Civil Engineering Dimension, Vol. 22, No. 1, March 2020, 1-5
ISSN 1410-9530 print / ISSN 1979-570X online
DOI: 10.9744/ced.22.1.1-5

Promoting Precipitation Technique using Bio-Chemical Grouting for Soil Liquefaction Prevention

Putra, H.[1]*, Yasuhara, H.[2], Kinoshita, N.[2], and Fauzan, M.[1]

Abstract: The applicability of bio-chemical grouting as an environmentally friendly method for liquefaction remediation was evaluated. Several combinations of organic and in-organic precipitations methods were conducted to obtain the optimum grouting solution. Organic precipitation method which employs a bio-agent of urease enzyme, promotes the precipitated calcite crystals. Meanwhile, the in-organic method was performed using chemical compounds only, without the bio-agent. Unconfined compression strength tests were conducted to assess the applicability of the grouting solutions for improving the soil strength. The experimental results showed that the organic precipitation produced a high precipitated amount and resulted in a significant improvement in the strength of the soil. The presence of the precipitated materials within the soil grains generated the strength of 272 kPa. The results of this study have elucidated that the organic precipitation method composed of reagents and enzyme of urease may be an alternative soil-improvement technique to prevent liquefaction susceptibility.

Keywords: Grouting; precipitation method; strength; liquefaction; soil improvement.

Introduction

Liquefaction commonly happens in the saturated granular soils, such as sandy and silty soil. It is subjected to cyclic loading during an earthquake and is characterized by the increase in pore water pressure in the soil, which is initiated by the cyclic undrained loading, and leads to a decrease in the effective confining pressure. Thus, in turn, causes a significant loss of shear strength in the soil [1–4]. This phenomenon able to trigger several damages in engineering structures, such as building toppling, settlement (floating), soil deforms, sand boils, and other failures. Some damaging effect of liquefaction has been reported during the Niigata earthquake in 1964, Hyogoken-Nambu earthquake in 1995, and Tohoku-Japan earthquake in 2011 [2,5,6].

Several soil improvement techniques have been developed for enhancing the soil resistance to liquefaction and reducing possible damages, such as densification, solidification by cement, epoxy, silicates or other chemical compounds, and bio-grouting methods using calcite precipitation techniques [4,7–9]. Zen [10] has conducted a premixing method using a cement to increase the cohesion of sandy soil. It was found that mixing 5.5% of cement improves the cohesion to 98 kPa, which equivalent to N-SPT of 15-20 and UCS 100 [10,11]. This result also reported that the premixing of 5.5% cement content appears enough to onset the liquefaction [10,11].

Calcite induced precipitation technique (CIPM) may be one of the innovative and emerging methods for liquefaction mitigation [8,12,13]. Many studies of CIPM have used bacterial to dissociate urea into NH_4^+ and CO_3^{2-}[14–17], thus are precipitated as calcite crystals in the existence of calcium ions. In this technique, the grouting solution, which produces calcite, is injected into the sand sample. The precipitated material in sandy soil may deliver bonds between the sand grains, limiting their movement, and thus, enhancing the soil strength. The deposited calcium carbonate fills the voids, thereby reducing the permeability and porosity [15,18,19].

The use of microorganisms in the calcite precipitation method has some complexities, such as the incubation of bacteria may be tough to control and required special treatments [18]. Yasuhara et al. [18] introduced a potential method among calcite precipitation techniques, which is called enzyme-mediated calcite precipitation (EMCP) [18,20]. In this method, the enzyme of urease is used to hydrolyze urea into NH_4^+ and CO_3^{2-} instead of microorganisms. Using the urease enzyme is more straightforward than using microorganisms because biological handlings do not need to be considered [18,19]. The mixture of enzyme and reagent, which produce the precipitated calcite, are applied to soil samples. Thus, the cultivation and the fixation of the enzyme are not mandatory [18,20]. The efficacy of the EMCP method has already been assessed in the previous study, in which levels of

[1] Department of Civil and Environmental Engineering, IPB University, Dramaga, Bogor, 16680, INDONESIA.
[2] Department of Civil and Environmental Engineering, Ehime University, 3 Bunkyo-cho, Matsuyama, 790-8577, JAPAN.
* Corresponding author; email: heriansyahptr@apps.ipb.ac.id

Note: Discussion is expected before July, 1st 2020, and will be published in the "Civil Engineering Dimension", volume 22, number 2, September 2020.

Received 17 December 2019; revised 27 January 2020; accepted 04 May 2020.

strength, ranging from 400 kPa to 1600 kPa, are obtained [14,21–23].

