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Mitigation of Rainfall-Induced Sandy Slope Erosion by Biostimulated Microbiologically Induced Calcite Precipitation

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ABSTRACT

Rainfall-induced soil erosion is a typical natural disaster, which is normally caused by the detachment and transport of soil particles under the action runoff flow. It can flash soil away gradually, damage infrastructure and threaten some vital habitats. In this study, the biostimulated MICP by using the indigenous ureolytic bacteria was applied to investigate its effectiveness in the erosion mitigation of sandy slope. Some artificial sandy slopes were prepared in the meter-scale rectangular container. The structure from motion (SfM) technique and unconfined compressive strength were applied to evaluate the erosion of biostimulated MICP-treated sandy slopes subjected to heavy rainfall. The surface elevation variation of sandy slope was compared by reconstructed 3D model before and after rainfall. The quantitative change of elevation of slope surface showed that MICP-treated sandy slopes had higher resistance to the rainfall-induced erosion compared to the untreated slope. Furthermore, longer cementation stage can induce higher unconfined compressive strength and less surface settlement.

INTRODUCTION

Rainfall-induced soil erosion is a typical natural disaster, which is normally caused by the detachment and transport of soil particles under the action of runoff flow. Sandy slope erosion in Hawaii is a process concerning the removal of sand by the actions of heavy rainfall. It can flash the find sand away gradually, damage infrastructure and threaten some vital habitats.

Microbiologically induced calcite precipitation (MICP) as an effective method to alter the soil characteristics has potentials to prevent sand dune erosion (Liu et al., 2021; Wang et al., 2022a). Based on the recent studies, bacteria have made greater contributions to the formation of precipitation than that made through abiotic process. The formed biocementation connects the adjacent soil particles together, enhances soil strength and mitigates the erosion processes (Wang et al., 2022b). The stabilization process can be achieved by inducing calcite precipitation within the sand matrix by microbial ureolysis procedure by ureolytic bacteria (Whiffin 2004). There were some previous studies on the feasibility of MICP in soil erosion prevention. For example, Xiao et al. (2022) investigated the effects of bioaugmented MICP on the natural soil slope (with a gradient of 38°, height of 6.2 m) subjected to a rainfall intensity of 175 mm/h. The results showed that the response time to rainfall and the velocity of wetting front could be increased and decreased, respectively, with the increase of biotreatment level. Liu et al. (2020) designed an up-scaled coastal sand dune erosion test subjected to simulated wave attack with two different simulated wave height. The results indicated that MICP treatment was in general found to be effective to mitigate sand dune erosion. In these studies, the erosion areas and failure patterns were normally evaluated visually by digital camera qualitatively.

In this study, the biostimulated MICP by using the indigenous ureolytic bacteria was applied to investigate its effectiveness in the erosion mitigation of sandy slope. Some artificial sandy slopes were prepared in the meter-scale rectangular box. The structure from motion (SfM) technique, a photogrammetric approach, was used to evaluate the surficial deformation of biostimulated MICP-treated sandy slopes subjected to rainfall. The surface elevation change of sandy slopes were visualized and compared by reconstructed 3D model before and after rainfall quantitatively. Finally the unconfined compressive strength of MICP-treated sandy slopes were measured.

MATERIALS AND METHOD

SOIL AND ENRICHMENT MEDIA

In this study, the sand was collected from the supratidal zone of Waikiki beach, Oahu Island, Hawaii. The physical properties of the soil sample are shown in Table 1. The particle size distribution of the sand is shown in Figure 1. All sandy soil sampled from the surface of the beach (depth from 0 to 5 cm) to ensure the oxic condition within the entire soil matrix, which can guarantee the growth of the aerobic microorganisms. The small twigs and roots were sorted out from the soil sample, and then the soil samples passed through the sieve with opening size of 2 mm to remove the oversized particles.

Table 1. The physical properties of collected soil sample.

Mean size d_{50} (mm)	Uniformity coefficient C_u	Coefficient of curvature C_c	Natural water content (%)	Initial pH	$CaCO_3$ content (%)
0.35	0.78	3.75	1.50	8.6	> 99.5

The enrichment medium used for stimulating indigenous ureolytic bacteria consisted of 20 g/L yeast extract (YE) and 170 mM urea as the selective ingredient for the enrichment of the indigenous ureolytic bacteria (Wang et al., 2020, 2022a, 2022b). The cementation solution was comprised of 500 mM $CaCl_2$ and 500 mM urea. All chemicals were autoclaved under 121℃, 17-20 psi for 35 minutes prior to prepare the enrichment medium. The urea was filter sterilized separately from YE.

