The Effect of Level of Cementation and Geometry on Stability of Cemented Coastal Bluffs and Slopes

Pegah Ghasemi, S.M.ASCE[1]; and Brina M. Montoya, Ph.D., P.E., M.ASCE[2]

[1]Dept. of Civil, Construction, and Environmental Engineering, North Carolina State Univ., Raleigh, NC. Email: pghasem@ncsu.edu
[2]Dept. of Civil, Construction, and Environmental Engineering, North Carolina State Univ., Raleigh, NC. Email: bmmorten@ncsu.edu

ABSTRACT

Coastal bluff erosion and recession are among the common mechanisms altering the geomorphology of the coastline in California. The accelerated erosion rate increasingly threatens the stability of structures located on these bluffs. Previous researchers have investigated the effect of material properties and strength on the generation of the shear plane and failure modes of coastal bluffs and cliffs. Monitoring the morphology of the moderately cemented coastal bluffs with time has indicated that a comparison of material strength with the expected in situ minor principal stress distribution can be used as a criterion to assess bluff stability. However, the effect of varying factors such as cementation levels and bluff geometry and dimensions on stress distribution patterns and material properties that determine bluff failure susceptibility requires further investigation. While bond breakage and disturbance during sampling and transportation undermine the quality of recovered soil samples, artificial cementation methods (e.g., Portland cement) may not properly replicate the natural formation processes. Instead, microbially induced carbonate precipitation (MICP) is a ground improvement method that simulates the cementation processes that occur in natural geological settings. This method harnesses the activities of bacteria to generate cementitious precipitation among soil particles. The formation of the cementing agent improves the mechanical properties of the soil. In the past two decades, extensive studies have been devoted to understanding the cementation formation mechanism and the improvement of mechanical properties that can be used as a proxy for natural cemented soil for stability analysis. In the study presented herein, a series of FEM models were developed in SIGMA/W software. The effect of the different cementation levels and variation of bluff geometry on minor principal stress distribution was investigated. Results of the study demonstrated that although the cementation level of the materials determines the failure mode, the stress distribution mainly depends on the bluff geometry. The obtained results offer further insights into the failure mechanism of coastal bluffs as well as MICP-treated slopes for future field implementation of this soil improvement method.

INTRODUCTION

Coastal cliffs and rocky coasts are steep landforms that are prevalent on the west, northeast, and Great Lakes coasts of the United States (Hampton and Griggs 2004). The constituent materials of such landforms include a wide range of very hard metamorphic rocks, sandstone, and very weak rocks including siltstones and unconsolidated sands (Bird 2016). About 72% of California's diverse coastline is comprised of steep coastal cliffs with hundreds of meters of height. Lower relief cliffs or bluffs typically eroded into uplifted marine terraces with a few meters to a maximum of 100 meters in height (Griggs and Patsch 2004). The terms “bluff” and "cliff" are often used interchangeably and refer to slopes with relatively low and high material strength, respectively. Bluffs/cliffs are slopes with a minimum height of about 3 m and a minimum 2:1 (V: H) inclination beyond which damage resulted from their failure may be significant (The City of San Diego 2004). A typical coastal cliff inclination typically ranges between 40° and 90° (Hampton and Griggs 2004). Such landforms play a critical role in the development of coastal communities by supporting properties, transportation infrastructure, and lifelines. Therefore, their instability and failure can result in substantial damage and economical loss.

Bluff failure can be initiated by different physical processes such as seepage, toe erosion, drying/wetting cycles, and seismic forces among others. Each triggering mechanism can result in different failure modes such as planar shear and rotational shear (Collins and Sitar 2011). Therefore, to select the appropriate stability analysis method, it is essential to understand the failure mode and mechanism associated with any bluff (Collins and Sitar 2011). Long-term monitoring of bluffs in Northern California indicated two distinct failure modes according to the soil properties and unconfined compression strength (UCS) of the materials (Collins and Sitar 2008). Bluffs with a relatively low material strength (i.e. weakly cemented soils with UCS< 30 kPa) indicated shear failure with failure planes parallel to the slope inclination. Bluffs with UCS values ranging between 30 and 400 kPa were classified as moderately cemented materials and demonstrated exfoliation and tension failure modes. Results indicated that in the latter case, with time the bluff profile evolved in a way that minor stress across the slope was larger than the material tensile stress. Considering the extremely diverse coastline, the effect of varying factors (e.g., cementation levels, bluff geometry, and dimensions) on stress distribution, particularly tensile stress, to determine the bluffs' failure susceptibility requires further investigations. However, difficulties and uncertainties associated with soil sampling, such as profile heterogeneity and cementation bond breakage during sampling and transportation, complicate efforts to identify the actual material properties. Similarly, the use of artificially cemented specimens, such as sand samples treated with Portland cement, may also result in different mechanical properties since the precipitation formation processes and resulted particle-particle bonds in natural settings may differs with that of artificially cemented ones.

