# Experimental Study on Strengthening Near-Surface of Slopes Using Bio-grouting Technique

**Sivakumar Gowthaman, Kazunori Nakashima, Hiromi Nakamura, and Satoru Kawasaki**

**Abstract** Near-surface instability due to incessant rainfall events poses challenges to the maintenance of earth structures. Bio-grouting (also be referred to as microbial induced carbonate precipitation (MICP)) is a recently emerged soil improvement technique, revealing high potential for stabilizing near-surface of slopes. The technique promotes the cementation of embedded soil using calcium carbonate that precipitates biochemically. This paper presents a bench-scale experimental program, and the objectives were (i) to understand how the treatment protocols impact the strengthening of near-surface and (ii) to assess the profile of treated slope. For those, a series of slope models was treated by various experimental protocols using surface spraying technique. During the treatment, bacteria culture and cementation resources were sprayed in two subsequent phases. The findings suggest that the bio-grouting responses vary depending on volume of cementation solution supplied. High supply of cementation solution developed a highly nonuniform-treated profile compared with low supplies. Also, 1 mol/L concentration of cementation solution is found to be the optimum for the treatment, providing strong intergranular bridging. The spatial distribution of calcium carbonate showed the treated slope can be considered into three layers: surface-crust layer, cemented soil layer and uncemented soil, suggesting that the application technique may provide erosion protection via the crust formed along the outer surface of the slope and cemented soil material formed on the interior.

**Keywords** Microbial induced carbonate precipitation (MICP) · Slope near-surface · Surface spraying · Slope model · Calcium carbonate

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# 1 Introduction

Stability of embankment slopes is always a crucial concern in the field of construction engineering, as the constancy of transportation structures are reliant on the stability of the slopes. As indicated in Fig. 1, the potential causes for slope instability ranges from deep-seated failures to sediment yield, suggesting that the stabilization needs to be considered by the means of enhancing (i) structural conditions and (ii) cover conditions [1]. Mass movements and failures occur along the weakest sub-surface, when the driving forces of a collective slope material exceed the resistive forces, without necessarily being influenced by water [2]. Shallow failures are often triggered during or immediately after prolonged rainfalls/ snow-melt, owing to the infiltration. The excess infiltration is found to be diminishing the effective stress, reducing the soil strength and may increase the failure potential in embankment slopes [3, 4]. As described in Fig. 1, mechanical methods are generally applied to enhance the structural stability and performance of the slopes.

Enhancing the cover conditions, on the other hand, is another important requirement to both natural and engineered slopes. Sediment yield is often reported to be a global threat [5, 6], occurring due to the complex interactions of sub-processes between the detachment and transport of surface materials. Human activities always have a major influence in natural slope processes. During constructions, the slopes are modified in a way to fit the construction requirements (e.g., clearance of vegetation and changes in topography); as the result, near-surface substrates are significantly disturbed [7]. Moreover, due to the direct impacts of climatic factors, near-surface substrates are tended to be weakened more rapidly [8], attaining high erodibility risk. Therefore, in terms of eliminating risks and saving economy, cover condition of the slope needs to be enhanced immediately after the construction processes.