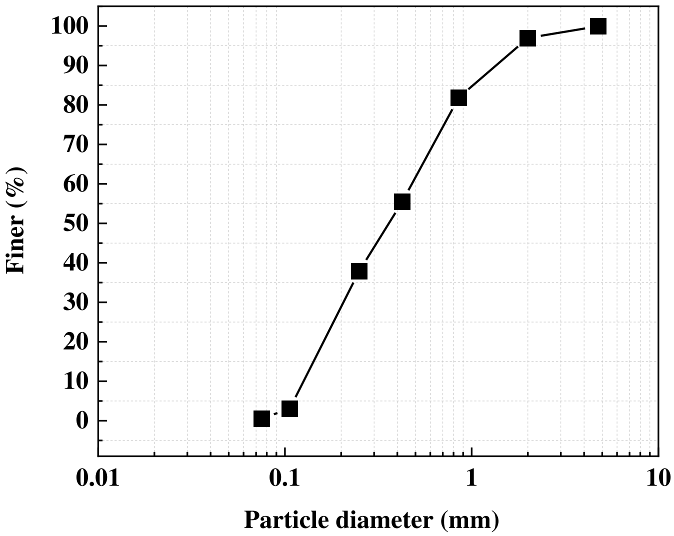


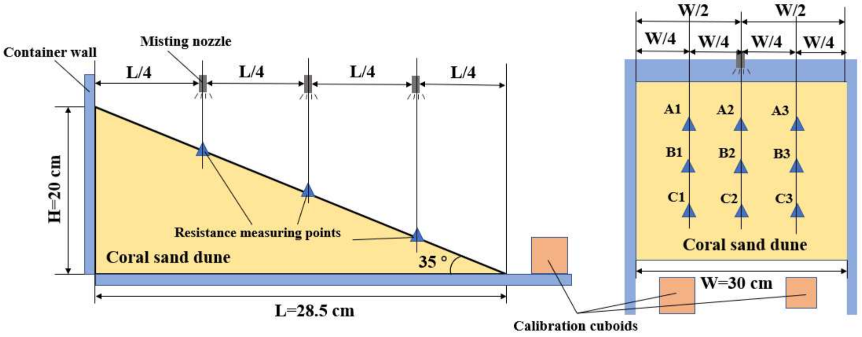
Figure 1. The particle distribution curve of the sand.

SETUP OF RAINFALL-INDUCED EROSION TEST

To perform the rainfall-induced erosion test, an artificial sandy slope measuring 28.5 cm × 30 cm × 20 cm (Length × Width × Height) with 35° slope angle was prepared in a rectangular box with one side cut off. The 12.5 kg sands were then poured into the container by the dry pluviation method to reach final relative density of approximately 20 %. The surface of slope was flattened after pouring. The schematic diagram of a representative prepared sandy slope is shown in Figure 2. Upon the completeness of sandy slope preparation, 900 mL enrichment medium was sprayed onto the slope surface evenly by spraying bottle and the sand slope was left for a 3-day enrichment stage. Then, 900 mL cementation solution was sprayed and left for 1, 2, and 4 days to obtain different biocementation contents. The selected volume of 900 mL equaled to the pore volume of the 2-cm thick sand from the slope surface. Finally, the sandy slope was subjected to the simulated rainfall-induced erosion. The rainfall was simulated using three misting nozzles with misting range of 50–100 cm placed over the sandy slope. The system was calibrated to produce a continuous rainfall intensity as high as 80 mm/h, which was violent rain according to Monjo (2016). The simulated rainfall lasted for 1 hour.

