Geomechanics and Engineering, *Vol. 26, No. 3 (2021) 289-299*
https://doi.org/10.12989/gae.2021.26.3.289

Enzyme induced carbonate precipitation for soil internal erosion control under water seepage

Jia He[a], Changhang Fang[b], Lei Hang[c], Yongshuai Qi[d], Xunyu Mao[e], Boyang Yan[f], Yundong Zhou[g] and Yufeng Gao*

Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China

(Received August 16, 2020, Revised June 10, 2021, Accepted August 3, 2021)

Abstract. Seepage induced internal erosion in earth dams, dikes, and their underlying soil strata may cause destruction of earthen structures and flooding of lowland regions. In this study, efforts were made to evaluate the use of the enzyme induced carbonate precipitation (EICP) method for the control of internal erosion under water seepage. Gap-graded soils with 15% fine particles were improved by the EICP method for 1 to 5 passes. In each pass of treatment, 1.5 pore volume treatment liquid containing soybean-derived urease and 0.5 mol/L equimolar urea-calcium chloride was applied to the soil sample. After the EICP improvement, the soil samples underwent seepage erosion of stepwise-increased flow rates. In addition to the EICP-treated soil samples, an untreated soil sample and a soil sample treated by the microbially induced carbonate precipitation (MICP) method were also tested for comparison. The results showed that, in terms of the amount and rate of eroded fine particles, the EICP soil samples had stronger resistance against seepage erosion as compared with the MICP sample and the untreated soil sample. The erosion control effects also improved with treatment passes. The EICP improvement was also effective in reducing the axial deformation of soil. The level of axial deformation was roughly consistent with the amount of fine particles eroded. The calcium carbonate distribution was relatively uniform in the EICP samples compared with the MICP sample. The results presented in the paper show that the EICP method is a promising solution for the control of seepage induced internal erosion in soils.

Keywords: biocement; enzyme induced carbonate precipitation; internal erosion; soil improvement

1. Introduction

Seepage induced internal erosion of soil may take place in earth dams, dikes, and their underlying soil strata. The internal erosion can cause disastrous consequences such as reservoir leakage, destruction of dams or dikes, and flooding of lowland areas. It has been reported that around 50% of failures or damages of these earthen structures are related to internal erosion (Bendahmane *et al.* 2008, Flores-Berrones *et al.* 2011, Adams *et al.* 2013). Therefore, seepage induced internal erosion is of great interests for geotechnical researchers and practitioners. Studies related to the internal erosion involve the initiation conditions of internal erosion, the progressions and consequences of internal erosion, and countermeasures against internal erosion, etc. The occurrence of internal erosion is considered to be affected by several complicated and coupled factors including soil particle gradations, soil minerals and compositions, hydraulic conditions, and stress states, etc. (Khilar *et al.* 1985, Bendahmane *et al.* 2008, Adams *et al.* 2013, Chang and Zhang 2013a, b, Bian *et al.* 2020). However, it appears to be a consensus in the literature that gap-graded soils and coarse soils with a flat tail of fines are often susceptible to the internal erosion (Chang and Zhang 2013b, Fannin and Slangen 2014). Under water seepage, fine particles can be eroded and transported by the seepage flow in the interconnected large pores formed by coarse particles. The loss or migration of fine particles due to seepage water may lead to adverse changes in soil physical and mechanical properties, such as reduction in shear strength, volumetric deformation, and the variation in hydraulic conductivity (Moffat *et al.* 2011, Xiao and Shwiyhat 2012, Ke and Takahashi 2012, 2014). Countermeasures against internal erosion involve the modification of soil properties, use of filter materials to relieve water pressure without causing erosion, reducing the hydraulic gradient by installing horizontal or vertical impervious curtains such as blankets, slurry trenches and diaphragm walls, increasing overburden pressure with

*Corresponding author, Professor
E-mail: yfgao66@163.com
[a]Associate Professor
E-mail: hejia@hhu.edu.cn
[b]Master Student
E-mail: changhangfang@163.com
[c]Ph.D. Student
E-mail: hlhhu@hhu.edu.cn
[d]Ph.D. Student
E-mail: ysshuai20@hhu.edu.cn
[e]Master Student
E-mail: 191304010006@hhu.edu.cn
[f]Master Student
E-mail: 181304010076@hhu.edu.cn
[g]Professor
E-mail: ydzhou@hhu.edu.cn

ISSN: 2005-307X (Print), 2092-6219 (Online)

weighing berms on downstream toes (Indraratna *et al.* 2008, Adams *et al.* 2013, Jiang and Soga 2017). As for the chemical modification of soils, various inorganic and organic materials such as lime, cement, fly ash, milled slag, and lignosulfonate can be used as stabilizers (Indraratna *et al.* 2008). These stabilizers can immobilize fine particle from being eroded, enhance the shear strength and stiffness of soils, and reduce the hydraulic conductivity of soils.

In recent years, alternative soil modification technologies using biological processes have also gained increasing interests in soil leakage control and rehabilitation of dams and dikes (Blauw *et al.* 2009, Jiang and Soga 2017, Jiang *et al.* 2017, Saracho and Haigh 2018, Naufila and Sreevidhya 2019, Haouzi *et al.* 2018, Wu *et al.* 2019). Using these biological methods can potentially bring more technical and environmental benefits to the construction projects. Several microbial processes have been experimentally studied for related applications. Bio-mineralization in soil can produce cementitious mineral crystals in soil pores, and in turn greatly enhance the shear strength and reduce the permeability of soils (Al Qabany and Soga 2013, Chu *et al.* 2012, DeJong *et al.* 2010, van Paassen *et al.* 2010). Extracellular polymeric substances (EPS), which is a slime-type material excreted by some soil microbial species, can reduce the soil permeability by around 2 orders-of-magnitude or even higher (Ivanov and Chu 2008, Proto *et al.* 2016, Thullner 2010, Kim *et al.* 2017, 2019). It has been reported that the leakage in earth dikes can be effectively controlled by facilitating the in-situ growth of bacteria for EPS production (Blauw *et al.* 2009). In addition, microbial excreted polymer can also increase the shear strength and mechanical behavior of sands and clays (Lee *et al.* 2019, Kwon *et al.* 2019). In sandy and silty soil grounds that are susceptible to liquefaction, large movement of grounds and destruction of the structures on the grounds may take place during earthquake events. It has recently been found that slight reduction in the soil degree of saturation by the in-situ production of biogenic gas bubbles can change the undrained responses of soils and improve the liquefaction resistance of soil grounds (He *et al.* 2013, He and Chu 2014, He *et al.* 2014). It can potentially be adopted as a simple and cost-effective method for liquefaction control. Among these microbial processes and methods, bio-mineralization based on the enzyme- or microbially-induced carbonate precipitation (EICP or MICP) by the ureolytic process has received most of the research focuses. The reaction involves the hydrolyzation of urea into ammonia and carbonate catalyzed by urease or ureolytic bacteria. With the aqueous calcium in the system, calcium carbonate can be precipitated in soil, as,

$$NH_2\text{-}CO\text{-}NH_2 + 2H_2O \xrightarrow[\text{ureolytic bacteria}]{\text{Urease Enzyme or}} 2NH_4^+ + CO_3^{2-} \quad (1)$$