Microbially induced carbonate precipitation (MICP) is a bio-mediated soil improvement method that results in the formation of calcium carbonate precipitation among soil particles. Precipitation generation may be a result of the biological activities of indigenous or exogenous soil bacteria such as *Sporosarcina pasteurii* that generate carbonate and ammonium (Gomez et al. 2017). Generated carbonate bonds with the available calcium and precipitates in the form of calcium carbonate minerals on soil grains and particle-particle contact points. As a result, MICP improves the engineering properties of soil through densification and bonding (DeJong et al. 2010). MICP has gained popularity over the past two decades and many researchers have investigated the underlying mechanisms and processes that result in the enhancement of soil's shear and tensile strength, stiffness increase, pore space, and compressibility reduction in controlled environments (Feng and Montoya 2016; Ghasemi et al. 2022; Montoya and DeJong 2015; Nafisi et al. 2019; Zamani et al. 2019). More recent large-scale and field applications of this technique have also demonstrated promising implications for coastal applications such as erosion susceptibility reduction and shoreline strengthening projects (Ghasemi and Montoya 2022; Gomez et al. 2015, 2017; Montoya et al. 2021; Terzis et al. 2020) The established body of literature on MICP-treated soils can be used as a proxy to understand the behavior of naturally cemented soils and landforms such as bluffs/cliffs that are prevalent in the geological setting.

This study builds upon the findings of the study presented by (Collins and Sitar 2011). In the study presented herein, the effect of different cementation levels and variations of bluff geometry on minor principal stress distribution and bluff failure was investigated. Simplified bluff geometries were developed in SIGMA/W software. Characteristics of the constituent materials of the cemented bluff were assigned according to the properties of the MICP-treated Ottawa 20-30 sand treated to varying cementation levels (Nafisi et al. 2020). The obtained distributions of the minor principal stresses across the modeled bluffs were compared with the tensile strength of the MICP-treated soils to understand the critical regions and to make conclusions about the equilibrium profile of the cemented coastal deposits. The results of this study can also provide implications for future MICP-field implementations to stabilize sandy slopes and landforms such as coastal dunes and lightly cemented bluffs.

MODEL DEVELOPMENT

Linear elastic, finite element analysis was performed to investigate the effect of geometry and varying cementation levels on the stability of cemented bluffs. Table 1 demonstrates the geometry and properties of the analyzed models. The bluff geometry studied by Collins and Sitar (2011) was simplified and used as a baseline for the analysis as shown in Fig.1. Models were developed in SIGMA/W (GeoStudio 2021, Alberta, Canada) to determine the in-situ stress distribution (i.e tensile and compression stresses) across the bluffs. Figure 1 presents the configuration of the materials, boundary conditions, and height parameters (i.e. toe height and bluff height) used for the numerical modeling. Mesh sizes smaller than about 3% of the bluff height (H_b) were used for the analysis.

Table 1. Characteristics of the modeled bluffs.

Case	inclination angle (°)	H_b: bluff height (m)	H_t: toe height (m)	Cemented material	Studied factor
1	45	25	10	M and H	cementation level
2	45, 60, and 75	25, 36, and 66	10	M	inclination
3	45	21, 25, and 29	6, 10, and 14	M	toe height

As it was stated earlier, the objective of the study was to investigate the effect of geometry and cementation level on coastal bluff stability. Therefore, the analysis was performed on models developed with varying levels of cementation (i.e. Case 1), slope inclination (i.e. Case 2), and toe height (i.e. Case 3) to determine stress distribution across the cemented bluffs. Details of the input material properties are shown in Table 2. Bedrock and untreated sand were modeled with the same material properties used by (Collins and Sitar 2011). No information on the properties of bluff materials with varying cementation levels was available. Therefore, input parameters for modeling soils with varying cementation levels were selected according to the material properties of Ottawa 20-30 MICP-treated sand under controlled conditions (Nafisi et al. 2020). Due to grain size similarities with the field soil, Ottawa 20-30 sand was selected for modeling. The elastic modulus, unit weight, and void ratio associated with moderately and heavily cemented levels were selected according to properties of MICP-treated sand with the mass of calcium carbonate precipitation of 1.5 and 4.2%, respectively presented by (Nafisi et al. 2020).