UNCONFINED COMPRESSIVE TEST

Three additional sandy slopes (i.e., MICP-1d, MICP-2d, and MICP-4d) were prepared for the measurement of unconfined compressive strength prior to erosion test using Gilson soil pocket penetrometer (HM-500) (also called hand penetrometer), which was specified by Occupational Safety and Health Administration (OSHA) for soil strength estimates when evaluating the stability. The 0.25 in (6.4 mm) diameter penetration piston is pushed into the soil surface to a groove machined on the piston at 0.25 in (6.4 mm) depth. Penetration resistance from the calibrated spring can be read from an integrated scale (122.58 kPa/cm) engraved on the penetrometer barrel. The locus of 9 measuring points (A1, A2, A3, B1, B2, B3, C1, C2, C3) were illustrated in Figure 2(b).



(a) (b)

Figure 2. The schematic setup of rainfall-induced erosion test: (a) side view; (b) top view.

MODEL CALIBRATION

To evaluate the erosion-resistance of uncemented and MICP-treated sandy slopes, the structure-from-motion (SfM) technique was applied. Firstly, a series of 2D images were captured by a high-resolution digital camera (Sony a7II) from various angles prior to and after the erosion. The 3D models of sandy slopes were then reconstructed by the software *Pix4D*, in which the point clouds and digital elevation models (DEMs) were generated. Finally, the DEMs were fed into the software *CloudCompare* v2.12 to obtain the change in elevation of the slopes prior to and after rainfall erosion. Due to the lack of the assistance by global positioning system in such a small-scale model test, the coordinates of the whole slope should be calibrated by other objects with known predefined size and coordinates. Consequently, the reconstructed model and DEMs were carefully calibrated using 8 ground control points (GCPs) (i.e., Point A-H) on two cuboids with different size as shown in Figure 3. The locus of the two cuboids made of hard wood were illustrated in Figure 2. The coordinate of point A was set to (0,0,0), and the coordinates of all GCPs can be calculated based on the size of cuboids and the distance between these two cuboids which was 20 cm.

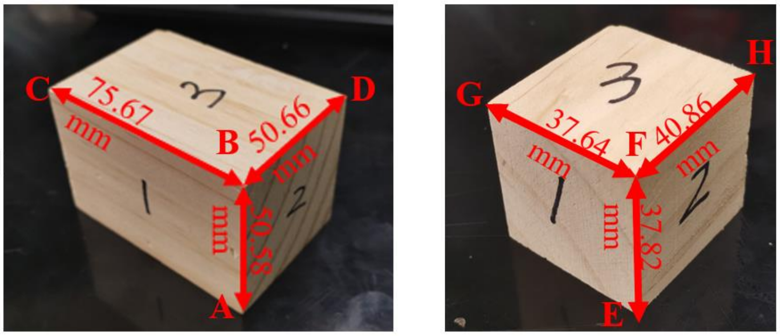


Figure 3. The size of calibration cuboids.

To further verify the accuracy of the reconstructed models, four 10 cm long reference lines were drawn on the surface of the container's side wall and subface plane as the check lines. The distance measured in the reconstructed models by software and the actual measuring distance were compared in Table 2. It was found that the absolute errors were less than 0.5%.

Table 2. The accuracy of the reconstructed models.

Reference line	Measuring distance (cm)	Distance in the reconstructed models (cm)	Error (%)
1	10.00	9.97	-0.3
2	10.00	9.95	-0.5
3	10.00	10.05	0.5
4	10.00	9.96	-0.4

RESULTS AND DISCUSSIONS

EVALUATION OF EROSION

The reconstructed 3D model and change of elevation of the slopes prior to and after rainfall erosion are presented in Figure 4. The blue color indicated soil erosion (i.e., the negative elevation or settlement), and the red soil accumulation (i.e., the positive elevation or accumulation). Apparently, for the untreated sandy slope, large areas showed significant erosion with blue color. In contrast, the sandy slopes after biostimulated MICP treatment generally exhibited much milder erosion. With the increase of treating period from 1 day to 4 days, the erosion became less severe. This was because that the longer treating duration can result in more biocementation which can fill the voids in the soil matrix more efficient and prevent the penetration of water. The chemical and biological reactions involved in MICP process were shown as the following equations.

