

Effect of Bio-Cementation on Drained Instability of Poorly Graded Sand with Sub-Angular Particle Shapes

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ABSTRACT

Case studies of slopes experiencing unstable behavior under drained conditions below the stress level that would cause a traditional failure have been reported in the literature. Here, unstable behavior refers to a sudden collapse of soil resulting from a small change in stress conditions. This response, which is known as drained (diffuse) instability, is quite different from the widely recognized static liquefaction mechanism of failure for sand under undrained conditions. Microbially induced carbonate precipitation (MICP) as a soil improvement technique has a promising effect on the shear strength of soils and has potential to be used to reduce the potential of instability in granular slopes. To provide a better understanding of this collapse mechanism, a series of monotonic triaxial tests on treated and untreated specimens have been carried out to evaluate the effect of bio-cementation improvement on the instability under drained conditions. The experiments were conducted in two stages. Different stress conditions, including stress-induced anisotropy, were used for the first stage of loading. After that, a constant shear-drained (CSD) stress path was used in the second stage of the test as the mean effective stress was continuously reduced by decreasing confining pressure with a constant rate until instability was reached. The onset of instability in treated and untreated samples was investigated in this study.

INTRODUCTION

Instability behavior of granular material has often been investigated under undrained conditions for loosely packed material (Lade, 1993; Leong et al., 2000). It has consistently indicated undrained instability may happen before the failure line (Lade et al., 1988; Wanatowski and Chu, 2007). Under undrained conditions, excess pore water pressure is the most important known cause of instability. However, case studies of slopes experiencing unstable behavior under drained conditions and below the stress level that would cause a traditional failure have been reported in the literature. Eckersley (1990) reported that slope failure occurred under drained conditions, and excess pore water pressure developed as a consequence of failure rather than the cause of triggering the run-away deformation. Recent analysis confirms that Nerlerk berm failure (Lade, 1993), collapse in Whalchusett Dam (Olsen et al., 2000), and Fundao Dam failure in Brazil (Morgenstern et al., 2016) occurred under drained conditions. In these cases, failure occurred due to the reduction in effective mean stress and as a consequence of soil inability to sustain a current stress state, large plastic deformations developed rapidly. As an

appropriate method to simulate changes in the stress state of soil elements during drained instability, the constant shear-drained stress path (CSD) has been utilized (Brand, 1981; Chu et al. 2003; Ning et al., 2013; Alipour and Lashkari, 2018). In this test, the reduction in mean effective stress is induced by decreasing the confining pressure while deviator stress maintains until instability is reached. Drained instability of granular slopes can be triggered due to variety of reasons, such as water infiltration and release of lateral stress.

Recently, microbially-induced carbonate precipitation (MICP) as a bio-mediated cementation technique has been popular among researchers. As a by-product of biochemical reactions, calcium carbonate precipitation is induced at soil particle contacts and bonds particles. Bonding effects enhance the strength parameters and stiffness of soil (Feng and Montoya, 2017).

This study presents a series of triaxial tests to investigate the effect of bio-cementation on the onset of drained instability. Different initial states at the beginning of the CSD path (constant deviator stress, q) were examined to provide a better understanding of drained instability in untreated and treated sand.

MATERIALS AND METHODOLOGY

CSD tests were conducted in two stages; in the first stage, specimens were sheared in a compression loading to the pre-determined deviator stress, followed by decreasing mean effective stress at a constant rate in the second stage. A reduction in mean effective stress was achieved by reducing confining stress at a slow rate while maintaining deviator stress until instability was reached. In this study, different stress conditions, including pre-shearing and without pre-shearing, were used for the first stage of the test. During pre-shearing, stress-induced anisotropy appears in the sand's force network, influencing the system's response (Gajo et al., 2003). Mechanical anisotropy plays an important role in mobilizing shear resistance in granular masses. In pre-sheared phase, the specimen is subjected to higher deviator stress afterward, unloaded to the pre-determined q and the second stage will commence.