For both cemented soils, the elastic modulus was determined at low confinement (i.e. at the confinement of 10 kPa). In addition, unit weights and void ratios of cemented soils were calculated from untreated values and by considering the effect of known cementation contents.

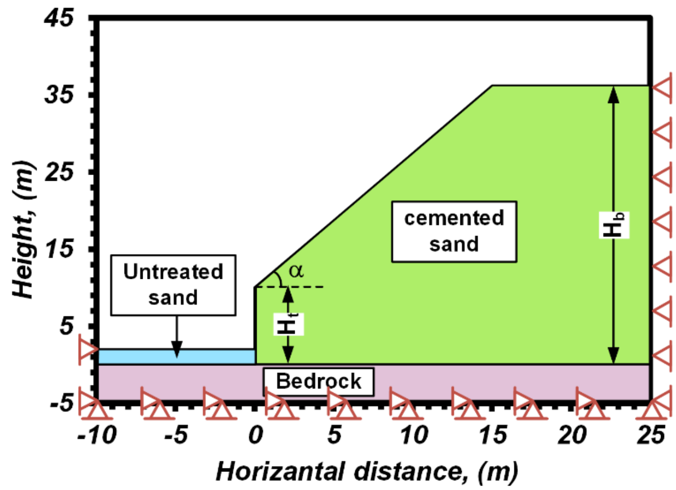

Figure 1. The geometry of the modeled bluff.

Table 2. Characteristics of the modeled materials.

NO.	Material	Elastic modulus, *E* (kPa)	Poisson's ratio, *ν*	Unit weight, *γ* (kN/m^3)	Void ratio, *e*
1	Untreated sand	3.5×10^4	0.3	17.2	0.45
2	Bedrock	5.74×10^7	0.2	28.3	0.2
3	M: Moderately cemented Ottawa 20-30	4.2×10^5	0.29	16.79	0.62
4	H: Heavily cemented Ottawa 20-30	7.8×10^5	0.29	17.24	0.57

RESULT AND DISCUSSION

The instability and general failure mode of the coastal bluffs are mainly controlled by the properties of the soil (Collins and Sitar 2009). In general tensile failure is the instability mode for cemented bluffs that consist of materials with UCS between 30 to 400 kPa (Collins and Sitar 2011). In all three cases considered in this study, soils had UCS values in the range of 30 to 400 kPa. In this study, the assumption of the tensile failure mode was used as a criterion to assess bluff stability. As shown in Eqs. 1 and 2, the expected mobilized minor principal stress from the model results was compared with the materials' tensile strength to comment on the failure susceptibility of the modeled bluffs. It should be noted that the purpose of the analysis was to identify the vulnerable regions of the bluff and not to provide a factor of safety against failure. In both equations σ_3 and σ_t denote minor principal stress and soil tensile strength, respectively.

Tensile strength was assumed to be about 10% of the cemented soil's measured UCS (Collins and Sitar 2009). Therefore, based on the measured UCS values tensile strength of about 7.5 and 40 kPa was assumed for moderately and heavily cemented soils, respectively.

$$|\sigma_t| \geq |\sigma_3| \text{ for } \sigma_3 < 0 \text{ (stable)} \quad (1)$$

$$|\sigma_t| < |\sigma_3| \text{ for } \sigma_3 < 0 \text{ (unstable)} \quad (2)$$

Effect of varying cementation levels. Figures 2(a-b) presents the results of the analysis performed on moderately and heavily cemented bluffs (i.e. Case 1 shown in Table 1). Although soils with two cementation levels were considered in this study, in both soils, deviator stress for drained triaxial tests under 10 kPa confinement ranged between 30 and 400 kPa (Nafisi et al. 2020). Therefore, for both cementation levels 30<UCS<400 kPa and the instability modes of the bluffs were expected to be tensile failure modes. Numerical analysis results for Case 1 demonstrate a similar compression and tensile stress distribution across both modeled bluffs. In both bluffs, the mobilized compression stresses are smaller in the shallower depths and increase with a depth increase. However, tensile stresses (σ_3<0 kPa) are mainly observed on the slope surface and particularly near the region where the slope gradient changes. In both bluffs, the maximum tensile stress of about -15 kPa is developed at the slope transition point. However, the increase in the tensile strength from 7.5 to 40 kPa may result in less failure susceptibility and a different equilibrium beach profile. The stress distribution pattern observed in bluffs implies that the material properties and cementation level define failure mode and also affect the final equilibrium morphology.