$$(NH_2)_2CO + 2H_2O \xrightarrow{\text{urease}} 2NH_4^+ + CO_3^{2-} \qquad (1)$$

$$\mathrm{CaCl_2 \rightarrow Ca^{2+} + Cl^{-}} \tag{2}$$

$$\mathrm{Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow} \tag{3}$$

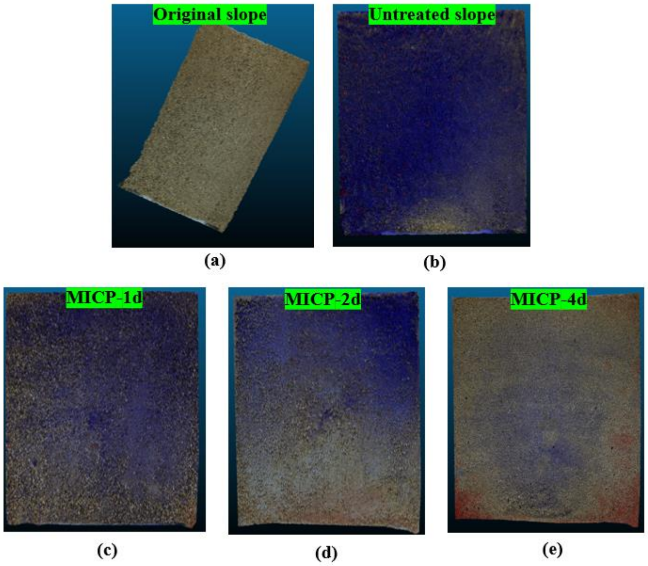


Figure 4. The reconstructed 3D models of (a) original slope prior to erosion; (b) untreated slope after erosion; (c) 1d-MICP-treated slope after erosion; (d) 2d-MICP-treated slope after erosion; (e) 4d-MICP-treated slope after erosion.

To quantify the change in elevation in different cases, the elevation change distribution across the entire slope surface is shown in Figure 5. The parameter R (percentage of cloud points), defined as the ratio of cloud point numbers at a given elevation change to the total count of cloud points, was calculated to quantify the elevation change distribution. As shown in Figure 5, it was found that the elevation changes mostly concentrated around -6.8 mm, -4.2 mm, -1.0 mm, and -0 mm for the untreated, MICP-1d, MICP-2d, and MICP-4d cases, respectively, suggesting that the case of MICP-4d had the least soil erosion, which was followed by MICP-2d and MICP-1d. In addition, the apparent accumulation was found in the case of MICP-4d, which is mostly located at the toe part of the slope.

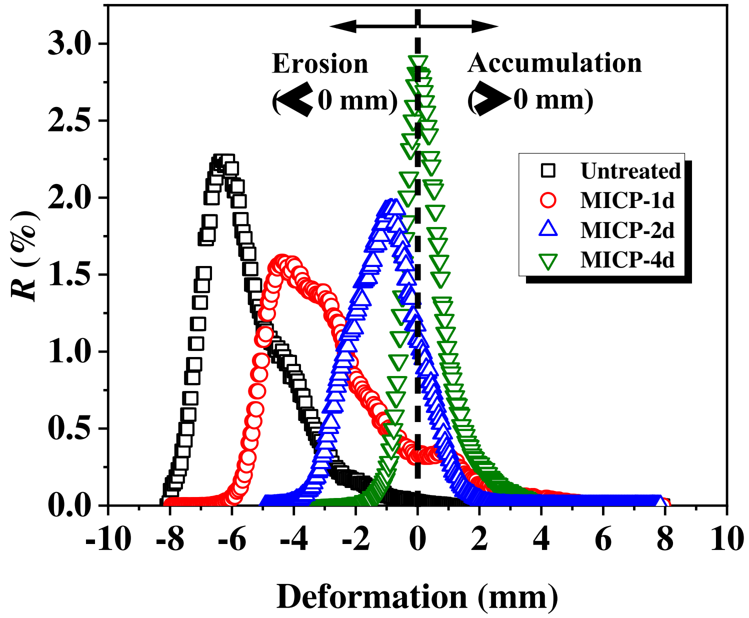


Figure 5. The surface deformation distribution of slopes after rainfall.

UNCONFINED COMPRESSIVE STRENGTH

Figure 6 showed the unconfined compressive strength of measuring points on the MICP-treated slope surface. It should be mentioned that the strength of non-MICP-treated slope was too low to detect, therefore only the MICP-treated cases were discussed. It was found that the unconfined compressive strength of MICP-1d, MICP-2d, and MICP-4d were around 85-100 kPa, 150-205 kPa, and 260-300 kPa, respectively, which was consistence with the results obtained from the erosion test. The longer cementation stage will induce more biocementation and higher unconfined compressive strength as indicated previous investigation (Feng and Montoya, 2016). It should be noted that the uniformity of treatment still needs to be improved by a more accurate way.