Various techniques have been introduced to identify the onset of drained instability. (1) The sudden increase in axial strain (Lashkari et al., 2019; Chu et al., 2012), (2) the zero-volume change point in which volumetric behavior changes from dilation to contraction (Chu et al., 2003), and (3) the second-order work (Hill 1958; Dong et al., 2016). Dilative materials cannot be examined using the zero volume change point criterion. Regardless of the density state of the assemblies, in this study, the rapid development of axial deformation is considered the instability criterion.

Material. This study investigated the effect of bio-cementation on drained instability using poorly graded and sub-angular sand. The sand was obtained from Agate Beach (BS) near Newport, Oregon. The physical properties and grading curve of sand are shown in Table 1 and Figure. 1, respectively.

Treated Soil (MICP). The authors conducted a near-prototype-scale experiment to investigate the efficacy of MICP in enhancing coastal dune erosion resistance during severe storms (Montoya et al., 2021; Yazdani et al., 2022). A surface-spray technique was used to apply biologic and cementation solutions on the face of the constructed dune. Afterward, the dune was subjected to a simulated severe storm. As a consequence of the surface treatment, a crust thickness of 35 cm was formed. Treated specimens were taken from the formed crust (Figure 2(left)).

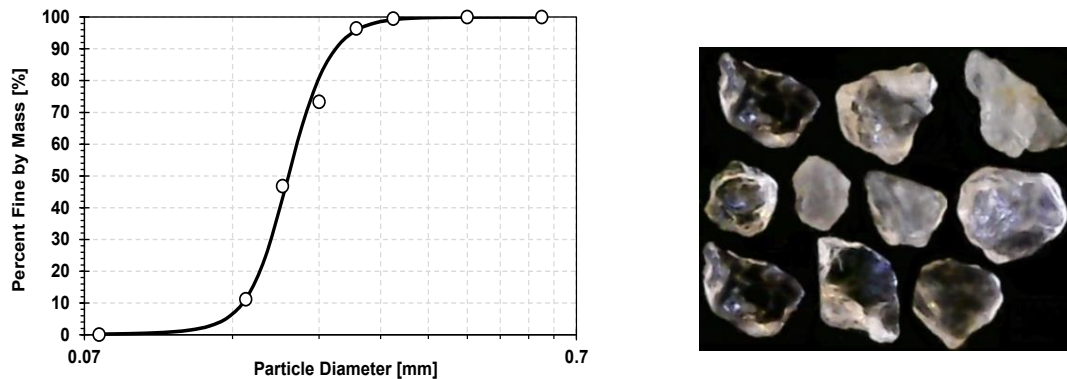


Figure 1. Grain size distribution (left) and particle shape of sand (right).

Table 1. Physical properties of sand

Material	G_s	e_{max}	e_{min}	c_u	c_c	k_{sat}
Sand	2.67	0.78	0.57	1.3	0.98	0.04 cm/s
G_s : Specific gravity				c_u : Uniformity coefficient		
e_{max} : Maximum void ratios				c_c : Curvature coefficient		
e_{min} : Minimum void ratios				k_{sat} : Hydraulic conductivity		

LABORATORY EXPERIMENTS

Test Procedure and Sample Preparation. The bio-cemented chunks were brought to the laboratory after the storm simulation, and cylinder cores were taken for the triaxial testing (Figure 2 (right)). A Series of drained triaxial tests were conducted on untreated sand and cemented cores. A constant shear-drained stress path was performed under confining pressures of 200, 400, and 600 kPa. Specimens were prepared with a diameter and height of about 36 mm and 72 mm, respectively. Specimens were saturated using CO_2 percolation for 30 min and flushing de-aired water at a low rate. In all cases, the B-value exceeded 0.95, and specimens were assumed to be saturated. The specimens were isotropically consolidated under preplanned confining pressure and sheared at a strain rate of 2.5 %/hr with the drainage valves opened until the desired level of deviator stress was reached.

Measurement of Calcium Carbonate Content. After the constant shear-drained stage was completed, calcium carbonate content of the treated specimens was measured using acid washing process (Yazdani et al., 2021). Calcium carbonate content can be easily measured from oven-dried masses before and after the acid washing process. Results indicated that calcium carbonate content was uniformly distributed along the specimens' height with a value of 4.8%. This founding confirms that the dune in the large-scale experiment and the cored specimens were heavily treated (Feng and Montoya, 2016).

