controlled, and then this block could be placed within the centrifuge model container.

This paper describes the methodology developed to build a centrifuge model with a discrete MICP block and then presents representative data obtained within these blocks during centrifuge testing. This methodology was used at the UC Davis Center for Geotechnical Modeling (CGM) by Zamani et al.

(2019) for a 9m centrifuge test and San Pablo et al. (2023) for a 1m centrifuge test program. The performance of the MICP treated zone was evaluated using shear wave velocities obtained within the model from the start of MICP treatment through the completion of centrifuge testing. The integration of shear wave velocity measurements within the cemented zone enabled tracking of MICP formation during treatment and then performance during earthquake shaking, which provides necessary information for developing guidelines for field design of MICP treatment.

2 MODEL CONSTRUCTION

The general protocol followed by Montoya et al. (2013) and Darby et al. (2019) for executing centrifuge tests with MICP treatment is outlined in the flowchart in Figure 1. Incorporating zoned MICP treatment into the model requires enhancements to steps 2, 3, and 4. Representative model designs with finite MICP treated zones are shown in Figure 2 from two different centrifuge test programs, San Pablo et al. (2023) for the 1m centrifuge and Zamani et al. (2021) for the 9m centrifuge. As evident, the presence of an MICP treated zone with embedded sensors requires alternate model building methods. The following section details the MICP treatment process as adapted for centrifuge testing, how the process is implemented to apply MICP treatment to an entire model, and how the process is implemented to create finite MICP treated blocks and then include them in a full centrifuge model.

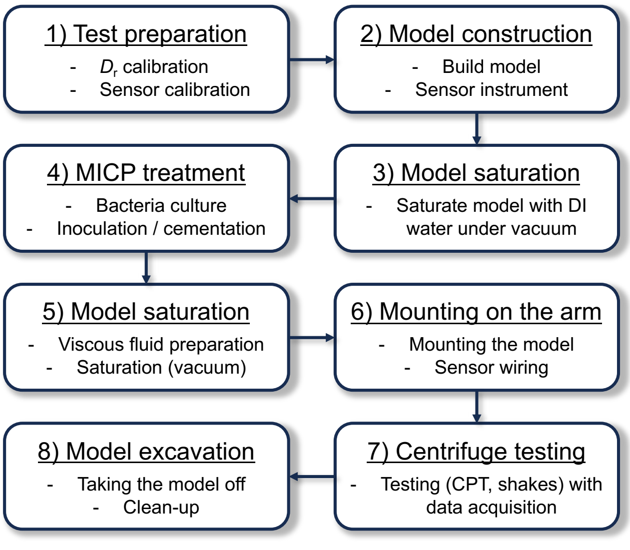

Figure 1. Flow chart of model preparation for centrifuge test.

2.1 Generalized MICP treatment

In the four test programs discussed herein, MICP treatment, conducted at 1g, followed the procedures outlined by DeJong et al. (2022). Before treatment, an overburden of 4 kPa was applied to the MICP model. The model was saturated with deionized (DI) water at a flow rate of 0.15 L/min using a peristaltic pump. Three different solutions were used for MICP treatment: (i) inoculation solution containing 50 mM urea, 0.2 g/L yeast extract, 42.5 mM sodium acetate, 100 mM ammonium chloride, and 1.28 g/L sodium hydroxide, (ii) flush solution containing 0.2 g/L yeast extract, 42.5 mM sodium acetate, and 12.5 mM ammonium chloride, and (iii) cementation solution containing 350 mM urea, 250 mM calcium chloride, 0.2 g/L yeast extract, 42.5 mM sodium acetate, and 12.5 mM ammonium chloride. In the inoculation phase, *Sporosarcina pasteurii*, a ureolytic soil bacteria, was cultured to achieve cell densities in the range of 2.18 – 2.81 × 10^9 cells/mL. The bacteria cells were diluted to 4 × 10^7 cells/mL and suspended in an inoculation. Six pore volumes of the inoculation solution were injected alternately from the bottom to the top and from the top to the bottom to produce more uniform cementation throughout the treatment zone and then retained for 24 hours without mass flux to allow for cell growth and attachment to the soil surface. To prevent the abiotic precipitation of calcite from the residual carbonate ions, 1.25 pore volumes of a flush solution were injected. This was followed by the injection of two pore volumes of cementation solution. The flushing and cementing processes were repeated every 24 hours until the desired improvement level, as assessed by shear wave velocity (V_s) measurements, was reached (typically, 2-3 treatments are needed to realize a ΔV_s of ~300 m/s).

