Bio-Cementation for Protection of Coastal Dunes: Physical Models and Element Tests

E. Yazdani, S.M.ASCE[1]; B. Montoya, M.ASCE[2]; M. Wengrove, M.ASCE[3]; and T. M. Evans, M.ASCE[4]

[1]Yamamuro Fellow and Graduate Research Assistant, School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR
[2]Associate Professor, Dept. of Civil, Construction, and Environmental Engineering, North Carolina State Univ., Raleigh, NC
[3]Assistant Professor, School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR
[4]Professor, School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR

ABSTRACT

Erosion of coastal dunes during storm events is an increasingly common problem in the face of global climate change and sea-level rise. To investigate the efficacy of bio-mediated ground improvement for reducing the impact of extreme events such as hurricanes, a near-prototype-scale experiment was performed. In the experiment, a model sand dune was constructed in a large wave flume and divided into treated and untreated zones which were instrumented with pressure and moisture sensors. One of the treated sections was subjected to a surface-spray technique to apply bio-cementation. Afterward, the dune was subjected to a discretized severe storm event (a scaled Hurricane Sandy) consisting of 25 trials. Surge runup and drawdown cause surface erosion and also internal instability due to liquefaction. Pore pressure sensors were embedded in different depths of the dune to study the pressure fluctuations during the wave action and the consequent momentary liquefaction phenomenon. Momentary liquefaction leads to detachment of fine sand particles and the initiation of internal erosion and sediment transport. In this project, remote assessment technology (lidar) was used between each trial to evaluate the performance of the dune under the surge flow by detecting the eroded volume of the sand. To better quantify material properties in-situ, a series of triaxial experiments were conducted on bio-cemented cores taken from the formed crust. The strength and stiffness of the cemented sand were measured under different drainage conditions. Element test results indicate a significant increase in critical bed shear stress (τ_c) due to cementation.

INTRODUCTION

There are 7.8 million km^2 of coastal shoreline counties in the United States with a population of 10 million people who are vulnerable to coastal hazards (Bryant et al. 2019). Global climate change and sea-level rise are a significant threat to the resilience of coastal communities. Coastal dunes constitute a protective element along coastlines to protect the inland area from the consequences of severe storms. These dunes are vulnerable to surge erosion and overtopping under elevated water levels and wave heights.

Conventional methods of coastal management, such as coastal walls, are increasingly becoming less effective due to the combined influences of climate change, development of coastal communities, and the increasing incidence and severity of storms. Therefore, risk management strategies seek sustainable solutions to reduce the effects of extreme events on the morphology of coastal dunes and therefore, on the coastal communities that are exposed to these hazards (Temmerman et al. 2013). Interest on using natural and nature-based features (NNBF) as sustainable solutions versus artificial coastal protection is steadily increasing (Bridges et al. 2015).

Due to the widespread use of conventional ground improvement methods, the environment is exposed to the adverse effects of producing the materials (cement, lime, etc.) needed for these methods. Microbially-induced calcite precipitation (MICP) is a bio-mediated cementation technique where, through a series of biochemical reactions, calcite is precipitated as a by-product (e.g. Feng and Montoya, 2017). In MICP, natural soil bacteria catalyze urea hydrolysis and, in the presence of calcium ions, cementation that is similar to natural cementation is induced at soil particle contacts (Molenaar and Venmans, 1993; DeJong et al., 2013; Mujah et al. 2017). Due to the bonding effects, the strength parameters, stiffness, and erosion resistance of the soil are improved (Gomez et al., 2014; Montoya et al., 2018). MICP has been applied to various ends, such as ground improvement (DeJong et al., 2014), bio-blocks (Javadi et al., 2018) and self-healing concrete (Lee and Park, 2018).