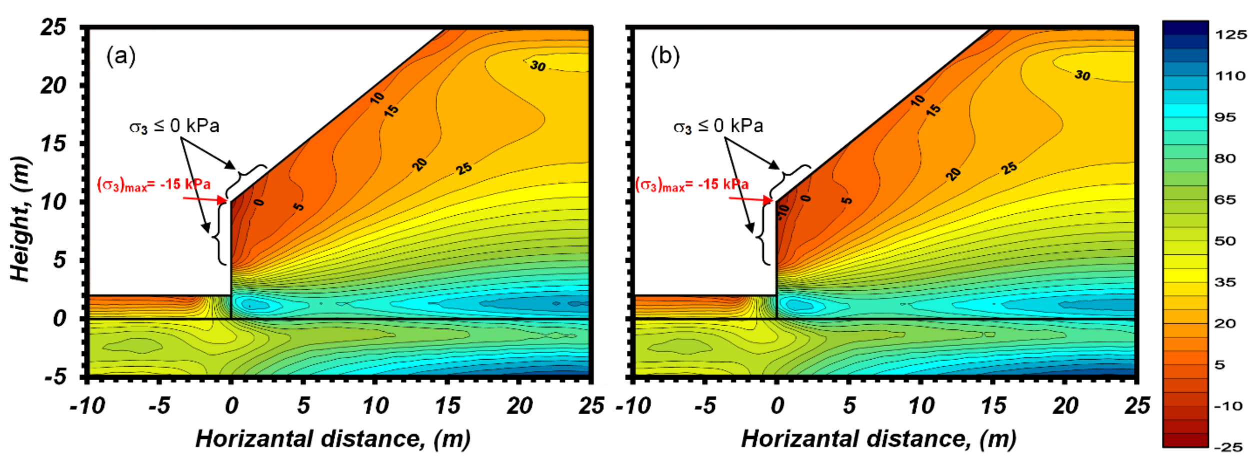

Figure 2. Minor principal stress (σ_3) distribution across (a) Moderately and (b) Heavily cemented bluffs.

Effect of varying slope inclinations. Figures. 3(a-c) present minor principal stress distributions obtained from the numerical analysis performed on moderately cemented bluff models (Case 2 in Table 1). Models comprised of slopes with a toe height of 10 m and gradients of 45°, 60°, and 75°. In all models regardless of slope inclination, compression stresses show lower values on the bluff surface and increase with a depth increase. Similar to Case 1, in all bluffs, the maximum tensile stress is observed at the slope transition point. With an increase in slope inclination, the maximum developed tensile strength increased from -15 to -50 kPa. In addition, with an increase in slope inclination the tension region (σ_3<0) shifted further into the bluffs. Therefore, as expected with an increase in slope angle the bluff becomes less stable, and a larger area of the bluff becomes susceptible to failure. The observation also implies that moderately cemented bluffs with inclination angles similar to that modeled in this study are more likely prone to failure and instability near the toe areas.