2.2 Model preparation method for MICP treatment of the entire model

The entire soil profile was treated with MICP for the 1m centrifuge tests by Montoya et al. (2013) and Darby et al. (2019). The small, flexible shear beam (FSB) container, having dimensions of 494 mm long × 235 mm wide × 183 mm deep in model scale, was used. In each test, the soil was placed dry and sensors embedded. The profile was then saturated with DI water under vacuum conditions (Step 3 in Figure 1). Before starting MICP treatment (Step 4 in Figure 1), an overburden stress of 4 kPa (47.65 kg of load for a small FSB container) was applied. The inoculation solution was injected using a peristaltic pump, alternating the flow direction from the bottom to the top and vice versa. After 24 hours, the flush solution

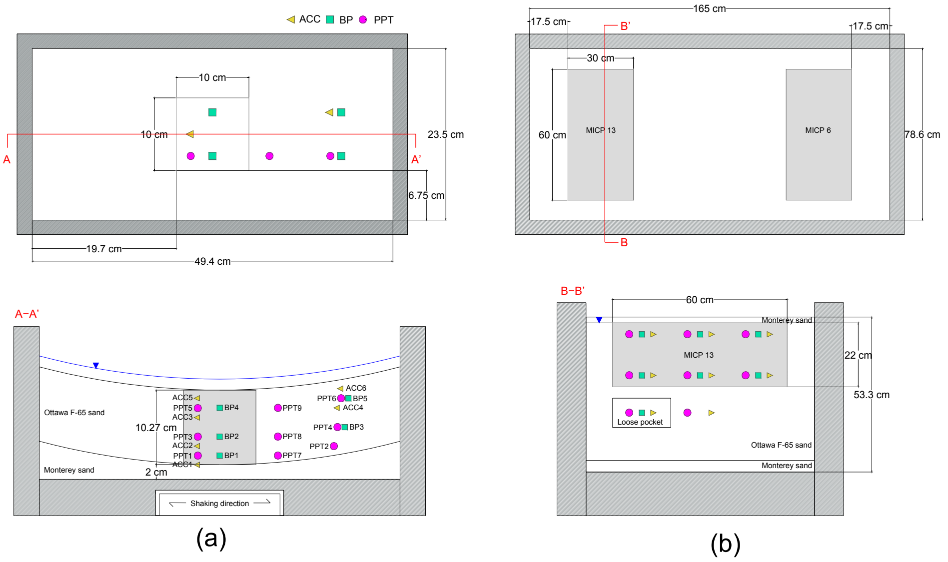

Figure 2. Plan and cross-sectional view of (a) a 1m centrifuge model (San Pablo et al., 2023) and (b) a 9m centrifuge model (Zamani et al., 2021).

was injected, followed by the injection of the cementation solution. This sequence was repeated at 24-hour intervals until a target shear wave velocity was achieved. After achieving the target shear wave velocity level, two pore volumes of viscous fluid were pumped through the cemented model from the base ports (Step 5 in Figure 1). Here, the viscous fluid was not injected under vacuum conditions for two concerns: firstly, the potential chemical reaction between precipitated calcium carbonate and carbon dioxide (CO_2) during the CO_2 flushing phase of vacuum application, and secondly, physical damage to the MICP block when vacuum pressure was applied. To avoid these issues, the model container was saturated first with de-aired DI water under vacuum conditions, and then a de-aired viscous fluid was injected at the end after MICP treatment. The overburden loads were removed, and then the container was ready to be used for the test.

2.3 Model preparation method for a model with discrete MICP block

The preparation process for the precast discrete MICP block and its placement technique within a model container (Step 2 in Figure 1) are described in this section. Due to the variation in MICP block size and the corresponding handling methods, the method for the 1m centrifuge test (San Pablo et al., 2023) is described first, followed by the method for the 9m centrifuge test (Zamani et al., 2021). The plan and cross-section view of the models are presented in Figure 2. A layer of dense Monterey sand was placed at the base of the container, followed by Ottawa F-65 sand (D_{50} = 0.2 mm).