In the present work, the efficacy of bio-chemical grouting, using enzyme induced calcite precipitation and chemical compounds for liquefaction mitigation, were evaluated. The optimum combinations regarding the mass precipitated minerals, and the chemical reaction was fixed by test-tube experiment. Sand samples were prepared in PVC mold and treated with the selected combinations of bio-chemical grouting. Then, the improvement of the strength of improved samples was assessed using the unconfined compression strength (UCS) tests. Finally, the applicability of grouting materials for enhancing the soil resistance to liquefaction was explicitly evaluated.

Materials and Methods

Material

Urea ($CO(NH_2)_2$), calcium chloride ($CaCl_2$), magnesium sulfate ($MgSO_4$), sodium dihydrogen phosphate (NaH_2PO_4), sodium bicarbonate ($NaHCO_3$), magnesium nitrate ($Mg(NO_3)_2$), and sodium hydroxide (NaOH) with claimed purity levels higher than 95%, were obtained from Kanto Chemicals Co. Inc. The enzyme of urease (020-83242, Kishida Chemical, Osaka, Japan), extraction from jack bean meal, and with urease activity of 2950 U/g, was used in the bio-catalytic dissociation of urea.

The silica sand with maximum void ratio (emax), minimum void ratio (emin) the coefficient of uniformity (Cu), and specific gravities (Gs) of 0.899, 0.549, 1.550, and 2.653, respectively was used to evaluate the effect of the application of bio-chemical grouting on the soil strength [23]. It was categorized as the most potential liquified soil based on the analysis of particle size distribution [24,25]. The grain size distribution curve of the silica sand and the liquefaction potential limit are shown in Figure 1 [25].

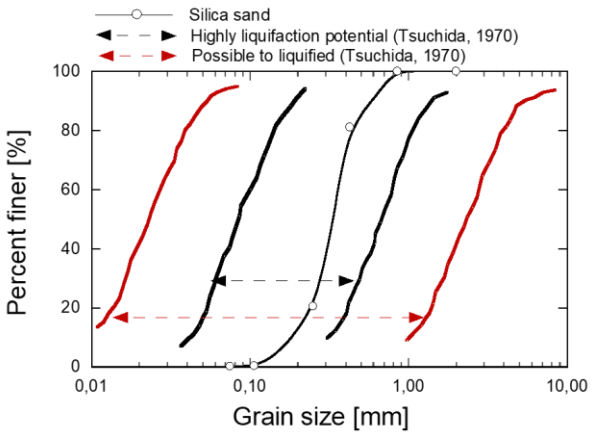

Figure 1. Grain Size Distribution of Silica Sand and the Liquefaction Potential Curve (25)

Precipitation Test

Precipitation tests using a transparent tube are conducted to evaluate the efficacy of several combinations of the potential bio-chemical grouting in the production of precipitation material as a cemented agent. Precipitation tests are performed for both organic and inorganic precipitation. Organic precipitation refers to the utilization of bio-agent (i.e., enzyme) as a catalyst in the chemical process. The sample preparation procedure, developed by Putra et al. [19], was adopted in this work. Firstly, an enzyme of urease was mixed into the distilled water and filtered using filter paper (pore size of 11 μm) to remove the undissolved particles of urease. Secondly, urea, calcium chloride, and magnesium sulfate are mixed thoroughly with distilled water, separately. Finally, the solution of $CaCl_2$ - $MgSO_4$ - $CO(NH_2)_2$ and the filtered enzyme were mixed thoroughly to obtain a total volume of 30 mL and permitted to react for 3-days curing times. The schematic of the procedure of precipitation test is illustrated in Figure 2 [19].

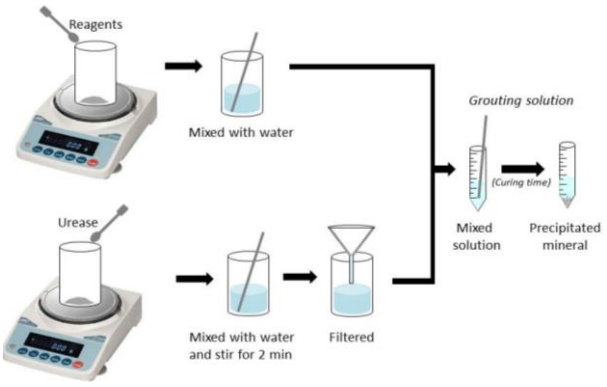

Figure 2. Schematic of the Procedure of Precipitation Test (19)

In-organic precipitations are performed without the bio-agent. Several combinations of sodium dihydrogen phosphate (NaH_2PO_4), sodium bicarbonate ($NaHCO_3$) magnesium nitrite ($Mg(NO_3)_2$), calcium chloride ($CaCl_2$), and sodium hydroxide (NaOH) are mixed to obtain the optimum combinations based on the amount of precipitation materials. NaH_2PO_4, $NaHCO_3$, $Mg(NO_3)_2$, $CaCl_2$, NaOH are mixed with distilled water separately, to make the chemical solutions, then, all the solution are mixed to obtain a total volume of 30 mL and permitted to react for 3-days curing times.