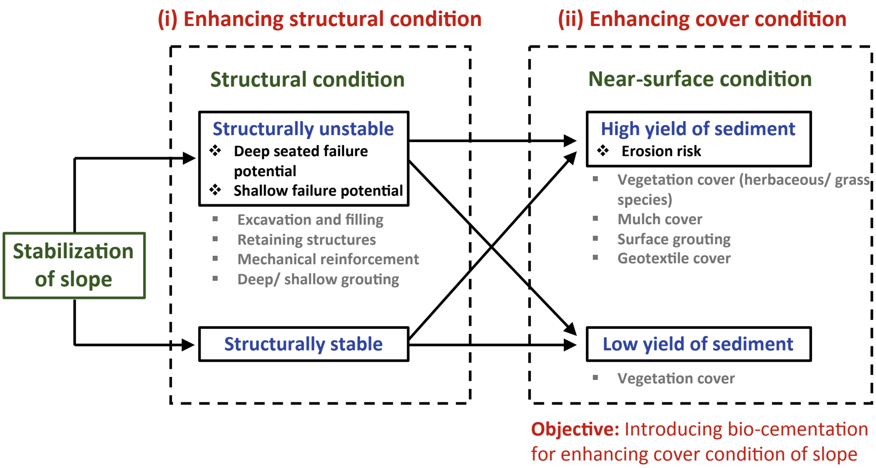


**Fig. 1** Slope stabilization processes and objective of the research work

The available methods for enhancing cover condition of the slope are diverse, having both benefits and drawbacks. Seeding/ vegetation is the eco-friendliest method; however, their growth and survival are reported to be limited in cold and arid regions, and it generally takes quite a long time to effectively achieve the benefits [7, 9]. Grouting is the most popular and widely used method, but from the sustainable perspective, the use of cement and other synthetic binders are reported to be less preferred [10, 11], and there continues to be a need to explore new reliable techniques.

Bio-grouting (also be referred to as microbial induced carbonate precipitation (MICP)) is a potential bio-mediated soil improvement technique that relies on sustainable and environmentally friendly processes [10, 12–14]. Within the recent past, number of studies have demonstrated that the technique could potentially be used to solve many geotechnical challenges including liquefaction mitigation [15], slope soil stabilization [16, 17], fugitive dust control [18] and erosion control [7, 19]. In the bio-grouting process, the ureolytic bacteria hydrolyze the urea into ammonium and carbonate ions (Eq. 1), and the calcium carbonate bio-cement is finally produced within embedded soil while supplying calcium ions (Eq. 2), effectively enhancing the physical and mechanical characteristics of soil.

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{ureolyticbacteria}} CO_3^{2-} + 2NH_4^+ \tag{1}$$

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

The objectives of this research work are to understand how the treatment protocols impact the strengthening of near-surface and to assess the profile of treated slope. To achieve the first objective, a series of slope models was treated by various experimental protocols using surface spraying technique. Finally, the treatment was advanced to bench-scale model slope to assess the profile of treated slope and to demonstrate the feasibility of bio-grouting under open cold environmental conditions.

## 2 Materials and Methods

### *2.1 Slope Soil*

One of the erosion-prone expressway slopes located in Hokkaido, Japan (the northernmost island of Japan, located in subarctic region, experiencing a cold climate), has been chosen for the investigation as the representative. The particle size distribution curve of the slope soil is presented in Fig. 2. Based on the Japanese Industrial Standard (JIS), the slope soil can be categorized as fine sand with the mean particle

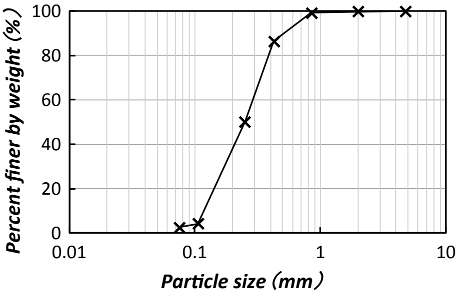


**Fig. 2** Grain size distribution of representative slope soil investigated

diameter of 0.23 mm. The intrinsic carbonate content of the soil was found to be 0.22% by weight.

## 2.2 *Slope Models and Test Cases*

Slope models used in this study were essentially chosen to be two different scales (as shown in Fig. 3): small-scale and bench-scale. In the first set of experiments (Part 1), small-scale slopes were used to optimize the treatment process considering the effects of supply volume and resources concentration on treatment efficiency. Table 1 presents the detail of the cases considered. The effects of supply volume were studied by Cases 1–3. Cases 2 and 4 were used to evaluate the effects of concentration of cementation solution on MICP improvement. In the second set of experiment (Part 2, indicated as Case 5), a full bench-scale slope was given the