In each 1m centrifuge test by San Pablo et al. (2023), an MICP block having a dimension of 10 cm × 10 cm × (3.78 to 10.27) cm (in model scale) was used within the FSB container described above. Model preparation images are shown in Figure 3. A PVC mold (10 cm × 10 cm × 15 cm) was used to produce the discrete MICP block. The mold was composed of a total of four separate side plates, and top and bottom caps were assembled with bolts and sealed with silicone to make it water tight. The mold had ports in the sidewalls to enable the cables from various embedded sensors (i.e., accelerometers (ACC), pore pressure transducers (PPT), and bender element pairs (BP)) to pass through. Both the top and bottom caps were configured for direct connection to the peristaltic pump used to apply the solution injections. A plastic filter was first placed against the bottom cap to retain the sand within the mold. The sand was air pluviated in lifts and then vacuumed flat at each depth of sensor placement. After pluviation was completed, a second plastic filter was placed on the surface. A layer of gravel (e.g., Figure 3b) was added to evenly distribute the overburden stress while allowing water flow. Finally, the top cap was placed, and 4 kPa of overburden stress was applied. The pore volume within the mold was approximately 0.8 L. The MICP treatment (inoculation and cementation) was performed following DeJong et al. (2022) as described in Section 2.1. The MICP treatment level was monitored with shear wave velocity (V_s) obtained from the benders. Soil in the mold had a V_s = ~130 m/s prior to treatment and a final V_s = ~460 m/s by the end of the three treatments (Figure 5a). After achieving the target shear wave velocity level, the treated soil within the mold was rinsed with DI water to stop any chemical reaction. Subsequently, the applied overburden loads were removed, and the PVC mold was split open and carefully removed, as shown in Figure 3b. The surface was trimmed to the target height. Then, the discrete MICP block was carefully transferred with a custom holder with designated spaces for sensor lines (Figure 3c) and then positioned at the predetermined height within the model container. The remaining lifts of uncemented sand surrounding the MICP block were then pluviated to complete model construction (Figure 3d). The entire model was then saturated with a viscous fluid under vacuum conditions.

For the 9m centrifuge test by Zamani et al. (2021), two MICP blocks having dimensions of 60 cm × 30 cm × 10 cm for the "MICP 6" zone and 60 cm × 30 cm × 22 cm for the "MICP 13" zone (both in model scale) were used in a large FSB container (165 cm × 78.6 cm × 58.2 cm) (Figure 2). These MICP blocks were prepared using two PVC containers (70 cm × 40 cm × 20 cm for MICP 6 and 70 × 40 × 32 cm for MICP13). Each container consisted of one bottom plate having 6 ports for fluid injection, two long-side plates where there were three ports each at the upper side, and two short-side plates. The lifting rings were installed to lift the block in the middle of the long-side plates. The plates were assembled and sealed with silicon. At the bottom, 5 cm of pea gravel was placed to provide a flat filter for the sand, and the rest of the model was constructed with air pluviation of the sand and sensor placement. In this case, the sensor wires were first routed horizontally to the boundary of the container and then turned upwards along the wall until they came out of the top of the mold (Figure 4a). A top 5 cm layer of pea gravel was added to provide 1 kPa overburden pressure. The pore volume for the MICP 6 and MCIP 13 blocks were 12 L and 26.4 L, respectively. Treatment again followed the procedure described in DeJong et al. (2022) until the target shear wave velocity was reached. The V_s increased linearly from ~70 m/s to ~560 m/s with three treatments (Figure 5b). After treatment, the mold was drained, the top 5 cm layer of gravel was removed, and the soil surface was gently trimmed to the desired size. As the large precast block, weighing ~150 kg, had low unconfined strength, making it difficult to handle, a vacuum lifting system was used. The MICP treated block was subjected to a vacuum from the bottom ports to keep the block stable within the mold and then lifted, inverted, and placed into the container using a crane (Figure 4b). After the placement of the MICP treated zone within the model, the supporting frame was detached, and the PVC mold was lifted with the crane (Figure 4c). The cemented blocks were then trimmed down to the design dimensions, removing about 5 cm from each side, which allowed the sensor wires to be reoriented to the horizontal positions (Figure 4d). Finally, pluviation of the untreated soil around the MICP blocks continued until the model was complete. It was important that this last step of pluviation around the zone occurred in a timely manner so that the side walls were not unsupported for a long period of time.