$$C_a^{2+} + CO_3^{2-} \longrightarrow C_aCO_3 \downarrow \quad (2)$$

Calcium carbonate can form crystals, and bring strong and persistent cementation effects between soil particles. The mechanical properties of soils can thus be greatly improved. It was demonstrated in many previous studies that the MICP method could successfully enhance the strength and reduce the permeability of sand (Ivanov and Chu 2008, DeJong *et al.* 2010, Van Paassen *et al.* 2010, DeJong *et al.* 2013, Dhami *et al.* 2013, Choi *et al.* 2019, Gao *et al.* 2019a, Hang *et al.* 2019, Xiao *et al.* 2018, Xiao *et al.* 2019). Recent studies also showed that the EICP method was also effective in enhancing the strength and mechanical properties of sand (Neupane 2013, Zhao *et al.* 2014, Neupane *et al.* 2015, Jiang *et al.* 2016, Hamdan and Kavazanjian 2016). But, most of these studies dealt with clean sand. In natural conditions, most of the sandy soils contain some fine particles. In addition, one of the major engineering problems related to silty sand is internal erosion under water seepage. Therefore, it is of practical interests to explore how to apply EICP or MICP method to the improvement of silty sand. However, limitations of the MICP method for the improvement of silty sand can be resulted from factors including relatively large sizes of bacterial cells and strong adherence of bacterial cells to solid surfaces. The MICP treatment uniformity of the silty sand can thus be affected. Typical bacterial cells are micrometers in size, and typical urease enzyme molecules are nanometers in size (Krajewska 2009, Erickson 2009). Recent experimental studies also showed that using the EICP method based on crude urease was a promising way for the improvement of silt or silty sand (Gao *et al.* 2019b, He *et al.* 2020). Therefore, in this study, we concentrated on the EICP method for the improvement of silty sand to control internal erosion under water seepage.

For the soil erosion control with the biological soil improvement technologies, several forms of erosions have been investigated in research studies, including wind erosion (Hamdan and Kavazanjian 2016, Zomorodian *et al.* 2019, Almajed *et al.* 2020, Fattahi *et al.* 2020, Nikseresht *et al.* 2020), surficial erosion by rainfall or waves (Salifu *et al.* 2016, Amin *et al.* 2017, Wang *et al.* 2018, Imran *et al.* 2019, Jiang *et al.* 2019, Shahin *et al.* 2020), soil desiccation (Cheng *et al.* 2020, Liu *et al.* 2020), and soil internal erosion under water seepage (Jiang and Soga 2017, Jiang *et al.* 2017). As for the internal erosion in soils, laboratory experimental studies were made to use the MICP method for the control of erosion. It was found that the MICP treatment was effective in controlling the piping- or suffusion-type erosion (Jiang and Soga 2017, Jiang *et al.* 2017, Naufila and Sreevidhya 2019, Haouzi *et al.* 2018). The amount of fine particles eroded and soil volume change were lower than those in the untreated soil. The critical hydraulic gradient was increased by the MICP treatment. The MICP method was also tested for the control of contact erosion, which was another form of internal erosion initiated by water seepage along the interface between two materials (Saracho and Haigh 2018). In addition to the laboratory studies, a field experiment conducted by Blauw *et al* (2009) showed that, by stimulating the in-situ bacterial growth for EPS production, the leakage in a dike was successfully sealed.

In this paper, experimental studies were made to evaluate the use of the EICP method for the control of internal erosion under water seepage. A specially designed apparatus was made which allowed to carry out both soil treatments and seepage erosion experiments. The treatment

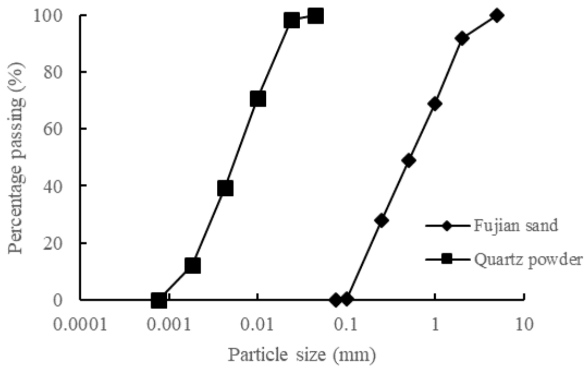
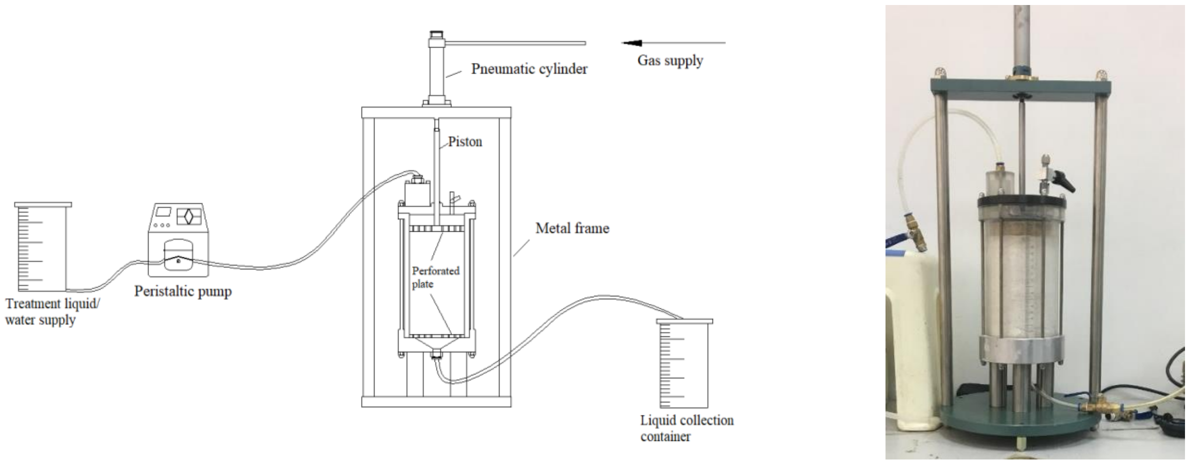


Fig. 1 Particle size distribution of testing soils



(a) Schematic diagram (b) Photograph of the test chamber

Fig. 2 Testing apparatus

effects were evaluated from several aspects including the amount of fine particles eroded, axial deformation of soil sample, change in hydraulic conductivity, and calcium carbonate content and distribution in soil. In addition to the EICP soil samples, the untreated and MICP samples were also tested for comparison purposes. To the authors' knowledge, the EICP method for soil internal erosion control has not been studied in the past.

2. Materials and methods

2.1 Materials

Testing soil used in the study was prepared by artificially mixing Fujian Sand and quartz powder at 85:15 ratio. Fujian Sand is a Chinese standard sand with angular particle shape and more than 96% quartz content. The specific gravity is 2.65. The quartz powder was supplied by Shengli Quartz Sand Co. Ltd. China. The specific gravity is 2.64. The particle size distribution curves of these two materials were given in Fig. 1. According previous studies regarding soil internal erosion, such a soil was highly susceptible to internal erosion under seepage flow (Chang and Zhang 2013b). In the experiment, the soil was compacted to achieve 1.82 g/cm^3 dry density before treatment.

As for the soil improvement with the EICP method, calcium salt, urea, and urease enzyme were required. Calcium chloride and urea used in the experiments were laboratory-grade reagents. Soybean purchased from the market was used for the extraction of crude urease. The soybeans were dried in a 40˚C oven for six hours. The soybeans were then ground into powder using a kitchen grinder. The soybean powders were stored in a 4˚C refrigerator before use. The soybean powders were added into deionized water at 25 g/L concentration and mixed in water using a magnetic stirrer to obtain a homogeneous suspension. The suspension was left for 3 hours. Then, the suspension was filtered with double-layer cotton gauze. The filtered liquid was further centrifuged at 3000 rpm and 4˚C for 15 minutes. After the centrifugation, the clean supernatant liquid containing crude urease was used for the soil treatment. The urease liquid prepared in this way had a urea-hydrolyzing activity of 4.2 – 4.5 mmol/L/min.