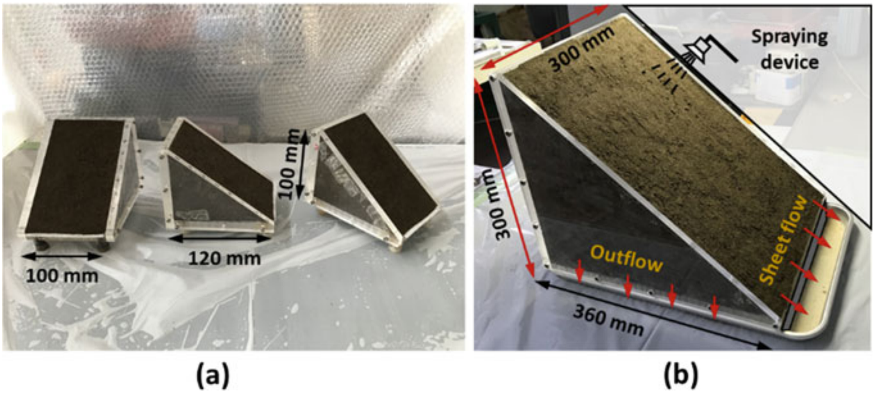


**Fig. 3** Slope models used in this study: **a** small-scale and **b** bench-scale slopes

**Table 1** Test cases and treatment conditions

| Case No | Scale | Initial density (g/cm$^3$) | No. of bacteria sprays | No. of cementation sprays | Spray volume (per spray) (mL) | Concentration of cementation resources ( mol/L) | Treatment duration (days) |
|---|---|---|---|---|---|---|---|
| Case 1 | Small | 1.58 | 2 | 14 | $0.25 \times P_v$ | 1 | 14 |
| Case 2 | Small | 1.52 | 2 | 14 | $0.5 \times P_v$ | 1 | 14 |
| Case 3 | Small | 1.52 | 2 | 14 | $1 \times P_v$ | 1 | 14 |
| Case 4 | Small | 1.51 | 2 | 14 | $0.5 \times P_v$ | 0.5 | 14 |
| Case 5 | Bench | 1.51 | 2 | 14 | $0.5 \times P_v$ | 1 | 14 |

$P_v$: pore volume of the target near-surface zone

optimum treatments (based on the findings in Part 1) under an open environment, followed by the assessment of treated slope profile.

## 2.3 Treatment Process

The ureolytic bacteria (*Lysinibacillus xylanilyticus*), isolated from native slope soil, were used for to treat the slope models. The isolation process of the bacteria can be found from our previous work [20]. The bacteria were cultured in $NH_4$-YE (ATCC 1376) medium in shaking incubator at 25 °C and 160 rpm for 48 h until the growth ($OD_{600}$) achieved around 4.0 (48–72 h). The growth conditions were chosen based on the optimal enzymatic performance of the bacteria [17]. $NH_4$-YE medium consisted of dissolved ammonium sulfate, yeast extract and tris buffer of 10 g/L, 15.7 g/L and 20 g/L, respectively. The cementation solution consisted of calcium chloride, urea and nutrient broth at required concentration (in accordance with the test conditions, refer Table 1). In this study, two potential concentrations were investigated: 0.5 and 1 mol/L (Cases 2 and 4, respectively, refer Table 1), using 1:1 chemical ratio of $CaCl_2$: urea.

During the treatment, a spraying device (as indicated in Fig. 3) was used to introduce the bacteria and cementation solutions to the surface of the slopes in two subsequent phases. In the first-phase, the bacteria culture was sprayed, followed by the spraying of cementation solution in second-phase. Between the two phases, a time gap (1–2 h) was given for effectively immobilizing bacteria cells within the near-surface soils, as suggested in previous works [17, 21]. A moderate spray rate of around 45 mL/min was chosen herein, which is relatively in consistent with previous spraying applications [22], and the sprayer was held vertically to the slope surface during the spraying. Cementation spaying was performed every 24 h, whereas the bacteria culture was sprayed at the beginning (day 1) and mid (day 7) of the 14 days treatment. The additional information regarding the treatment conditions are presented in Table 1. As shown in Fig. 3b, the sheet flow solutions (i.e., the solutions flown over the surface) were collected during the treatment to quantify the efficiency, and the outflow solutions (i.e., the solutions which attained the outlet through infiltration) were used to monitor the internal chemical conditions (i.e., pH and $Ca^{2+}$ concentrations).