The performance of MICP-bonded soil matrices under loading has been extensively investigated through experimental and numerical studies (Cheng et al., 2013; Nafisi et al., 2020; Evans et al. 2014; Feng et al, 2017). The shear strength improvement that can be realized has boosted the interest in using microbially induced calcite precipitation (MICP) in field-scale applications (Van Paassen, 2011; Shanahan and Montoya, 2016). The authors have investigated the efficacy of MICP for reducing the impact of extreme events on dune erosion resistance in an effort to introduce bio-cemented dunes as a NNBF in coastal risk management. For this purpose, two near-prototype-scale experiments with different levels of cementation were subjected to a discretized severe storm. To provide better insight into material properties *in-situ*, a series of laboratory element tests were conducted on the formed surface crust. The model sand dunes were instrumented with pressure and moisture sensors to capture the pore water fluctuation and subsurface water table changes during the wave action. Remote sensing technology (lidar) was used between each trial for morphological change detection as a metric to evaluate the performance of the dune under the surge.

MATERIALS AND METHODS

The experiment was started with a large-scale dune construction followed by the implementation of a bio-mediated technique to treat the surface of the dune. Afterward, a hurricane condition was simulated to evaluate the morphology changes of the dune during the storm.

Wave characteristics. A near-prototype scale dune was constructed in the O.H. Hinsdale Wave Research Laboratory (HWRL) Large Wave Flume (LWF) ($104\,m \times 3.7\,m \times 4.6\,m, L \times W \times D$) at Oregon State University to investigate the performance of the bio-treated dune during a severe storm event. Surface treated and untreated zones were subjected to a discretized hurricane (scaled Hurricane Sandy) consisting of 21 individual wave trials each containing 300 irregular waves. Water level, wave height, and wave period were matched to the scaled Hurricane Sandy. Because hurricanes have irregular patterns in increasing water levels, hurricane Sandy was chosen as the forcing condition to create slow ramp-up erosion. The Texel-Marsen-Arsloe (TMA) spectrum (Bouws et al. 1985a) was used to convert the fitted parameters to time series (Figure 1). The obtained design condition is representative of Hurricane sandy and expected to have similar consequences.

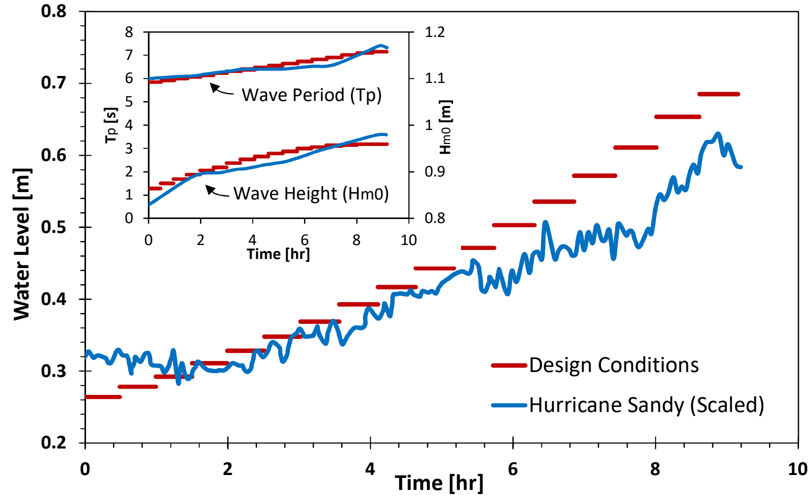

Figure 1. Wave characteristics.

Dune Material. Approximately 1000 m^3 of beach sand was harvested from Newport, OR and used for constructing dunes in the LWF. The dunes were compacted in 30-cm layers. Dynamic cone Penetration (DCP) testing, in accordance with ASTM D6951-09 (2009), was employed to confirm the compaction of the constructed dunes consistent with natural dunes in the field. Physical properties (specific gravity, G_s; extreme void ratios, e_{max} and e_{min}; uniformity coefficient, C_u, curvature coefficient, C_c, and hydraulic conductivity, K_{sat}), including grain size distribution, of the sand are given in Figure 2.