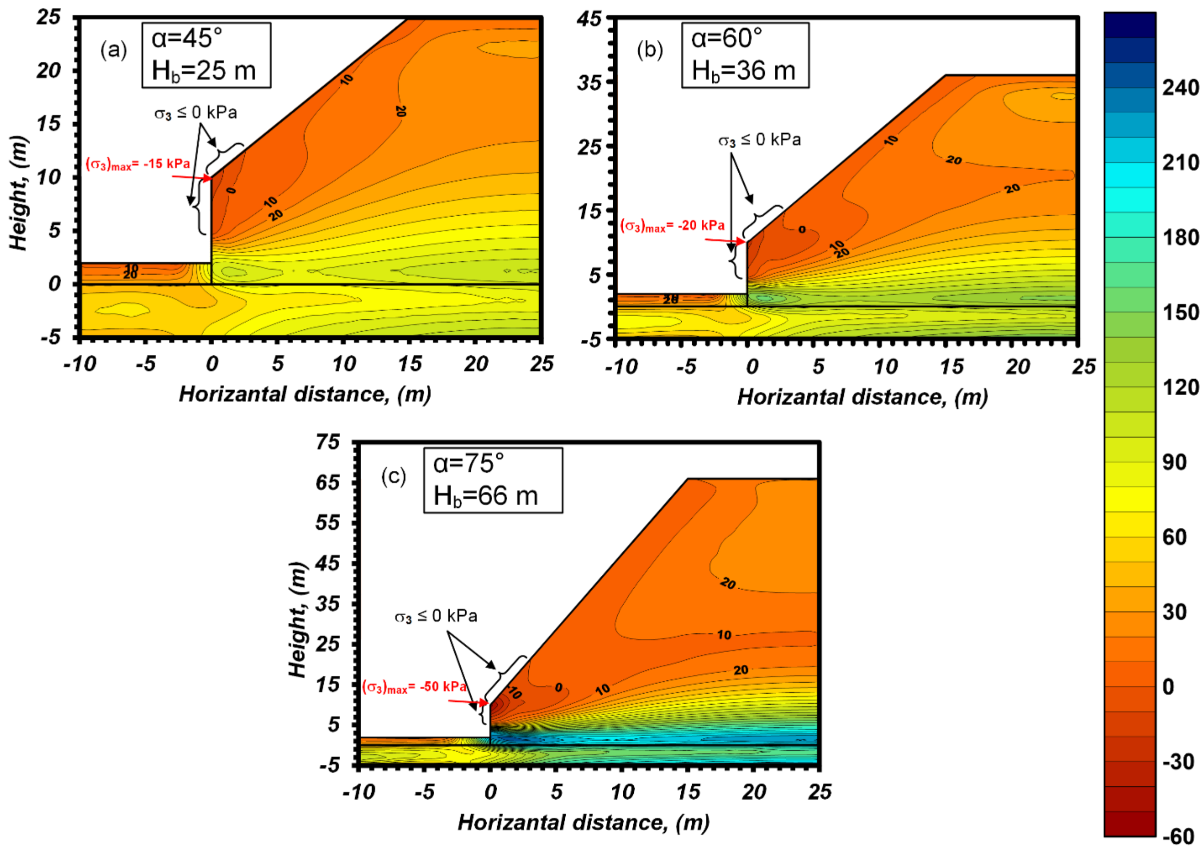

Figure 3. Distribution of minor principal stress (σ_3) across moderately cemented bluffs with varying inclinations and bluff heights.

Effect of varying toe heights. The minor principal stress distributions across the bluffs developed in Case 3 are demonstrated in Figures. 4(a-c). Bluff models were developed with the same slope inclination of 45° and toe heights of 6, 10, and 14 m. Similar to the previous cases compression stress started with a low value on the bluff surface and increased with a depth increase. In all bluffs, a tensile stress region is observed on the bluff face with a maximum value developed at the slope transition point. With an increase in the toe height, the tensile stress region expanded and shifted away from the inclined face and moved towards the vertical section of the bluff. Results of Case 3 indicate that with an increase in the toe height the area of the susceptibility around the slope transition zone shifted from the slope face towards the vertical section of the bluff toe. Therefore, in bluffs with the same inclination angles with an increase in bluff height, it is more likely to observe erosion and mass loss in the vertical section of the toe.