After curing, the grouting solution was filtered through the filter paper. The deposited particles on the filter paper and residual in the tubes were dried, and the amount was assessed to obtain precipitated mass. Finally, the optimum combinations obtained from the inorganic and organic precipitation are selected to apply in the soil sample. Two tests were performed for each case to obtain the reproducibility. The experiment conditions for precipitation tests are

shown in Table 1. OC and OS refer to the organic precipitation with combination reagent of $CaCl_2$-$MgCl_2$ and $CaCl_2$-$MgSO_4$, respectively, and IP refers to the in-organic precipitation.

Table 1. Experimental Conditions for Precipitation Test

Case	Material concentration				
	$CaCl_2$ [mol/L]	$MgCl_2$ [mol/L]	$MgSO_4$ [mol/L]	$CO(NH_2)_2$ [mol/L]	Urease [g/L]
OC-1	0.95	0.05	-	1.00	2.00
OC-2	0.90	0.10	-	1.00	2.00
OS-1	0.95	-	0.05	1.00	2.00
OS-2	0.90	-	0.10	1.00	2.00

(a) Organic precipitation

Case	Material concentration				
	NaH_2PO_4 [mol/L]	$NaHCO_3$ [mol/L]	$Mg(NO_3)_2$ [mol/L]	$CaCl_2$	NaOH [mol/L]
IP-1	1.00	-	0.50	-	0.20
IP-2	1.00	-	-	1.00	-
IP-3	-	0.50	0.25	-	0.10

(b) In-organic precipitation

Unconfined Compression Strength Test

Unconfined compression strength (UCS) tests were performed to assess the improvement of the strength of the treated sand. The experimental procedures developed by Putra et al. [19] were followed in this study. The PVC cylinder (5 cm in diameter and 10 cm in height) was used for preparing the sand specimen. Firstly, 300 g of the dry silica sand was poured into the cylinders to obtain a relative density of 50%. Secondly, the 75 mL (i.e., 1 pore volume (PV)) of optimum grout solutions were applied to the sand samples. After curing time, the treated sample was removed from the PVC cylinder. Before the UCS test was performed, the surface of the improved sample was flattened. The mechanical properties of the treated samples were evaluated by the UCS test of the specimens in wet conditions [19,26]. Two tests were conducted for each condition to check the reproducibility. The schematic of the procedure of the UCS test is illustrated in Figure 3 [19].

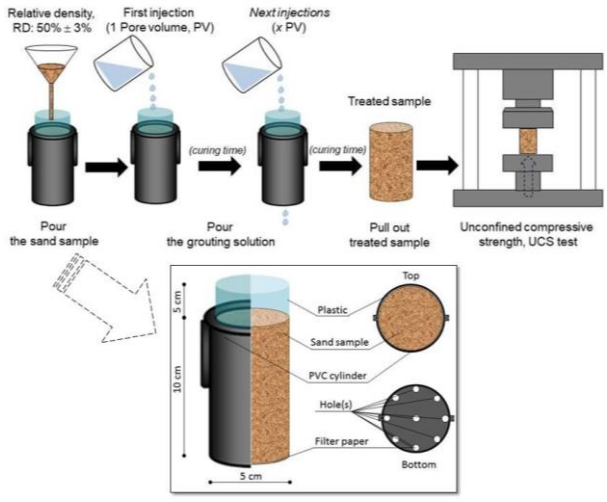

Figure 3. Schematic of Procedure of UCS Test [19]

Results and Discussion

The precipitation test results for several combinations of organic and in-organic precipitations method were evaluated. The summary of precipitation tests result is shown in Figure 4.