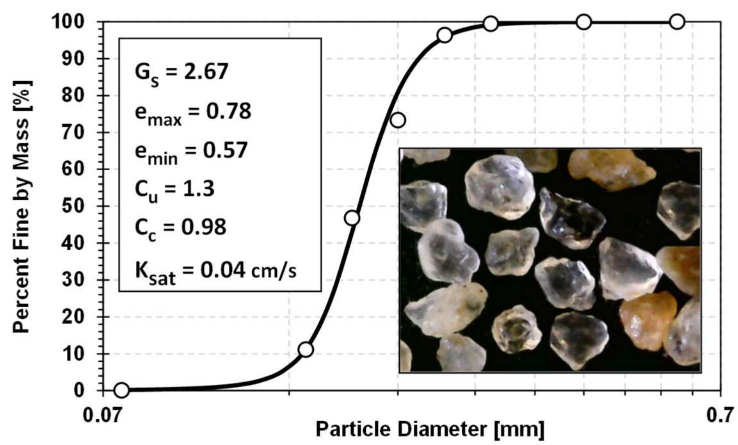

Figure 2. Grain size distribution and physical characteristics of dune sand.

MICP Treatment. After dune construction, biological and chemical solutions were sprayed on the surface of the dunes. In the first experiment, the treated zone was a surface with a width of 1.22 m and a length of 7.4 m and in the second experiment, the treated zone had a width of

1.85 m and a similar length as the first experiment. Two sets (for the first dune) and three sets (for the second dune) of 24 sprayers were evenly distributed along the dunes to apply the surface treatment (Figure 3). To ensure a uniform crust on the surface of the dunes, the spacing between nozzles was selected such that the influence zones overlapped.

Figure 3. Surface spraying setup and used for the second dune (left); treated and untreated zones durning testing (right).

The surface of the dune was treated using a common soil bacterium known as *Sporosarcina pasteurri* (American Type Culture Collection (ATCC) 11859) to increase shear strength and stiffness (DeJong et al., 2014; Feng and Montoya, 2017). The biologic organisms were inoculated aerobically at $30°C$ in a liquid medium consisting of ammonium and yeast extract (ATCC 1376) to grow bacteria to the target population density. Optical density at a wavelength of 600 nm (OD_{600}) was used to estimate the concentration of biomass in the growth solution, with a target value of $0.8 \leq OD_{600} \leq 1.2$ to ensure the appropriate number of microorganisms in the solution.

A two-phase spraying process was used for the treatment: a biological solution followed by multiple cementation solutions. The time between biological and cementation solution spraying was three hours. The biological and cementation solutions were sprayed on the surface of the dune at a constant flow rate. The chemical recipe is presented in Table 1.

Table 1. Chemical recipe for the treatment

Chemicals	Biological solution concentration (mM)	Cementation solution concentration (mM)
Urea	300	300
Calcium Chloride	0	100

Two levels of cementation (lightly treated and heavily treated) have been considered in this research. Different treatment cycles and solution volumes were used to achieve different levels of cementation. The first dune was considered to be heavily cemented thus, 24 cycles of $450\ L$ of biological and cementation solutions were used for this purpose (5 and 19 cycles of the biological and cementation solutions, respectively). For the second, lightly treated dune, 20 cycles of $160\ L$ of the biological and cementation solution were used (4 and 16 cycles of the biological and cementation solutions, respectively).

Real-time monitoring is necessary for the control and management of the bio-cementation process. To this end, non-destructive measurements of shear wave velocity can be used to identify the levels of cementation indirectly. Pairs of bender elements were embedded in different depths from the final surface of the dunes to monitor the calcite precipitation process. The goal for the level of cementation for the first and second dunes was to raise the corresponding shear wave velocity to 1000 m/s and 600 m/s, respectively. As the amount of cementation in the soil increases, the shear wave velocity also increases due to enhanced coupling at particle contacts.

REMOTE SENSING ASSESSMENT OF DUNE PERFORMANCE

Remote sensing technology was used to assess the efficacy of the treated dunes during the simulated storm surges. A Reigl Z390i lidar and a 3D BLK360 scanner were employed for capturing the evolution of the dune profile between wave trials. Dunes were scanned prior to the first trial to develop the baseline for tracking the erosion during the next trials. Dune scarp and morphological development in treated and untreated zones were used to evaluate the performance of the bio-cemented dunes under wave loading.