RESULTS AND DISCUSSION

Stress-Strain Behavior. Figure 3 depicts the typical response of an untreated specimen to the CSD path. The second stage of the CSD test was divided into two parts (B-C and C-D).

During the first part (B-C) specimen is stable and can easily tolerate the constant deviator stress. In this part, developed axial strains are very small. At point C, progressive plastic axial strains began inducing in the specimen and continued to reach point D, where the failure occurred. Point C, where the large axial strain starts, is identified as the onset of instability leading to catastrophic failure. The line passes the onset of instability is known as instability line (IL).

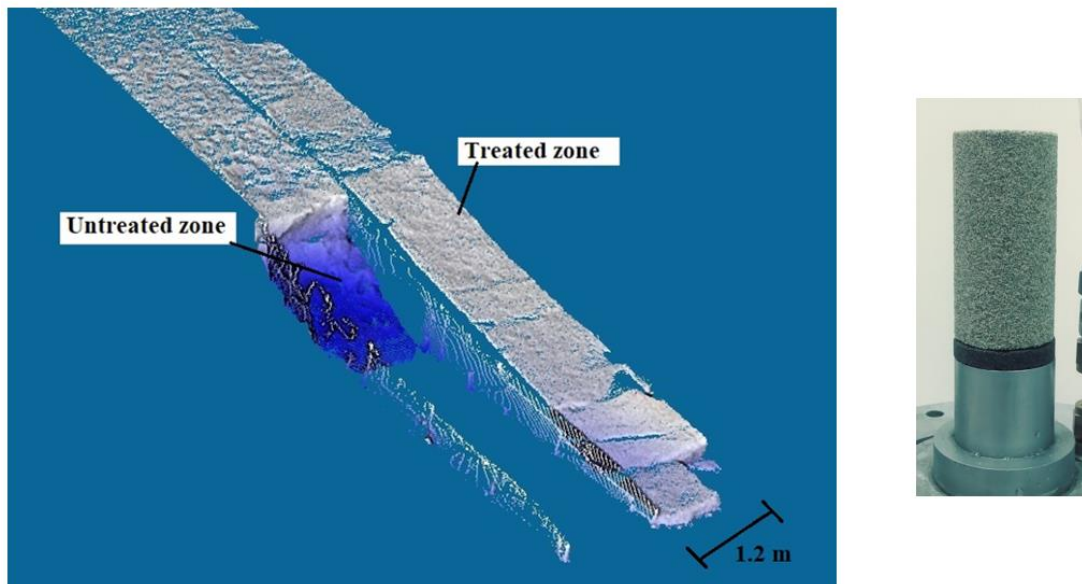


Figure 2. Treated and untreated zones during large-scale testing (left) and a prepared specimens for a triaxial test (right)

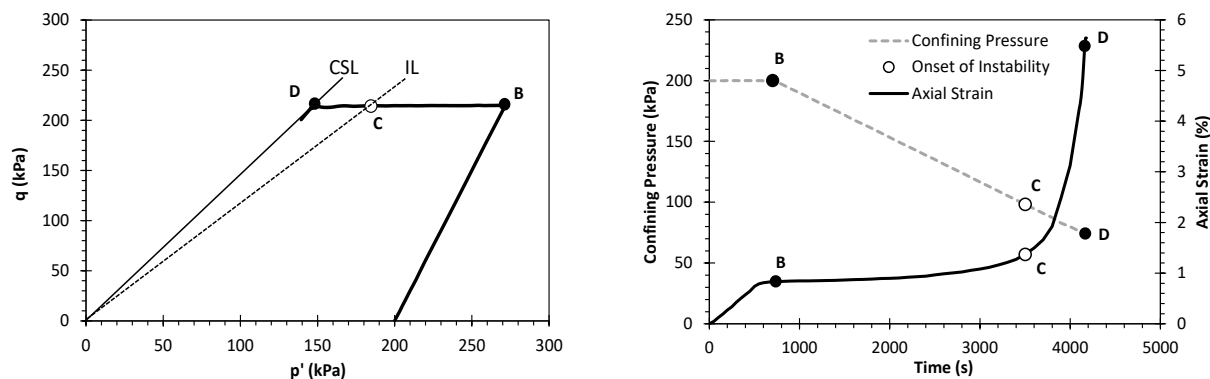


Figure 3. Typical stress path (left), and axial strain behavior and confining pressure (right) of a CSD path (untreated specimen); Note: back pressure was 150 kPa.