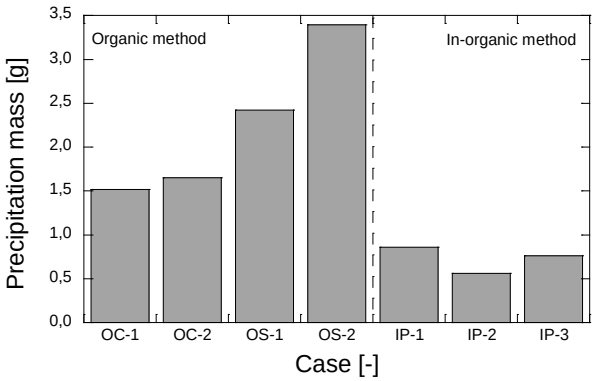

Figure 4. Results of Precipitation Tests

As is apparent, in the organic precipitation of OC, the utilization of $MgCl_2$ of 0.10 (i.e., OC-2) produced a higher amount of precipitation compared than OC-1, which are 1.52 g and 1.65 g, respectively. In the case of OS, the use of 0.10 $MgSO_4$ has promoted a higher mass of the precipitated material compared to 0.05 $MgSO_4$. In the in-organic precipitation, the precipitated mass obtained from the IP-1 and IP-3 resulted in a similar mass, which is higher than that of IP-2. This results indicated that the presence of $Mg(NO_3)$ and NaOH have a higher contribution to increase the mass of precipitated mass compared to the NaH_2PO_4. The optimum conditions from each case of precipitation tests are selected to apply to the prepared sand samples. The summary of selected grouting solutions is shown in Table 2. UCS tests were performed to evaluate the impact of the application of grouting material on the strength of the treated sand. The injected volume of the grouting solution was controlled by a number of pore volume (PV), all the samples were treated by 1 and 2 PV, one PV being ~78 mL. The UCS test results are shown in Figure 5.

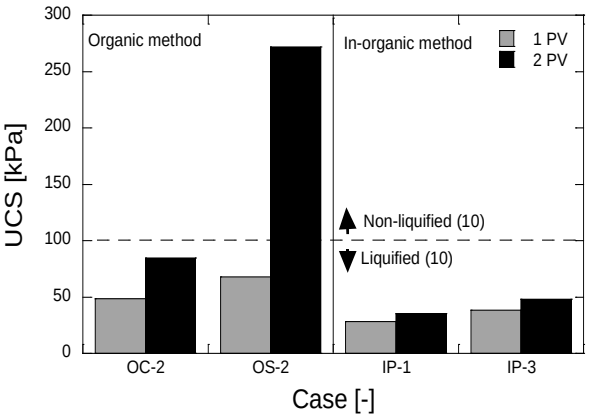

Figure 5. UCS Test Results

Table 2. Selected Materials for Grouting Solution

Case	Material concentration								
	$CaCl_2$ [mol/L]	$MgCl_2$ [mol/L]	$MgSO_4$ [mol/L]	$CO(NH_2)_2$ [mol/L]	Urease [g/L]	NaH_2PO_4 [mol/L]	$NaHCO_3$ [mol/L]	$Mg(NO_3)_2$ [mol/L]	NaOH [mol/L]
OC-2	0.90	0.10	-	1.00	2.00	-	-	-	-
OS-2	0.90	-	0.10	1.00	2.00	-	-	-	-
IP-1	-	-	-	-	-	1.00	-	0.50	0.10
IP-3	-	-	-	-	-	-	0.50	1.00	0.10

The strength of treated sand varies in the range of 28-272 kPa are obtained by the treatment of 1-2 PV grouting solutions. The significant improvements in soil strength are obtained in the case of OC-2 and OS-2, with the greatest improvement is obtained in the case of OS-2, where the strength increases from the 67 kPa to 272 kPa. In contrast, in the cases of IP-1 and IP-3, further treatment has no a significant effect on the strength of the treated soil. The results of this study show that the utilization 2PV of grouting solution OS-2 composed of calcium chloride, magnesium sulfate, urea and enzyme of urease is a promising method for liquefaction mitigation, as mention by Zen [10] that UCS (strength) of 100 kPa is enough to prevent the onset of liquefaction [10,11].

Conclusions

The applicability of several combinations of biochemical grouting has been evaluated for its possible application as the liquefaction mitigation. The organic and in-organic precipitation have been conducted to evaluate the mass of the precipitation materials, and the optimum grouting solutions were selected. UCS tests have also been performed using the selected material regarding the precipitation test result. The selected grouting solution was applied to the soil sample, and the improvement in the strength was evaluated.

The results of this study show that the organic precipitations promoted a higher amount of precipitated material compared to the in-organic precipitation. The addition of tretment has also had significant effect on the improvement of soil strength. The strength of 272 kPa is obtained in case of OS-2 treated by 2 PV treatment. This result revealed that the grouting solution of OS-2 might be a potential method to prevent the onset of the liquefaction.

Acknowledgments

This work has been partly supported by a research grant from the Penta-Ocean Constructions Co. and Ehime University, Their support is gratefully acknowledged.

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