A cross-shore cross-section of the dunes during the experiment is shown in Fig. 4. Surge-induced erosion and scarp formation are evident in the untreated zone while the heavily surface-treated zone indicated high resistance to erosion in face of the wave action. Two different mechanisms result in dune erosion. First, initiation of grain movement due to exceeding the applied shear stress from the critical shear stress. Second, the internal erosion that is caused by momentary liquefaction as a consequence of PWP generation during the wave runup and drawdown. Fig. 4 confirms that the heavily cemented dune indicates an acceptable performance in resisting erosion during the wave actions. As waves collide with the cemented crust, maximum erosion occurred at the toe. The exposed crust at the toe dissipates the wave energy and the high critical shear stress of the heavily treated surface caused the treated zone to remain intact after 22 trials. Due to lack of energy dissipation, waves travel longer landward in the untreated zone and in addition, as a result of infiltration from swash, subsurface hydrodynamic processes impact the PWP regime near the dune surface and cause internal instability. As the wave trials progressed, the untreated zone exhibited progressive geomorphological changes and an escarpment line of $0.65\ m$ has been formed. The lightly treated dune shows more vulnerability to erosion compared to the heavily treated dune. Specifically, substantial fragmentation of the treated zone occurs in the lightly treated dune, whereas similar behavior is not observed in the heavily treated dune (Figure 4).

LABORATORY ELEMENT EXPERIMENTS

Test Procedure and Sample Preparation. In addition to using remote sensing to capture the morphology changes of dunes in face of wave actions and to provide insight on the effect of different levels of bio-cementation on critical shear stress of treated dunes, series of compression triaxial tests were conducted on cores taken from the surface crust after the storm simulation. The thickness of the formed crusts was approximately 35 cm and 25 cm for the heavily and lightly treated dunes, respectively. Cemented chunks from the lightly and heavily treated dunes were brought to the laboratory afterward, cylindrical cores were precisely taken from the cemented chunks (Figure 5). The height and diameter of the prepared specimens were about 7.2 mm and 3.6 mm, respectively. Tests were performed under confining pressures of 5, 25, 50, 200 and, 400 kPa. The saturation process was performed using CO_2 percolation for 30 min followed by flushing water from the bottom of the specimens. Prior to testing, back pressure was applied to ensure in all cases B-value exceed 0.95. Specimens were isotopically consolidated under scheduled confining pressure and then sheared at a strain rate of 2.5 $\%/hr$ under drained conditions.

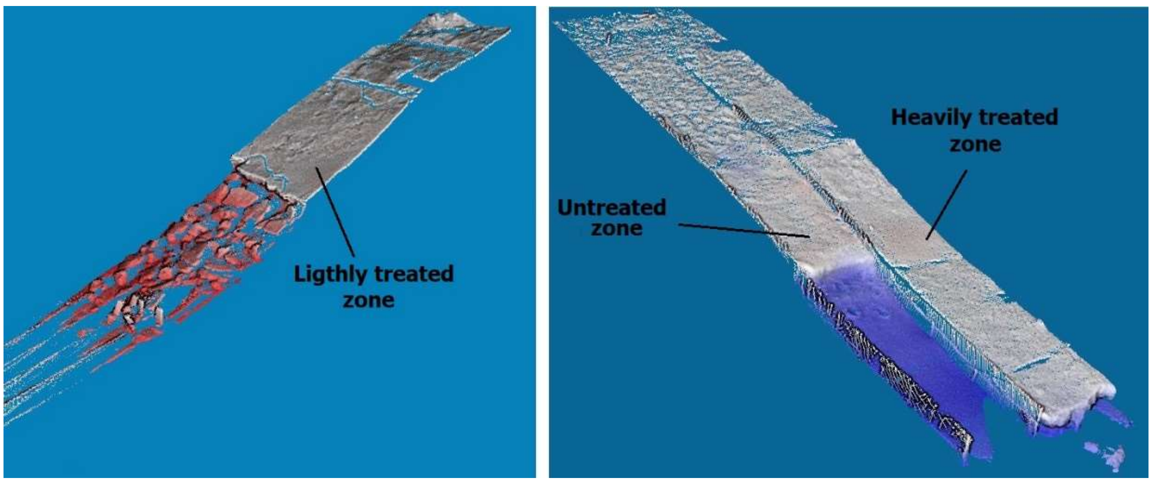

Figure 4. Changes in dunes profile during the experiment after trial #15, lightly treated dune (left) and heavily treated dune (right).