Three sets of tests were conducted to examine the instability behavior under the CSD stress path. First, untreated sand was subjected to various constant q to study its instability behavior. The second set examined the effect of bio-cementation on drained instability. The third set evaluated the effect of the stress-induced anisotropy on the deformation response of the untreated soil during the CSD test. Figure 4 presents the results of the first set, where the response of the untreated soil to various q was depicted. Specimens sheared up to pre-determined deviator stress

of 85, 215, and 430 kPa. The level of constant q influenced the axial deformation response of the specimens. As the level of constant q increases, axial strain develops at higher rates ($\frac{d\epsilon_a}{dp'}$). In the specimen subjected to the constant q of 85 kPa, there was a very low rate of strain development (nearly zero) prior to instability. It can also be inferred from Figure 4 that confining pressure at the onset of instability in untreated sand is highly influenced by the level of q . The specimen subjected to 85 kPa of deviator stress during the constant q stage was sustained until the confining pressure was reduced by 82% of the initial value. In comparison, the specimen that underwent 400 kPa of constant q sustained only until 28% reduction in confinement.

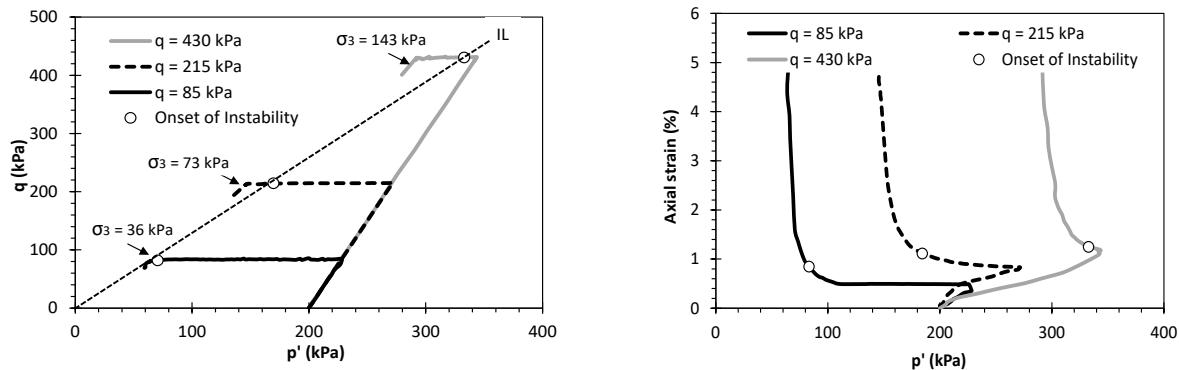


Figure 4. Untreated sand under various q (left), and axial deformation behavior (right)

Effect of MICP on Drained Instability. The behavior of the treated specimens was profoundly affected by cementation. Figure 5 confirms that bio-cementation results in strong bonds between sand particles and leads to improved shear strength and, therefore, stability of sand slopes. Regardless of the values of the constant q , treated specimens tolerated a more significant reduction in mean effective stress. In contrast, untreated specimens at the same level of deviator stress were more vulnerable to reducing mean effective stress. This can be confirmed by considering the distinguished slope of the treated specimens' instability line (IL). Besides the onset of instability points, cemented specimens exhibit significant effects on pre-failure deformability (Figures 5 (right)). The obtained results agree with Nafisi et al. (2021), which demonstrated in CSD tests on treated samples that an insignificant axial strain developed at failure (less than 0.2 %). It must be noted that cemented samples experienced an abrupt rise in axial strain followed by a catastrophic collapse.