For the comparison purpose, the microbially induced carbonate precipitation (MICP) with ureolytic bacteria were also investigated in the experiment. *Sporosarcina pasteurii* (No. CGMCC1.3687 from China General Microbiological Culture Collection Center) was used in this study. It was a ureolytic species which was widely used in the MICP and biocement studies. The bacterial cultivation medium consisted of: 20g/L yeast extract, 10g/L NH_4Cl, 24 mg/L $N_iCl_2•6H_2O$, 12 mg/L $M_nSO_4•H_2O$, and N_aOH for the

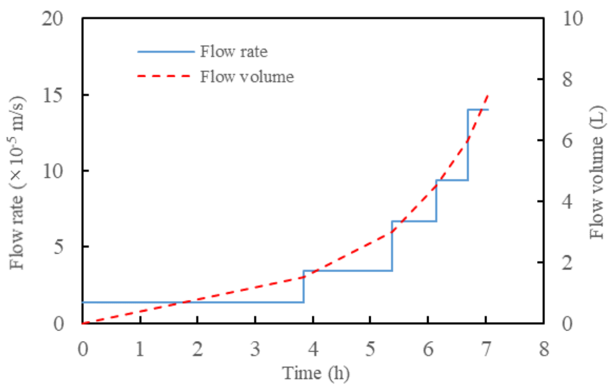


Fig. 3 Flow rate and volume of water seepage during the internal erosion test

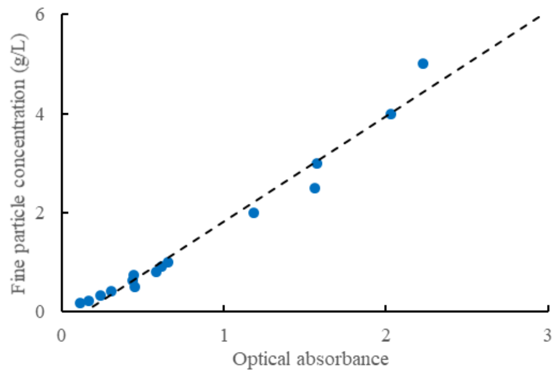


Fig. 4 Relationship between fine particle concentration and optical absorbance

adjustment of pH to 8.0. The cultivation medium was autoclaved and inoculated aseptically. The liquid medium was incubated aerobically at 30˚C and 100 rpm shaking condition for 24 hours. The harvested bacteria suspension was diluted to a level with 4.5 mmol/L/min urea hydrolyzing activity, which was similar to that of the urease derived from soybeans.

2.2 Testing apparatus

The apparatus for the internal erosion tests is schematically shown in Fig. 2. The chamber for the soil sample had 100 mm inner diameter and 200 mm inner height. There were openings at the top and bottom of the chamber for water flow during the EICP soil improvement and the seepage erosion experiment. The bottom outlet the of chamber was funnel-shaped to prevent the clogging by fine particles. Overburden pressure could be applied to the top of the soil sample by a pneumatic pressure-driven piston. Two perforated plates were placed on the top and bottom of the soil sample to hold the sample and allow the water seepage at the same time. Water pressure difference acting on the soil sample could be measured using a differential pressure gauge. The test chamber was fixed in a metal frame to allow the easy conduction of the experiments. During the soil treatment and the seepage erosion experiment, treatment liquid or water was pumped into the soil chamber through the top opening at constant flow rates using a peristaltic pump. Effluent could also be collected from the bottom of the chamber.

2.3 Soil preparation

Testing soil used was prepared by artificially mixing Fujian Sand and quartz powder at 85:15 ratio as stated in Section 2.1. Testing soil was placed into the chamber by five equal portions. The final height of the sample was 16 cm. Woven geotextile was placed at the top and bottom of the soil sample. A coarse sand cushion was also placed on top of the soil sample.

After the formation of a soil sample, the sample was saturated using a vacuum pumping method. The top opening valve was closed, and a vacuum pressure was applied to the soil sample through the bottom opening for 3 hours. Then, the bottom opening valve was then closed, and the top opening valve was open to suck water into the soil sample. The water saturation process maintained for 3 hours.

2.4 Soil treatment

The soil treatment liquid contained 1/4 urease enzyme liquid (or bacterial suspension) and 3/4 equimolar calcium chloride-urea solution. The two liquid was mixed together right before injecting into the soil sample. After mixing, the concentration of calcium chloride and urea was 0.5 mol/L, and the pH was from 7-8. In each treatment pass, 1.5 pore-volume treatment liquid was injected into the sample at a rate of 5.3×10^{-6} m/s. This injection rate could not trigger any internal erosion in the soil. After completing the injection, the treatment liquid retained in the soil sample for

Table 1 Test programme

Test No.	Treatment method	Concentration of C_aCl_2 and urea (mol/L)	Treatment passes
TW-1	-	0	1 (de-ionized water)
TE-1	EICP	0.5	1
TE-3	EICP	0.5	3
TE-5	EICP	0.5	5
TB-3	MICP	0.5	3

24 h before the next pass of treatment.

There were totally five tests as listed in Table 1. Three soil samples, TE-1, TE-3, and TE-5, were treated by the EICP method with 1, 3, and 5 treatment passes, respectively. One soil sample, TB-3, was treated by the MICP method with 3 treatment passes. For the control sample TW-1 without any treatment, 1.5 pore-volume de-ionized water was injected into the soil as one treatment pass.

2.5 Internal erosion test

Internal erosion tests under water seepage were carried out after the soil improvement. An overburden pressure of 40 kPa was applied to the soil sample during the internal erosion tests. For each soil sample, water seepage was applied to the soil from the top down with stepwise increasing flow rates, as shown in Fig. 3. The incremental flow rates consisted of five steps: 1.4×10^{-5}, 3.4×10^{-5}, 6.7×10^{-5}, 9.4×10^{-5},1.4×10^{-4} m/s, respectively. At each step of flow rate, 1.5 L water was injected, and totally 7.5 L water was injected for each internal erosion test on one soil sample.

At each step of flow rate, fine particle concentration in the effluent, axial deformation, and the water pressure difference to maintain the flow rate were measured. The fine particle concentration in the effluent was measured using an optical absorbance method. The particle concentration in relation to the optical absorbance under 460 nm wavelength showed a linear relationship, as could be seen in Fig. 4. The optical absorbance was measured using Type-723 UV-vis spectrophotometer, Jinghua Instruments Corporation. Such a relationship was used for the determination of particle concentration in the effluent. The axial deformation was obtained by measuring the relative displacement of the piston to the soil chamber during the erosion tests. The water pressure difference acting on the soil sample was measured using a differential pressure gauge. It should be also mentioned that, in each step, the initial flow rate was regulated by adjusting the water pressure difference. During each step of internal erosion, the fine particles in the soil body redistributed, causing the change (mostly decrease in this study) in the soil permeability. At a constant pressure difference, the flow rate also changed accordingly.