Figure 5. A bio-cemented chunk from the treated surface (left) and prepared specimens for triaxial tests (right).

Measurement of Calcium Carbonate Content. After the shearing stage was completed, specimens were divided into four 18 mm sections along their heights. The oven-dried samples were washed with 1 M HCl. For this purpose, samples were soaked in 30 ml of acid solution (adding in multiple steps) and rested until no more CO_2 bubbles were produced. afterward, dissolved calcium carbonate and acid solution extract carefully and soil was rinsed multiple times. This process was repeated several times and finally, samples were oven-dried. Calcium carbonate content can be easily measured from oven-dried masses before and after the acid washing process. The same procedure was used for untreated soil to eliminate the error associated with dissolving soil particles.

RESULTS AND DISCUSSION

Distribution of Calcium Carbonate. The distribution of calcium carbonate content along the samples' height is shown in Figure 6. Results confirmed that the first dune was heavily treated with a $CaCO_3$ content average of 4.8% (w/w) while the second dune was lightly treated with a $CaCO_3$ content average of 2.4% (w/w). It's clear that that the amount of $CaCO_3$ has been uniformly distributed along with the height of the specimens.

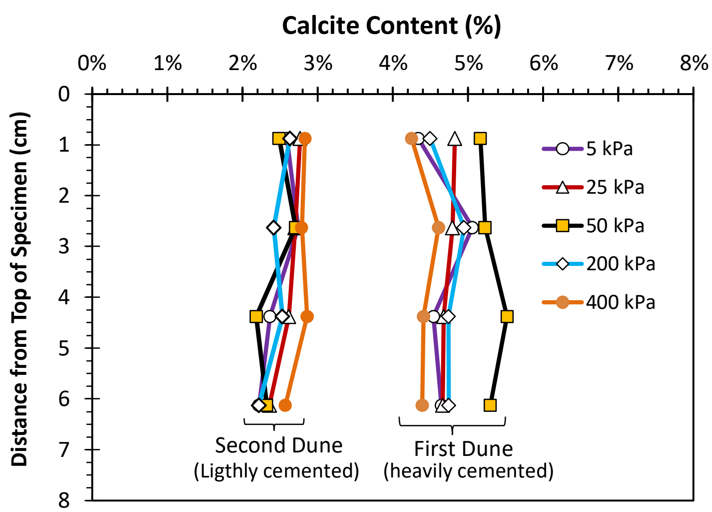

Figure 6. Calcium carbonate distribution along the height of triaxial specimens.

Effect of MICP on Stiffness of Sand. The level of cementation influenced the response of the specimens to monotonic loading. Figure 7 shows that heavily cemented specimens experienced higher strength and stiffness at small strains compared to specimens taken from lightly treated dunes or untreated ones. Due to the lower compaction of the second dune, the initial void ratio of lightly cemented specimens was greater than heavily cemented and also untreated specimens. Visual observation after the experiment confirms that the majority of the interparticle bonds in lightly cemented specimens had been broken while a large part of the heavily cemented specimens remained intact.

Soil stiffness is significantly affected by confining pressure and void ratio. Initial tangent modulus (E) values of the treated and untreated sand were obtained from stress-strain curves. Results have been normalized by the atmospheric pressure (P_a) and plotted versus confining pressure (σ_3) in Figure 8. It can be inferred from the presented data that confinement profoundly affected the initial modulus of untreated sand while cemented sand is less influenced by confining pressure variations. MICP increases the shear stiffness of sand significantly and this improvement especially at the lower level of confining pressure is more distinguished. These findings are consistent with those presented by Montoya et al. (2013) and Feng and Montoya (2016).

Failure Mechanism. The post-failure specimens under two different levels of confinement are depicted in Figure 9 and it can be inferred that lightly cemented samples experienced the bulging type of failure while the shear band mechanism developed due to failure in heavily cemented specimens. The small particle size of the sand ($d_{50} = 0.17\ mm$) in this experiment leads to the formation of a narrower shear band (Desrues and Ando 2015; Frost et al. 2004; Evans and Frost 2010). Besides, due to the high level of cementation, particles bond will be stronger in the vicinity of the failure surface that causes lower contribution in shear band formation hence, these factors force the shear bond to become narrower. A qualitative explanation can be understood from Figure 9 that the shear band failure type (usually develops in dilative behavior) that happened in lightly treated specimens at the lower confinement have changed to the bulging failure type (an indicator of contractive behavior) at higher confinements. But, heavily treated specimens have indicated the shear band failure mechanism (and therefore, dilative behavior) regardless of the confining pressure level.