## *2.4 Evaluation Methods*

After the treatment, the slopes were allowed to cure for 72 h under the same environmental conditions. The assessment program consisted of needle penetration tests, measurement of calcium carbonate content and scanning electron microscopy (SEM). The needle penetration tests (SH-70, Maruto Testing Machine Company, Tokyo, Japan, see Fig. 4) were performed in accordance with JGS 3431–2012 [23], evaluating the unconfined compression strength (UCS) of treated near-surface. In each point, tests were performed in triplicate, and the average value was used for the representation.

For measuring the calcium carbonate content in cemented soil, a simplified device (shown in Fig. 5a) was used to measure the pressure of $CO_2$ (g) released when the cemented specimen was reacted with HCl in a closed controlled system [24]. Using the calibration curve developed between calcium carbonate and gas pressure (Fig. 5b), the carbonate content (%) was estimated as the ratio between mass of the precipitated $CaCO_3$ and mass of the soil before treatment. The SEM analysis was performed by using Miniscope TM 3000 (Hitachi, Tokyo, Japan).

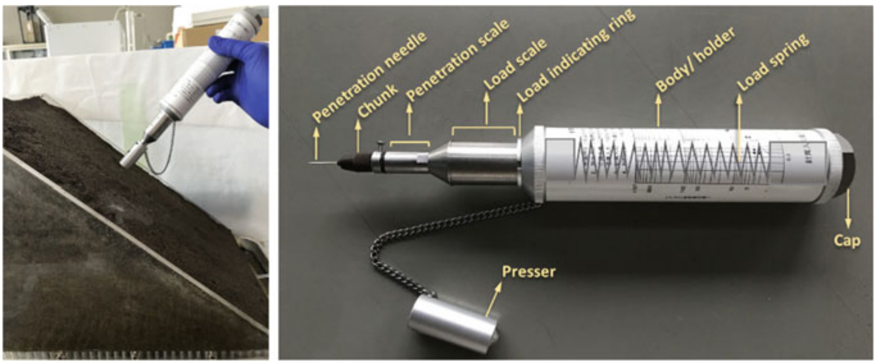


**Fig. 4** Needle penetrometer (SH-70)

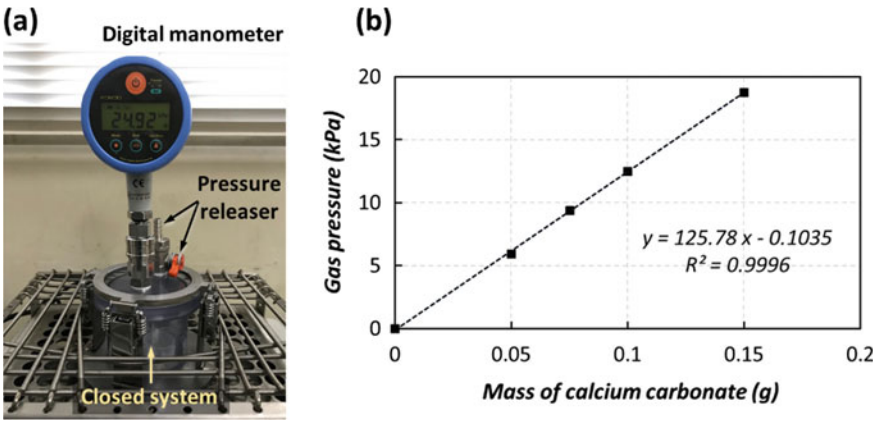


**Fig. 5** Figures of the **a** device used to measure the $CaCO_3$ content and **b** calibration curve developed between mass of $CaCO_3$ and gas pressure