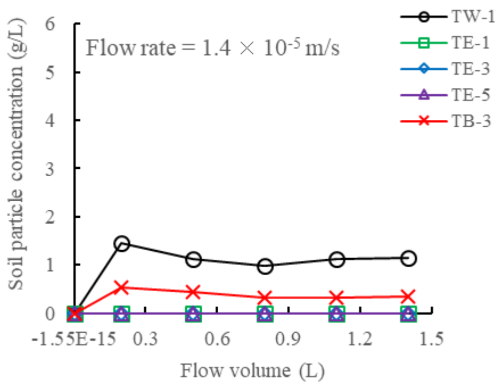
After the internal erosion test, small pieces of soils were taken from the top, middle, and bottom part of the soil sample for the determination of calcium carbonate content and distribution. The soil pieces were rinsed in deionized water and dried to remove soluble salts. Then, each piece of soil was placed in hydrochloric acid to dissolve all the C_aCO_3. The concentration of aqueous calcium in the hydrochloric acid was measured using the EDTA titrimetric method (ISO, 1984). This concentration of aqueous calcium was consistent with the calcium carbonate content in the soil. It should be clarified that there was around 20% calcium carbonate loss during the seepage erosion tests, according to the preliminary test. The calcium carbonate contents given in the paper were those after the erosion tests.

3. Results and discussions

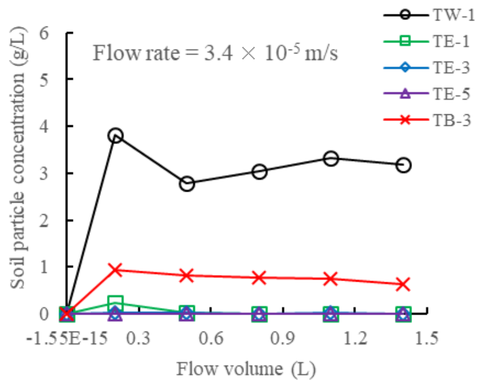
3.1 Soil particle loss

Soil particle concentrations in the effluents at different steps of flow rates are presented in Fig. 5. In the tests with large amount of soil particle outflow, the particle concentration rapidly increased to the peak value, followed by a gradual decrease to a stable value until the end the test step. This might be due to the redistribution of fine particles and the decrease in the soil permeability, as could be seen in Section 3.3. Compared with the EICP or MICP treated samples, the untreated sample TW-1 was more susceptible to seepage erosion. The particle concentration in the effluent was the largest among the five soil samples at each step of flow rates. The EICP sample had a relatively strong ability to resist seepage erosion. The treatment effect also improved with the number of treatment passes. When the flow rate was low (1.4×10^{-5} and 3.4×10^{-5} m/s), there was no obvious soil particle outflow in the three EICP samples. When the flow rate increased to 6.7×10^{-5} and 9.4×10^{-5} m/s, small amounts of solid particles flowed out at the early stages in Tests TE-1 and TE-3. These part of soil particles could be weakly cemented, and the resistances to seepage erosion was not very strong. When the flow rate increased to 1.4×10^{-4} m/s, Tests TE-1 and TE-3 showed evident soil particle outflow. However, Test TE-5, which was treated by the EICP method for 5 passes, showed almost no soil particles in the effluents at all levels of flow rates, indicating strong resistance to seepage erosion. The strong resistances to internal erosion was mainly due to the calcium carbonate cementation inside the soil after the EICP improvement. Calcium carbonate effectively brought cementation between soil particles, so that the silt particles were not easily taken away by water seepage erosion. The figures also showed that the MICP sample TB-3 had higher soil particle concentrations in the effluents compared with the three EICP soil samples. However, the particle concentrations in the TB-3 were lower than those in the untreated sample TW-1. These comparative results showed that the MICP treatment had some effect for seepage erosion control. But it was not as effective as the EICP method. This might be due to the size of the bacterial cells as compared with the size of enzyme molecules. Detailed discussions will be made in Section 3.4.

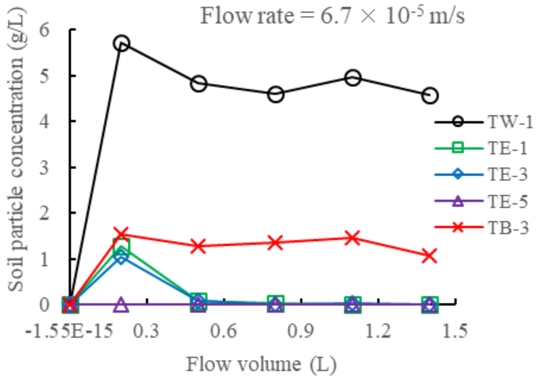
The results of erosion rates at different levels of flow rates are presented in Fig. 6. The erosion rate here was defined as the average amount of soil particles flowed out



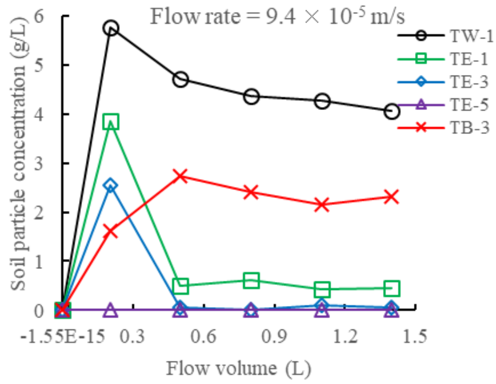
(a) 1.4×10^{-5} m/s



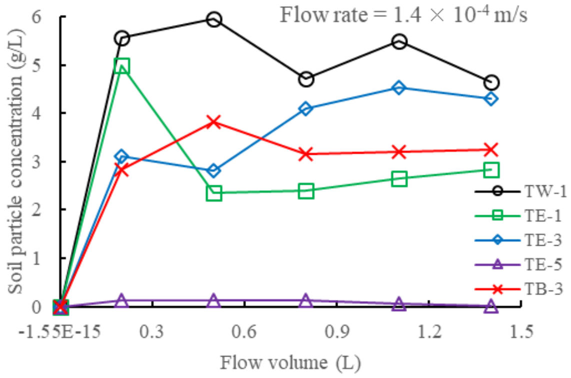
(b) 3.4×10^{-5} m/s



(c) 6.7×10^{-5} m/s



(d) 9.4×10^{-5} m/s;



(e) 1.4×10^{-4} m/s

Fig. 5 Soil particle concentrations in the effluents at different steps of flow rates

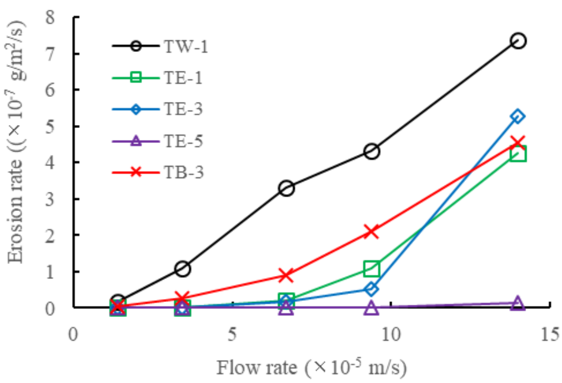


Fig. 6 Erosion rates at different levels of flow rates

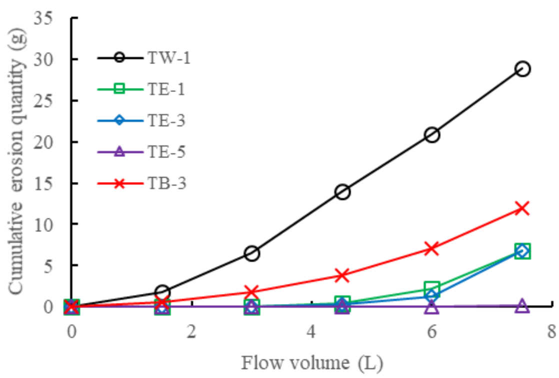


Fig. 7 cumulative erosion quantity in relation to flow volume

of the soil sample per second over the unit cross-sectional area. The overall trend was that the erosion rate increased with the increase in the flow rate. The flow rate was directly related to the seepage force and the hydraulic shear stress