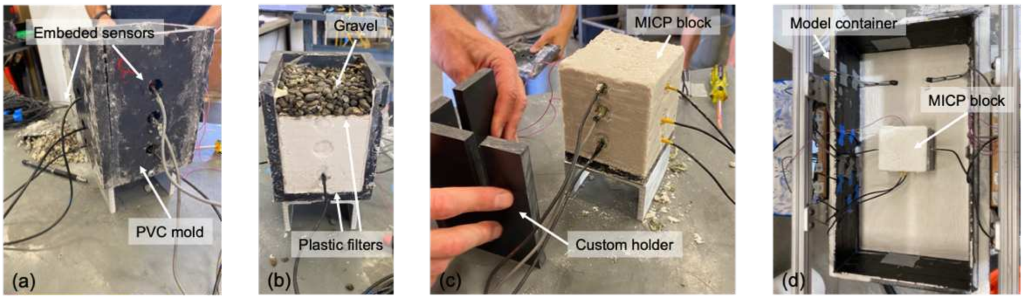

Figure 3. Model preparation images for the small container: (a) PVC mold with embeded sensors, (b) one side of the mold being removed, (c) MICP-treated block and a custom holder, and (d) placement of the MICP block into the model container.

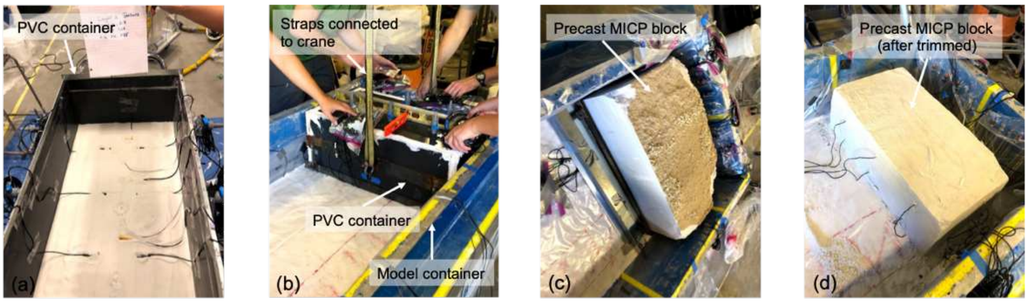

Figure 4. Model preparation images for the large container: (a) Building the MICP block within PVC mold with sensor embedment, (b) employing a vacuum lifting system and overhead crane to position the MICP block, (c) placing the MICP block into the model container, and (d) trimming the MICP block.

3 RESULTS AND DISCUSSION

Shear wave velocity (V_s) measurements were used to monitor the cementation level during treatment as well as the integrity of the MICP-treated zones (and the densification of the uncemented soil) during the earthquake shaking sequences. The measurements were obtained at different stages of the experiment, including during the MICP treatment and before and after each shaking event. During the MICP treatment stage the improvement level was monitored by V_s measured at 1g at two elevations (i.e., BP1 at the deep depth and BP2 at the middle depth in Figure 2a) for 1m centrifuge test and at two elevations (i.e., TR13-DP-S at a shallow depth of MICP13 block and TR13-DP-M at a middle depth of MICP13 block in Figure 2b) for the 9m centrifuge test.

Progressive changes in V_s throughout the entire testing sequence for the 1m (San Pablo et al., 2023) and 9m (Zamani et al., 2021) centrifuge tests are shown in Figure 5. In Figure 5, the data from the benders inside MICP blocks were denoted by empty symbols with colored lines (purple and green), and data from the untreated sand were denoted by solid symbols with black lines. The V_s increased linearly during treatment from ~130 m/s to ~460 m/s and from ~70 m/s to ~560 m/s for the small and large tests, respectively. However, V_s values were observed to decrease prior shaking, by ~70 m/s for V_s data in the 1m model and by ~100 m/s for the middle-depth bender in the 9m model. These reductions were likely due to the stress loading-unloading cycles induced from spinning up and spinning down the centrifuge model before the first shake event, while CO_2 flushing could have also had a minor contribution. The shear wave velocity is related to shear stiffness, and the MICP treatment increases soil stiffness by bonding soil particles together. The precipitation of cementation from MICP treatment occurs primarily at particle contacts, and this cementation may be weakened as contact stress increases due to loading from centrifuge spin-up.