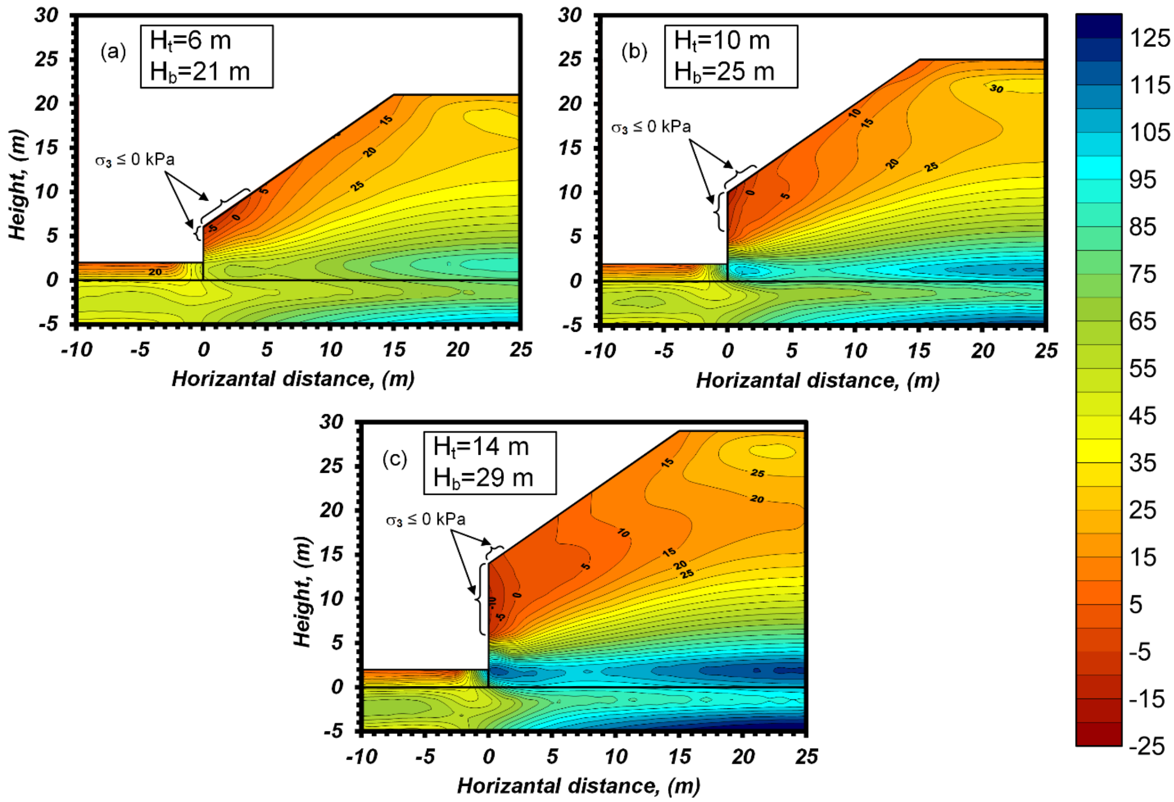

Figure 4. Distribution of minor principal stress (σ_3) across moderately cemented bluffs with toe and bluff heights.

CONCLUSION

FEM analyses were performed on simplified bluff models developed by in-situ monitoring of cemented coastal bluffs in Northern California (Collins and Sitar 2011). Previous researchers have demonstrated that the instability and failure mode of the cemented bluffs is dependent on the slopes' geometry and material strength. Also, tensile failure is the general instability mechanism for the cemented bluffs with 30<UCS<400 kPa. In the presented study, bluff models that consist of materials with the same UCS range were developed in SIGMA/W. Materials properties of MICP-treated Ottawa 20-30 sand that are available in the literature were used as the input parameters to understand the effect of varying levels of cementation on bluff stability. A comparison of the developed in-situ distribution of the minor principal stress across the models with the tensile strength of the cemented material was used as a criterion to assess the stability of the bluffs. The effect of varying levels of cementation, slope inclinations, and toe height on the stability and equilibrium morphology of the bluffs was investigated. Results demonstrated that although the variation of the tested cementation levels did not change the stress distribution pattern, it resulted in lower failure susceptibility for the material with higher tensile strength. In addition, results indicated that with an increase in slope gradient and toe height bluff becomes less stable and more prone to the toe failure.

In addition to the coastal bluff stability assessment which is of critical importance for the development of coastal communities, the results of this study can also have implications for future MICP field implementations. For example, to design and construct a stable MICP-treated earth structure (e.g. slopes or retaining walls) sudden changes in the slope gradients should be avoided. The use of a higher cementation level will bring about a higher level of stability. In addition, modeling the in-situ stress distribution can provide design recommendations and information about the level of stability or expected failure morphology.

ACKNOWLEDGMENTS

Funding from the National Science Foundation (NSF) Cooperative Agreement No. EEC1449501 and as a Payload Project under NSF Grant No. CMMI-1933350 is appreciated. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Bird, E. (2016). *Coastal cliffs: morphology and management*. Springer.