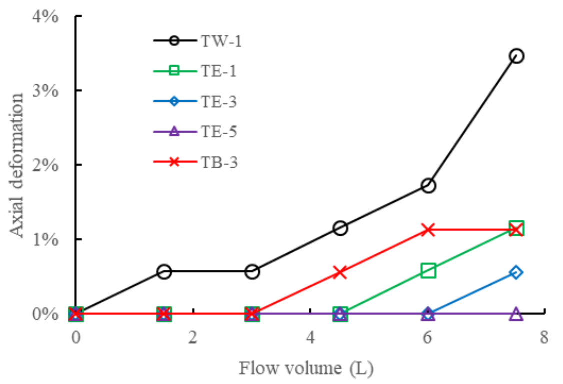


Fig. 8 Axial deformation in relation to flow volume

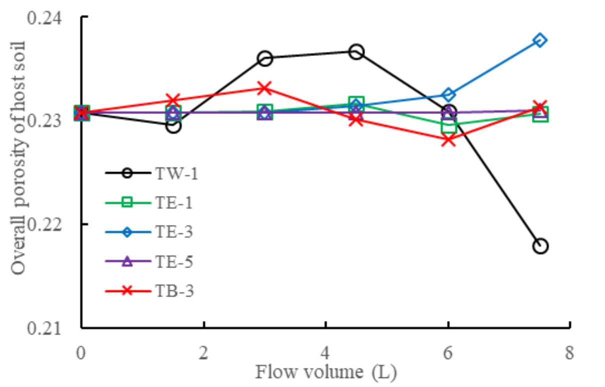


Fig. 9 Overall soil porosity of host soil in relation to flow volume

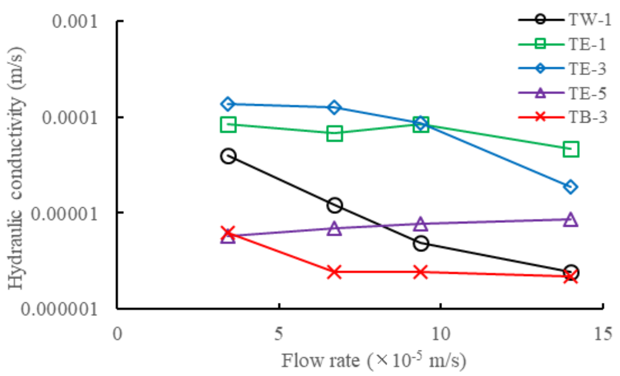


Fig. 10 Variation of hydraulic conductivities during seepage erosion

acting on the soil skeleton (Jiang *et al.* 2017). Thus, when the seepage-induced shear stress exceeded the shear resistance of the fine particles in the soil, the erosion of this portion of particles took place. The soil samples with different treatment methods and levels also differed in the performance of the erosion resistance. Test TW-1 without any cementation treatment had the highest erosion rate each level of flow rates. The soil samples treated by the EICP method had stronger resistance to seepage erosion as compared with the MICP sample. And as for the comparison among the three EICP samples, the resistance to the seepage erosion increased with treatment levels. For example, at the flow rate of 9.4×10^{-5} m/s, the erosion rates were 0, 0.5, 1.1, 2.1, and 4.3 ($\times10^{-7}$ g/m^2/s) for TE-1, TE-3, TE-5, TB-3, and TW-1, respectively. The cumulative erosion quantity in relation to the flow volume is presented in Fig. 7. It was clearly seen that, at the same level of treatment, the EICP soil sample had a resistance against seepage erosion several times higher than the MICP soil sample in terms of the erosion rate and the cumulative erosion quantity. The erosion resistance also improved significantly with the treatment passes when using the EICP method.

3.2 Deformation

The axial deformation in relation to the flow volume is presented in Fig. 8. The EICP treated sample TE-5 did not have any evident axial deformation during the seepage process. The untreated sample TW-1 had the highest axial deformation 3.5%. Both the EICP and the MICP method could reduce the seepage-induced deformation in soil. However, the EICP method had better performance than the MICP method in the deformation control by showing smaller axial deformation and initiation of deformation at larger flow volume (or higher flow rate). The overall trend of the axial deformation was similar to that of the cumulative erosion quantity as shown in Fig. 7. The mechanisms of the EICP method for the deformation control under water seepage could be explained in three aspects. First, the cementation effect could fix fine particles in soil and improve the shear resistance against water seepage erosion. The less soil particle loss led to small axial deformation. This could be evidenced by the less fine particles flowed out in the EICP treated soil shown in Figs. 6 and 7. Second, the EICP improvement led to the cementation of sand matrix in the soil. The sand matrix could sustain its structure in spite of some level of fine particle loss within the sand matrix. Fig. 9 shows the variations of the overall soil porosity of host soil under seepage erosion. For the untreated sample TW-1, there was an increase in the porosity at the early stage of the seepage erosion, followed by a drop in the porosity. These results might imply that there was a collapse of the soil skeleton due to the loss of fine particle within the soil. For the EICP treated soils, there were slight increasing trends in the porosity. This could be due to the loss the fine particles without any radical change in the soil skeleton. Last, the cementation material calcium carbonate could occupy pore spaces, which might help reducing the deformation of the soils.

3.3 hydraulic conductivity

The variations of hydraulic conductivities during the seepage erosion experiments are presented in Fig. 10. In the soil samples TW-1, TB-3, TE-1, and TE-3, there were gradual decreases in the hydraulic conductivities. In the sample TE-5, the hydraulic conductivity showed a slightly increasing trend. For the samples TW-1, TB-3, TE-1, and TE-3, the movement of fine particles could accumulate within the soil and clog soil pores, leading to the decrease in the hydraulic conductivities. In TE-5, a small amount of fine particles along the seepage paths flowed out of the sample without causing any clogging. As a result, the

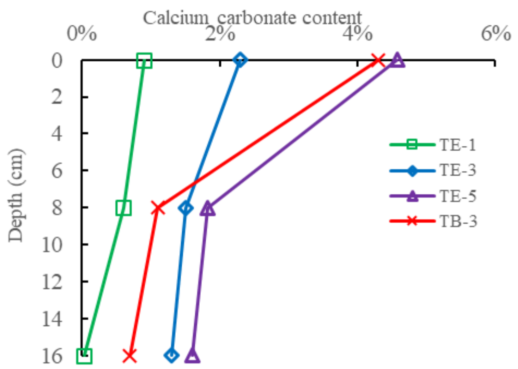


Fig. 11 Calcium carbonate content in the soil samples

hydraulic conductivity slightly increased. It was interesting to note that in Tests TW-1 and TB-3, hydraulic conductivities decreased to a rather low level, implying that the movement of particles and pore clogging could be radical. In the three EICP treated samples, the hydraulic conductivities were relatively high at the end of the tests. It was reported in Khilar *et al* (1984) that, in a gap-graded soil under water seepage, whether eroded fine particles flowed out or plugged the pore throats was related to the concentration of eroded particles. This concentration in turn depended upon the rate at which fine particles were eroded from the pore walls. This may explain why hydraulic conductivities decreased in TW-1, TB-3, TE-1, and TE-3, but increased in TE-5.