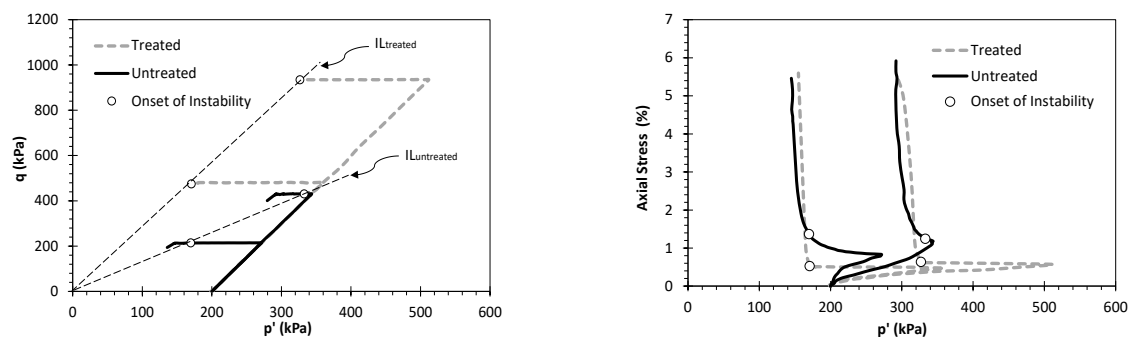


Figure 5. Treated and untreated specimens' behavior in p' - q space

Effect of Pre-shearing on Drained Instability. Re-orientation of particles in the direction of principal stress is the main consequence of pre-shearing, leading to greater stiffness. Figure 6 clearly shows that shear-induced anisotropy affects pre-failure deformability. The axial strains in the constant q stage are very small compared to those developed at the similar stage in the specimen without pre-shearing.

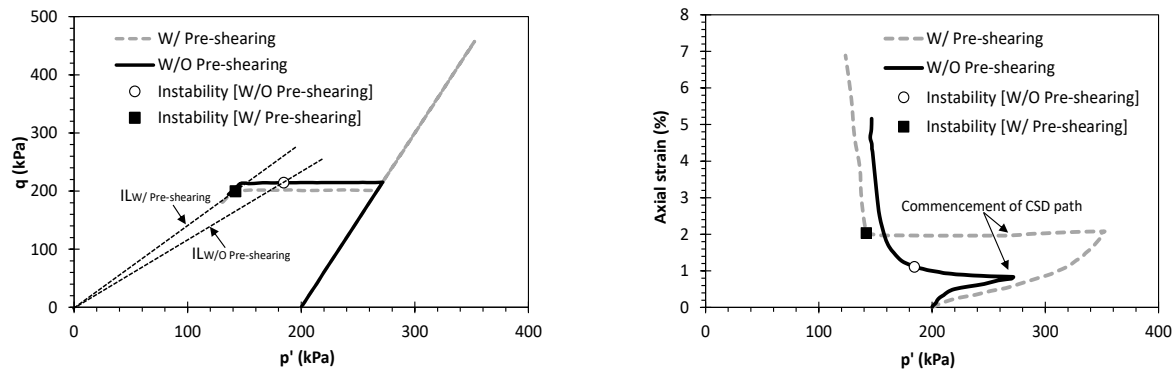


Figure 6. Effect of pre-shearing on untreated sand

CONCLUSIONS

A series of CSD tests were performed to investigate the effect of bio-cementation on the drained instability of sand slopes, a series of CSD test were performed. CSD test is an appropriate way to investigate the drained instability of granular masses. Cemented specimens were taken from a near-prototype-scale experiment conducted previously to evaluate the efficacy of MICP in improving dune erosion resistance. The following findings can be deduced from the results:

- Test results confirmed that bio-cementation significantly delays the onset of instability and decreases the deformability of the soil prior to the failure.
- Once treated specimens became unstable, a catastrophic failure occurred with an abrupt rise in axial strains.
- The deformation response of the untreated soil is significantly affected by stress-induced anisotropy due to pre-shearing. The rate of axial strains development with mean effective stress is significantly lower compared to the sample without pre-shearing.

ACKNOWLEDGEMENTS

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