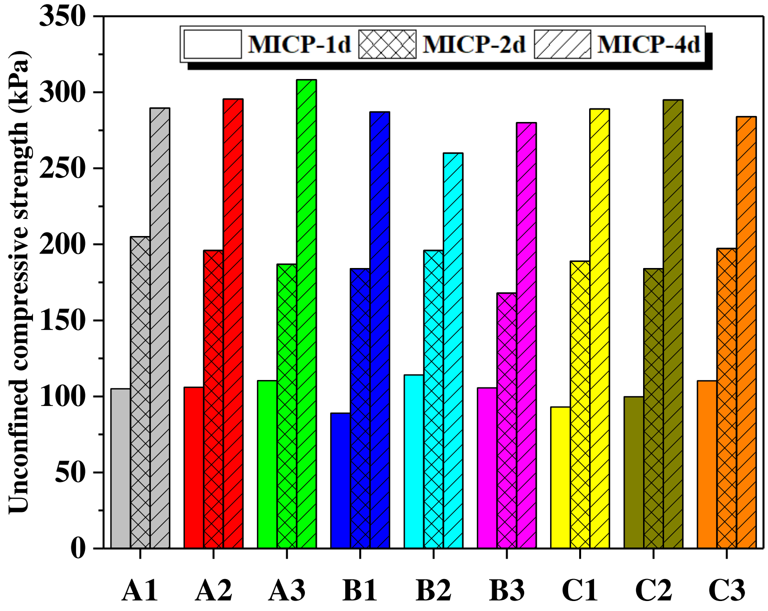


Figure 6. The unconfined compressive strength of measuring points from A1-C3 in the case of MICP-1d, MICP-2d, and MICP-4d.

APPLICATION OF BIO-STIMULATION APPROACH IN THE FIELD

Based on the preliminary test in this study, bio-stimulation is a promising approach for MICP in the field. However, some possible issues in terms of the practical problems such as the environmental influence and the ways to implement the bio-stimulation should also be considered. For example, how to introduce the enrichment medium into soil under different site conditions should be considered carefully. Spraying the medium directly onto the surface of the soil can be the simplest approach. Gravitational penetration makes the treated area more homogenous. However, the depth to which the enrichment media can gravitate may be limited. Moreover, injecting the enrichment medium via mechanically pressurization such as biogrout can be an alternative approach for the field application. The application of biogrout has some specific requirements to the field and is assumed to be limited to the fine sands or coarser materials due to the size constraints (van Paassen 2009). The procedures are more complicated. To make the in-situ application reliable, the biogrout should be predictable, controllable and homogenous. Last but not least, while the MICP is still relatively new, several environmental concerns have yet to be comprehensively addressed and examined. These include potential risks associated with the process, such as employing urea as a substrate, the release of byproducts, and the ramifications on the local environment. Consequently, it is imperative to conduct additional long-term studies to ascertain the full extent of MICP's environmental impacts, thus ensuring its sustainable and responsible implementation.

CONCLUSION

The study investigated the feasibility of biostimulated MICP on the mitigation of rainfall-induced erosion of sandy slope. The SfM technique and unconfined compressive test were applied to evaluate the erosion quantitatively. The following conclusions can be drawn from this study:

1) Biostimulated MICP approach can significantly reduce the rainfall-induced sandy slope erosion. With the increase of cementation stage (from 1 day to 4 days), less settlement occurred. The elevation changes mostly concentrated around -6.8 mm, -4.2 mm, -1.0 mm, and 0 mm for the untreated, MICP-1d, MICP-2d, and MICP-4d, respectively
2) The longer cementation stage of MICP treatment can induce higher unconfined compressive strength due to the void filling effect. The unconfined compressive strength of MICP-1d, MICP-2d, and MICP-4d can reach to 85-100 kPa, 150-205 kPa, and 260-300 kPa, respectively.
3) SfM (Structure from motion) technique, as a quantified method, shows great potential on the evaluation of laboratory soil erosion test and in-situ condition.

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