3.4 Calcium carbonate content

The calcium carbonate contents and distributions along the depths in the soil samples are presented in Fig. 11. It should be noted that the EICP or MICP treatments were applied from the top down. So, there were more calcium carbonate at the top than that at the bottom in the samples. In the three EICP treated samples, calcium carbonate content increased with the treatment passes. In Test TB-3, the calcium carbonate distribution was rather uneven along the depth of the sample. The calcium carbonate contents were 4.3%, 1.1%, and 0.7% at the top, middle and bottom parts, respectively. In comparison, in Test TE-3, The calcium carbonate contents were 2.3%, 1.5%, and 1.3% at the top, middle and bottom parts, respectively. In Test TE-5, calcium carbonate was produced mostly at the top part. This could be because of the reduction in the hydraulic conductivity after 3 passes of treatments. Nevertheless, it could clearly be found that the treatment by the EICP method could provide relatively uniform calcium carbonate distribution within the soil. It was also of interest to see that, although TE-1 had lower calcium carbonate content than TB-3, its resistance against seepage erosion was stronger. This was possibly because that calcium carbonate produced by the EICP method was more uniform at not only macroscale, but also soil particle scale. It was also possible to determine the calcium source conversion rates from $CaCl_2$ to $CaCO_3$ in the treatment processes. Based on the data given in Fig. 11 and those used in the treatment liquid, it was found that the calcium source conversion rates were 59-65% in the EICP treatment process, and 71% in the MICP treatment process. Such results were in agreement with Gao *et al.* (2019b) and He *et al.* (2020), which proved that intact bacterial cells had more stable ureolytic activity and higher reaction conversion rate than crude urease enzyme during urea hydrolyzing process. However, in the tested conditions adopted in this study, the calcium source conversion rates of the EICP treatment were still high enough to be used in practice.

These comparative results of calcium carbonate distribution shown in Fig. 11 are likely to be due to that enzyme molecules are smaller than the bacterial cells, and enzyme molecules have weaker tendency to adhere to solid surfaces. Typical bacterial cells are micrometers in size. The molecular weights of plant urease are 480 – 545 kDa (Krajewska and Barbara 2009). So, the sizes of urease molecules are several nanometers, according to the calculation given by Erickson (2009). Compared with enzyme molecules, some bacterial cells have particular surface organs or materials, such as flagella, pili and extracellular polysaccharides which lead to stronger surface adherence (Peng *et al.* 2001, Dan *et al.* 2014). It was also reported in (Gao *et al.* 2019b, He *et al.* 2020) that, for the treatment of silty sand or silt, the use of EICP method could produce better treatment uniformity as compared with the MICP method. As for the control of seepage-induced internal erosion, another advantage of the EICP method was that the treatment materials could flow together the seepage water to a larger extent, so that the cementation effect could be formed along the flow path. As a result, fine soil particles along the flow path could also be fixed. For the field application of internal erosion control, treatment liquid can be conveyed to the required location by injection or grouting. It is also worth taking note that conventional cement grout may have high viscosity, so that the treatment range for internal erosion control could be limited.

4. Conclusions

In this paper, experimental studies were made to evaluate the use of the EICP method for the control of internal erosion under water seepage. The following conclusions can be made,

- In terms of the amount and rate of eroded fine particles, the EICP soil samples had stronger resistance against seepage erosion as compared with the MICP sample and the untreated soil sample. The erosion control effects improved with treatment passes. In the soil sample with 5 treatment passes, the amount of eroded particles were negligible.
- The EICP method had better performance than the MICP in deformation control by showing smaller axial deformation and initiation of deformation at larger flow volume (higher flow rate). The level of axial deformation was roughly consistent with the amount of fine particles eroded.
- The variations of the hydraulic conductivity were dependent on whether eroded soil particles clogged in or flowed out of the soil sample. The hydraulic conductivities of soil samples with relatively large amount of eroded

particles decreased during the seepage erosion processes. However, in the soil sample with 5 EICP treatment passes, the hydraulic conductivity slightly increased compared with the initial condition.

• In the EICP samples, calcium carbonate content increased with the treatment passes. The calcium carbonate distribution was relatively uniform in the EICP samples compared with the MICP sample.

Acknowledgments

The research presented in this paper was financially supported by Natural Science Foundation of China (Projects No. 51978244, 51979088, and 52078188).

References

Adams, B.T., Xiao, M. and Wright, A. (2013), "Erosion mechanisms of organic soil and bioabatement of piping erosion of sand", *J. Geotech. Geoenviron. Eng.*, **139**(8), 1360-1368. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000863.

Almajed, A., Lemboye, K., Arab, M.G. and Alnuaim, A. (2020), "Mitigating wind erosion of sand using biopolymer-assisted EICP technique", *Soils Found.*, **60**(2), 356-371. http://doi.org/10.1016/j.sandf.2020.02.011.

Al Qabany, A. and Soga, K. (2013), "Effect of chemical treatment used in MICP on engineering properties of cemented soils", *Geotechnique.*, **63**(4), 331-339. http://doi.org/10.1680/geot.SIP13.P.022.

Amin, M., Zomorodian, S.M.A. and O'Kelly, B.C. (2017), "Reducing the hydraulic erosion of sand using microbial-induced carbonate precipitation", *Proc. Inst. Civ. Eng. Ground Improv.*, **170**(GI2), 112–122. http://doi.org/10.1680/jgrim.16.00028.

Bendahmane, F., Marot, D. and Alexis, A. (2008), "Experimental parametric study of suffusion and backward erosion", *J. Geotech. Geoenviron. Eng.*, **134**(1), 57-67. http://doi.org/10.1061/(ASCE)1090-0241(2008)134:1(57).

Bian, X., Cui, Y., Zeng, L. and Li, X. (2020), "State of compacted bentonite inside a fractured granite cylinder after infiltration", *Appl. Clay Sci.*, **186**. http://doi.org/10.1016/j.clay.2020.105438.

Blauw, M., Lambert, J.W.M. and Latil, M.N. (2009), "Biosealing: A method for in situ sealing of leakages", *Proceedings of the International Symposium on Ground Improvement Technologies and Case Histories*, Singapore, December.

Chang, D. and Zhang, L.M. (2013a), "Critical hydraulic gradients of internal erosion under complex stress states", *J. Geotech. Geoenviron. Eng.*, **139**(9), 1454-1467. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000871.

Chang, D. and Zhang, L.M. (2013b), "Extended internal stability criteria for soils under seepage", *Soils Found.*, **53**(4), 569-583. http://doi.org/10.1016/j.sandf.2013.06.008.

Cheng, Q., Tang, C., Zeng, H., Zhu, C., An, N. and Shi, B. (2020), "Effects of microstructure on desiccation cracking of a compacted soil", *Eng. Geol.*, **265**. http://doi.org/10.1016/j.enggeo.2019.105418.

Choi, S., Chu, J. and Kwon, T. (2019), "Effect of chemical concentrations on strength and crystal size of biocemented sand", *Geomech. Eng.*, **17**(5), 465-473. http://doi.org/10.12989/gae.2019.17.5.465.

Chu, J., Stabnikov, V. and Ivanov, V. (2012), "Microbially induced calcium carbonate precipitation on surface or in the bulk of soil", *Geomicrobiol. J.*, **29**(6), 544-549. http://doi.org/10.1080/01490451.2011.592929.

Dan, V.N., Nicolau, D.V., Paszek, E. and Fulga, F. (2014), "Mapping hydrophobicity on the protein molecular surface at atom-level resolution", *Plos One*, **9**(12). http://doi.org/10.1371/journal.pone.0114042.