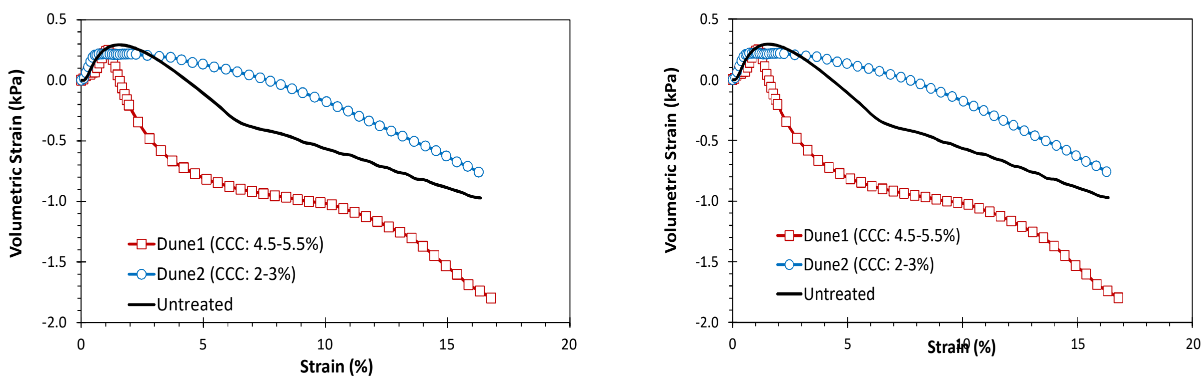

Figure 7. Stress-strain behavior of untreated and untreated sand under 200 kPa of confinement (CCC: calcium carbonate content).

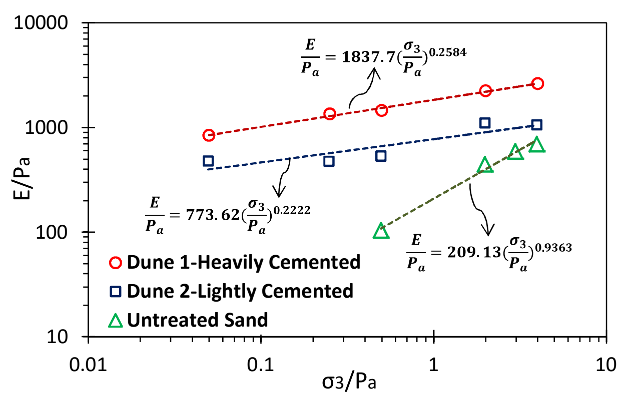

Figure 8. Stiffness of the treated and untreated sand.

a) Heavily cemented (25 kPa) b) Heavily cemented (400 kPa) c) Lightly cemented (25 kPa) d) Lightly cemented (400 kPa)

Figure 9. Failure mechanisms in triaxial compression at two confining stresses for specimens with varying cement contents.

CONCLUSIONS

To evaluate bio-cemented dunes as a NNBF solution to coastal dunes protection, near-prototype-scale experiments were subjected to a scaled hurricane condition. The efficacy of MICP for reducing the impact of extreme events on dune erosion resistance was evaluated using remote sensing technology to capture the evolution of the dune profile between wave trials, and a series of laboratory triaxial compression tests to track the changes in strength parameters of treated and untreated sand. Lidar data demonstrates that the treated zone reduces the susceptibility of sand dunes in face of severe storms.

Triaxial tests results demonstrated that an increase in cementation level results in stronger bonds and leads to an improvement in stiffness and shear strength of sand. Initial tangent modulus values are significantly affected by confining pressure level and level of cementation. Bond breakage was observed at failure surface and its vicinity region in highly treated samples regardless of confining pressure while in lightly treated specimens especially at higher confining pressure levels, remarkable degradation of cementation occurred at all locations along the height of specimens.

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