Collins, B. D., and Sitar, N. (2008). "Processes of coastal bluff erosion in weakly lithified sands, Pacifica, California, USA." *Geomorphology*, 97(3–4), 483–501.

Collins, B. D., and Sitar, N. (2009). "Geotechnical properties of cemented sands in steep slopes." *Journal of Geotechnical and Geoenvironmental Engineering*, 135(10), 1359–1366.

Collins, B. D., and Sitar, N. (2011). "Stability of Steep Slopes in Cemented Sands." 137(January), 43–51.

DeJong, J. T., Mortensen, B. M., Martinez, B. C., and Nelson, D. C. (2010). "Bio-mediated soil improvement." *Ecological Engineering*, 36(2), 197–210.

Feng, K., and Montoya, B. M. (2016). "Influence of Confinement and Cementation Level on the Behavior of Microbial-Induced Calcite Precipitated Sands under Monotonic Drained Loading." *Journal of Geotechnical and Geoenvironmental Engineering*, 142(1), 04015057.

Ghasemi, P., Liu, Q., and Montoya, B. M. (2022). "Compressibility Behavior of MICP-Treated Sand Treated under Unsaturated Conditions." *Geo-Congress 2022*, 309–317.

Ghasemi, P., and Montoya, B. M. (2022). "Field implementation of microbially induced calcium carbonate precipitation for surface erosion reduction of a coastal plain sandy slope." *Journal of Geotechnical and Geoenvironmental Engineering*.

Gomez, M. G., Anderson, C. M., Graddy, C. M. R., DeJong, J. T., Nelson, D. C., and Ginn, T. R. (2017). "Large-Scale Comparison of Bioaugmentation and Biostimulation Approaches for Biocementation of Sands." *Journal of Geotechnical and Geoenvironmental Engineering*, 143(5), 04016124.

Gomez, M. G., Martinez, B. C., DeJong, J. T., Hunt, C. E., DeVlaming, L. A., Major, D. W., and Dworatzek, S. M. (2015). "Field-scale bio-cementation tests to improve sands." *Proceedings of the Institution of Civil Engineers - Ground Improvement*, 168(3), 206–216.

Griggs, G. B., and Patsch, K. B. (2004). "California's coastal cliffs and bluffs." Formation, Evolution, and Stability of Coastal Cliffs-Status and Trends USGS Professional Paper, 1693, 53–64.

Hampton, M. A., and Griggs, G. B. (2004). "Formation, Evolution, and Stability of Coastal Cliffs – Status and Trends." USGS Professional Paper 1693, (March), 129.

Montoya, B. M., and DeJong, J. T. (2015). "Stress-Strain Behavior of Sands Cemented by Microbially Induced Calcite Precipitation." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(16), 04015019.

Montoya, B. M., Evans, T. M., Wengrove, M. E., Bond, H., Ghasemi, P., Yazdani, E., Dadashiserej, A., and Liu, Q. (2021). "Resisting dune erosion with bio-cementation." *Proceedings of the 10th International Conference on Scour and Erosion (ICSE-10)*, M. Rice, J., Liu, X., McIlroy, M., Sasanakul, I., and Xiao, ed., Arlington, Virginia, USA, 11.

Nafisi, A., Mocelin, D., Montoya, B. M., and Underwood, S. (2019). "Tensile strength of sands treated with microbially induced carbonate precipitation." *Canadian Geotechnical Journal*, 57(10), 1611–1616.

Nafisi, A., Montoya, B. M., and Evans, T. M. (2020). "Shear Strength Envelopes of Biocemented Sands with Varying Particle Size and Cementation Level." *Journal of Geotechnical and Geoenvironmental Engineering*, 146(3), 04020002.

Terzis, D., Laloui, L., Dornberger, S., and Harran, R. (2020). "Full-Scale Application of Slope Stabilization via Calcite Bio-Mineralization Followed by Long-Term GIS Surveillance." *Geo-Congress 2020: Biogeotechnics*, 65–73.

The City of San Diego. (2004). *Land Development Code Coastal Bluffs and Beaches Guidelines*. San Diego, CA.

Zamani, A., Montoya, B. M., and Gabr, M. A. (2019). "Investigating challenges of in situ delivery of microbial- induced calcium carbonate precipitation (MICP) in fine-grain sands and silty sand." 1900(August 2018), 1889–1900.