DeJong, J.T., Mortensen, B.M., Martinez, B.C. and Nelson, D.C. (2010), "Bio-mediated soil improvement", *Ecol. Eng.*, **36**(2), 197-210. http://doi.org/10.1016/j.ecoleng.2008.12.029.

DeJong, J. T., Soga, K., Kavazanjian, E., Burns, S., Van Paassen, L.A., Al Qabany, A., Aydilek, A., Bang, S.S., Burbank, M., Caslake, L.F., Chen, C.Y., Cheng, X., Chu, J., Ciurli, S., Esnault-Filet, A., Fauriel, S., Hamdan, N., Hata, T., Inagaki, Y., Jefferis, S., Kuo, M., Laloui, L., Larrahondo, J., Manning, D.A.C., Martinez, B., Montoya, B.M., Nelson, D.C., Palomino, A., Renforth, P., Santamarina, J.C., Seagren, E.A., Tanyu, B., Teserarsky, M., Weaver, T. and Laloui, L. (2013), "Biogeochemical processes and geotechnical applications: Progress, opportunities and challenges", *Geotechnique.*, **63**(4), 287-301. http://doi.org/10.1680/geot.SIP13.P.017.

Dhami, N.K., Reddy, M.S. and Mukherjee, A. (2013), "Biomineralization of calcium carbonates and their engineered applications: A review", *Front. Microbiol.*, **4**, 314-314. http://doi.org/10.3389/fmicb.2013.00314.

Erickson, H.P. (2009), "Size and shape of protein molecules at the nanometer level determined by sedimentation, gel filtration, and electron microscopy", *Biol. Proc. Online*, **11**(1), 32-51. http://doi.org/10.1007/s12575-009-9008-x.

Fannin, R.J. and Slangen, P. (2014), "On the distinct phenomena of suffusion and suffusion", *Geotech. Lett.*, **4**(4), 289-294. http:/.doi.org/10.1680/geolett.14.00051.

Fattahi, S.M., Soroush, A. and Huang, N. (2020), "Biocementation control of sand against wind erosion", *J. Geotech. Geoenviron. Eng.*, **146**(6), 04020045. http://doi.org/10.1061/(ASCE)GT.1943-5606.0002268.

Floresberrones, R., Ramirezreynaga, M. and Macari, E.J. (2011), "Internal erosion and rehabilitation of an earth-rock dam", *J. Geotech. Geoenviron. Eng.*, **137**(2), 150-160. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000371.

Gao, Y.F., Hang, L., He, J. and Chu, J. (2019a), "Mechanical behaviour of biocemented sands at various treatment levels and relative densities", *Acta Geotech.*, **14**(3), 697-707. http://doi.org/10.1007/s11440-018-0729-3.

Gao, Y.F., He, J., Tang, X.Y. and Chu, J. (2019b), "Calcium carbonate precipitation catalyzed by soybean urease as an improvement method for fine-grained soil", *Soils Found.*, **59**(5), 1631-1637. https://doi.org/10.1016/j.sandf.2019.03.014.

Hamdan, N. and Kavazanjian, E.J. (2016), "Enzyme-induced carbonate mineral precipitation for fugitive dust control", *Geotechnique*, **66**(7), 546-555. http://doi.org/10.1016/j.sandf.2019.03.014.

Hang, L., Gao, Y., He, J. and Chu, J. (2019), "Mechanical behaviour of biocemented sand under triaxial consolidated undrained or constant shear drained conditions", *Geomech. Eng.*, **17**(5), 497-505. http://doi.org/10.12989/gae.2019.17.5.497.

Haouzi, F.Z., Filet, A.E. and Courcelles, B. (2018), "Performance studies of microbial induced calcite precipitation to prevent the erosion of internally unstable granular soils", *Proceedings of the GeoChina 2018: Advancements on Sustainable Civil Infrastructures*, Hangzhou, China, July.

He, J., Chu, J. and Ivanov, V. (2013), "Mitigation of liquefaction of saturated sand using biogas", *Geotechnique*, **63**(4), 267-275. http://doi.org/10.1680/geot.SIP13.P.004.

He, J. and Chu, J. (2014), "Undrained responses of microbially desaturated sand under monotonic loading", *J. Geotech. Geoenviron. Eng.*, **140**(5). http://doi.org/10.1061/(ASCE)GT.1943-5606.0001082.

He, J., Chu, J. and Liu, H. (2014), "Undrained shear strength of desaturated loose sand under monotonic shearing", *Soils Found.*, **54**(4), 910-916. http://doi.org/10.1016/j.sandf.2014.06.020.

He, J., Gao, Y.F., Gu, Z.X., Chu, J. and Wang, L.Y. (2020), "Characterization of crude bacterial urease for C_aCO_3 precipitation and cementation of silty sand", *J. Mater. Civ. Eng.*, **32**(5). http://doi.org/10.1061/(ASCE)MT.1943-5533.0003100.

Imran, M. A., Nakashima, K., Evelpidou, N. and Kawasaki, S. (2019), "Factors affecting the urease activity of native ureolytic bacteria isolated from coastal areas", *Geomech Eng.*, **17**(5), 421-427. http://doi.org/10.12989/gae.2019.17.5.421.

Indraratna, B., Muttuvel, T., Khabbaz, H. and Armstrong, R. (2008), "Predicting the erosion rate of chemically treated soil using a process simulation apparatus for internal crack erosion", *J. Geotech. Geoenviron. Eng.*, **134**(6), 837-844. http://doi.org/10.1061/(ASCE)1090-0241(2008)134:6(837).

International Organization for Standardization (ISO) (1984), Water quality -- Determination of calcium content -- EDTA titrimetric method, ISO 6058:1984.

Ivanov, V. and Chu, J. (2008), "Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ", *Rev. Environ. Sci. Biotechnol.*, **7**(2), 139-153. http://doi.org/10.1007/s11157-007-9126-3.

Jiang, N.J., Yoshioka, H., Yamamoto, K. and Soga, K. (2016), "Ureolytic activities of a urease-producing bacterium and purified urease enzyme in the anoxic condition: Implication for subseafloor sand production control by microbially induced carbonate precipitation (MICP)", *Ecol. Eng.*, **90**, 96-104. http://doi.org/10.1016/j.ecoleng.2016.01.073.

Jiang, N. J. and Soga, K. (2017), "The applicability of microbially induced calcite precipitation (MICP) for internal erosion control in gravel–sand mixtures", *Geotechnique*, **67**(1), 42-55. http://doi.org/10.1680/jgeot.15.P.182.

Jiang, N. J., Soga, K. and Kuo, M. (2017), "Microbially induced carbonate precipitation for seepage-induced internal erosion control in sand-clay mixtures", *J. Geotech. Geoenviron. Eng.*, **143**(3), 04016100. http://doi.org/10.1061/(ASCE)GT.1943-5606.0001559.

Jiang, N. J., Tang, C., Yin, L., Xie, Y. and Shi, B. (2019), "Applicability of microbial calcification method for sandy-slope surface erosion control", *J. Mater. Civ. Eng.*, **31**(11). http://doi.org/10.1061/(ASCE)MT.1943-5533.0002897.

Ke, L. and Takahashi, A. (2012), "Strength reduction of cohesionless soil due to internal erosion induced by one-dimensional upward seepage flow", *Soils Found.*, **52**(4), 698-711. http://doi.org/10.1016/j.sandf.2012.07.010.

Ke, L. and Takahashi, A. (2014), "Triaxial erosion test for evaluation of mechanical consequences of internal erosion", *Geotech. Test. J.*, **37**(2). http://doi.org/10.1520/GTJ20130049.