Both research teams observed degradation of stiffness due to repeated shaking of increasing amplitude. V_s was measured before and after each shaking event in the precast blocks and within the untreated soil. In the 1m test (Figure 5a, San Pablo et al., 2023), there were only minor decreases in V_s until the 0.16g Shake 3 (S3) event, while a significant drop was observed after the 0.71g Shake 4 (S4) event. This means that the S4 shaking event was sufficiently large enough to damage the MICP zone, reducing the integrity of the cementation bonds between particles and resulting in approximately the same V_s as the untreated soils (i.e., BPs 3 and 5 in Figure 5a). Minor progressive increases in V_s were observed in the untreated zone due to the densification of uncemented soil induced by the shaking events. The results from the 9m experiment were similar to those of the small test. That is, V_s in the MICP block decreased progressively with each shaking event, reaching values similar to the untreated zones after S3 for TR13-DP-M and after S5 for TR13-DP-S (as shown in Figure 5b).

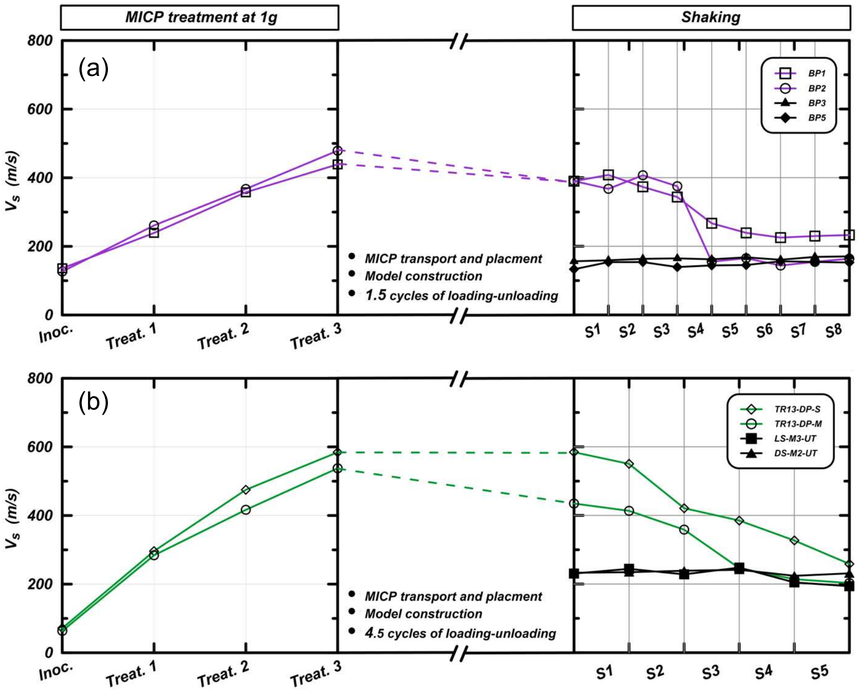

Figure 5. Bender data with MICP treatment and shaking process for (a) the 1m centrifuge model and (b) the 9m centrifuge model.

4 CONCLUSION

This study has enhanced the understanding of soil improvement through MICP by introducing a centrifuge model preparation method with a discrete MICP block. This model can more accurately represent MICP treatment in the field compared to the model where the entire soil within a container is treated, which has limitations in reflecting field applications with limited spatial extent. Our method integrates precast discrete MICP blocks into centrifuge models to evaluate soil liquefaction mitigation strategies. While specific procedures varied based on the target size of the MICP block, PVC molds were used for the MICP treatment. Following the completion of the cementation, the MICP block was carefully lifted, inverted, and placed on top of the soil surface with a custom holder for a small block and a vacuum lifting system for a large block. The performances of the MICP treated block and untreated soil during shake events were assessed with the shear wave velocities (V_s). The V_s in the MICP treated block demonstrated decreases, indicating a loss in stiffness, while V_s in untreated soil slightly increased due to densification. The findings from this study can be used to make geotechnical applications more accurate and practical in areas prone to liquefaction.

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