Khilar, K.C., Fogler, H.S. and Gray, D.H. (1985), "Model for piping-plugging in earthen structures", *J. Geotech. Eng.*, **111**(7), 833-846. http://doi.org/10.1061/(ASCE)0733-9410(1985)111:7(833).

Kim, Y., Kwon, T. and Kim, S. (2017), "Measuring elastic modulus of bacterial biofilms in a liquid phase using atomic force microscopy", *Geomech. Eng.*, **12**(5), 863-870. http://doi.org/10.12989/gae.2017.12.5.863.

Kim, Y., Park, T. and Kwon, T. (2019), "Engineered bioclogging in coarse sands by using fermentation-based bacterial biopolymer formation", *Geomech. Eng.*, **17**(5), 485-496. http://doi.org/10.12989/gae.2019.17.5.485.

Krajewska, B. (2009), "Ureases I. Functional, catalytic and kinetic properties: A review", *J. Mol. Catal. B. Enzym.*, **59**(1), 9-21. http://doi.org/10.1016/j.molcatb.2009.01.003.

Kwon, Y., Chang, I., Lee, M. and Cho, G.C. (2019), "Geotechnical engineering behavior of biopolymer-treated soft marine soil", *Geomech. Eng.*, **17**(5), 453-464. http://doi.org/ 10.12989/gae.2019.17.5.453.

Lee, S., Im, J., Cho, G.C. and Chang, I. (2019), "Laboratory triaxial test behavior of xanthan gum biopolymer-treated sands", *Geomech. Eng.*, **17**(5), 445-452. http://doi.org/ 10.12989/gae.2019.17.5.445.

Liu, B., Zhu, C., Tang, C., Xie, Y., Yin, L., Cheng, Q. and Shi, B. (2020), "Bio-remediation of desiccation cracking in clayey soils through microbially induced calcite precipitation (MICP)", *Eng. Geol.*, **264**. http://doi.org/10.1016/j.enggeo.2019.105389.

Moffat, R.M., Fannin, R.J. and Garner, S.J. (2011), "Spatial and temporal progression of internal erosion in cohesionless soil", *Can. Geotech. J.*, **48**(3), 399-412. http://doi.org/10.1139/T10-071.

Naufila and Sreevidhya, V. (2019), "Internal erosion control in sand-gravel mixtures using MICP", *Int. J. Eng. Res. Mech. Civ. Eng.*, **4**(4), 15-20.

Neupane, D., Yasuhara, H., Kinoshita, N. and Unno, T. (2013), "Applicability of enzymatic calcium carbonate precipitation as a soil-strengthening technique", *J. Geotech. Geoenviron. Eng.*, **139**(12), 2201-2211. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000959.

Neupane, D., Yasuhara, H., Kinoshita, N. and Ando, Y. (2015), "Distribution of mineralized carbonate and its quantification method in enzyme mediated calcite precipitation technique", *Soils Found.*, **55**(2), 447-457. http://doi.org/10.1016/j.sandf.2015.02.018.

Nikseresht, F., Landi, A., Sayyad, G., Ghezelbash, G. and Schulin, R. (2020), "Sugarecane molasse and vinasse added as microbial growth substrates increase calcium carbonate content, surface stability and resistance against wind erosion of desert soils", *J. Environ. Manage.*, **268**, 110639. http://doi.org/10.1016/j.jenvman.2020.110639.

Peng, J., Tsai, W. and Chou, C. (2001), "Surface characteristics of Bacillus cereus and its adhesion to stainless steel", *Int. J. Food Microbiol.*, **65**(1), 105-111. http://doi.org/10.1016/S0168-1605(00)00517-1.

Proto, C.J., Dejong, J.T. and Nelson, D.C. (2016), "Biomediated permeability reduction of saturated sands", *J. Geotech. Geoenviron. Eng.*, **142**(12), 04016073. http://doi.org/10.1061/(ASCE)GT.1943-5606.0001558.

Salifu, E., Maclachlan, E., Iyer, K.R., Knapp, C.W. and Tarantino, A. (2016), "Application of microbially induced calcite precipitation in erosion mitigation and stabilisation of sandy soil foreshore slopes: A preliminary investigation", *Eng. Geol.*, **201**(4), 96-105. http://doi.org/10.1016/j.enggeo.2015.12.027.

Saracho, A.C. and Haigh, S.K. (2018), "Experimental optimization of microbially induced calcite precipitation (MICP) for contact erosion control in earth dams", *Proceedings of the 9th International Conference on Scour and Erosion (ICSE 2018)*, Taipei, Taiwan, November.

Shahin, M.A., Jamieson, K. and Cheng, L. (2020), "Microbial-induced carbonate precipitation for coastal erosion mitigation of sandy slopes", *Geotech. Lett.*, **10**(2), 1-5. http://doi.org/10.1680/jgele.19.00093.

Thullner, M. (2010), "Comparison of bioclogging effects in saturated porous media within one- and two-dimensional flow systems", *Ecol. Eng.*, **36**(2), 176-196. http://doi.org/10.1016/j.ecoleng.2008.12.037.

Van Paassen, L.A., Ghose, R., Der Linden, T.J., Der Star, W.R. and Van Loosdrecht, M.C. (2010), "Quantifying biomediated ground improvement by ureolysis: Large-scale biogrout experiment", *J. Geotech. Geoenviron. Eng.*, **136**(12), 1721-1728. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000382.

Wang, X., Tao, J., Bao, R., Tran, T.V. and Tuckerkulesza, S.

(2018), "Surficial soil stabilization against water-induced erosion using polymer-modified microbially induced carbonate precipitation", *J. Mater. Civ. Eng.*, **30**(10), 04018267. http://doi.org/10.1061/(ASCE)MT.1943-5533.0002490.

Wu, C., Chu, J., Wu, S. and Hong, Y. (2019), "3D characterization of microbially induced carbonate precipitation in rock fracture and the resulted permeability reduction", *Eng. Geol.*, **249**, 23-30. http://dx.doi.org/10.1016/j.enggeo.2018.12.017.

Xiao, M. and Shwiyhat, N. (2012), "Experimental investigation of the effects of suffusion on physical and geomechanic characteristics of sandy soils", *Geotech. Test. J.*, **35**(6), 890-900. http://doi.org/10.1520/GTJ104594.

Xiao, P., Liu, H., Xiao, Y., Stuedlein, A.W. and Evans, T.M. (2018), "Liquefaction resistance of bio-cemented calcareous sand", *Soil Dyn. Earthq. Eng.*, **107**, 9-19. http://doi.org/10.1016/j.soildyn.2018.01.008.

Xiao, Y., Stuedlein, A. W., Ran, J. Y., Evans, T. M., Cheng, L., Liu, H. L., Van Paassen, L. A. and Chu, J. (2019), "Effect of particle shape on strength and stiffness of biocemented glass beads", *J. Geotech. Geoenviron. Eng.*, **145**(11). http://doi.org/10.1061/(ASCE)GT.1943-5606.0002165.

Zhao, Q., Li, L., Li, C., Li, M., Amini, F. and Zhang, H. (2014), "Factors affecting improvement of engineering properties of MICP-treated soil catalyzed by bacteria and urease", *J. Mater. Civ. Eng.*, **26**(12). http://doi.org/10.1061/(ASCE)MT.1943-5533.0001013.

Zomorodian, S. M., Ghaffari, H. and Okelly, B.C. (2019), "Stabilisation of crustal sand layer using biocementation technique for wind erosion control", *Aeolian Res.*, **40**, 34-41. http://doi.org/10.1016/j.aeolia.2019.06.001.

IC