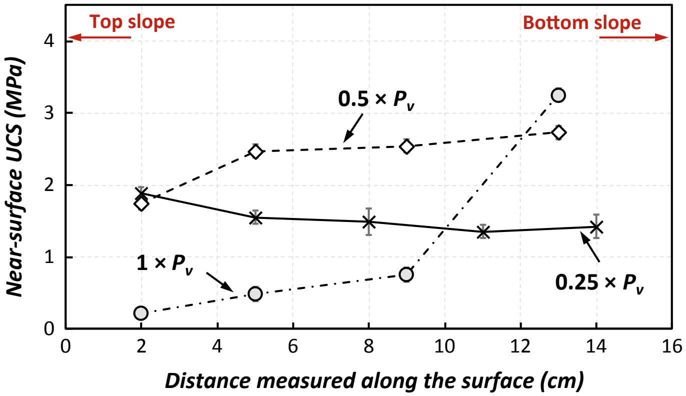


**Fig. 6** Near-surface UCS of the slopes treated using different supply volumes

# 3 Results and Discussion

## 3.1 *Effect of Spray Volume*

The MICP treatment was designed to target the topmost 30 mm near-surface of the slope for enhancing the cover condition. Based on the pore volume of target near-surface zone ($P_v$), three volumes of cementation solution ($0.25 \times P_v$, $0.5 \times P_v$ and $1 \times P_v$) were systematically chosen (Cases 1–3, see Table 1). Figure 5 presents the near-surface UCS of the slopes treated using different supply volumes. It should be noted that the reference strength, i.e., the UCS of the untreated soil material was found to be around 50 kPa. From Fig. 5, it can be seen that the MICP treatment could enhance the UCS significantly, up to around 3 MPa. However, the uniformity of the treatment appears to be influenced by the supply volume. For the slope treated by 0.25 × $P_v$, UCS value slightly decreases toward the slope bottom, and that slightly increases when the spray volume is 0.5 × $P_v$. However, in both the cases, an acceptable uniformity could be seen in strengthening along the surface. On the other hand, the near-surface treated by 1 × $P_v$ of supply volume shows a heterogeneous distribution in UCS, varying between 0.2 and 3 MPa. The UCS value at the bottom slope is around 12 times higher than that of top slope. The similar tendency was observed in repeated experiments as well. Overall, from the results, the effective spray volume can therefore be suggested to be 0.5 × $P_v$.

Many previous studies have evidenced that the increase in number of cementation treatments increased the precipitation content of calcium carbonate in soil columns, hence enhanced the strength characteristics [25, 26]. Thus, before this work, it was expected in a similar way that the increase in supply volume might contribute to effective enhancement of near-surface. However, the observation has disproven the hypothesis, revealing that spraying high volume of solutions (i.e., 1 × $P_v$) results non-uniformity in cementation. Basically, supply of high bacteria culture was reported to have positive effect in MICP, which increases both the yield of calcium carbonate and crystal nucleation sites [27]. In slopes, high supply of cementation solution would tend to cause increased generation of sheet flow over the surface/ near-surface (further explained in subsequent paragraphs), which is suspected to be stimulating the transportation of bacteria cells toward bottom slope, leading to non-uniformity in surface UCS. However, the available results are deficient to fully demonstrate the above conclusion; therefore, further investigations need to be performed.

The inclined nature of slope naturally typically leads to the production of sheet flow, and that highly depends on the soil type (i.e., gradation) and slope gradient. At the beginning of every spraying, the generation of sheet flow was low; when the near-surfaces reach nearly the saturation stage, further spraying would partially turn into sheet flow. In all the cases, it can also be observed that with the increase in number of sprays, the generation of sheet flow increased, and the outflow decreased (refer Fig. 7). This could be explained by the occurrence of crystallization. The progression of calcium carbonate crystals decreased the permeability of the near-surface, which led to the reduction in infiltration, increasing the sheet flow generation. Nevertheless, the quantity that infiltrated into the surface (measured in terms of outflow) is considered to be contributing to the MICP, determining the efficiency of supply.

In the case of 0.25 × $P_v$, low quantity of cementation solution was sprayed every 24 h, which resulted less generation of sheet flow (Fig. 7a). On the other hand, in 1 × $P_v$ case, high quantity was sprayed every 24 h, resulted the development of high sheet flow during the treatment (Fig. 7c). For instance, on 14th spraying, the sheet flow was around 120 mL among total effective supply of 180 mL. In fact, the generation of sheet flow represents the leftover of non-utilized resources, which directly affects the economy and efficiency of the treatment. In order to relate the supply quantity and efficiency of the treatment, the "supply efficiency (SE)" is proposed herein as an index parameter (Eq. 3). Simply, the SE can be defined as the effective supply that contributes to the MICP among total supply. Herein, the infiltrated quantity (Eq. 4)

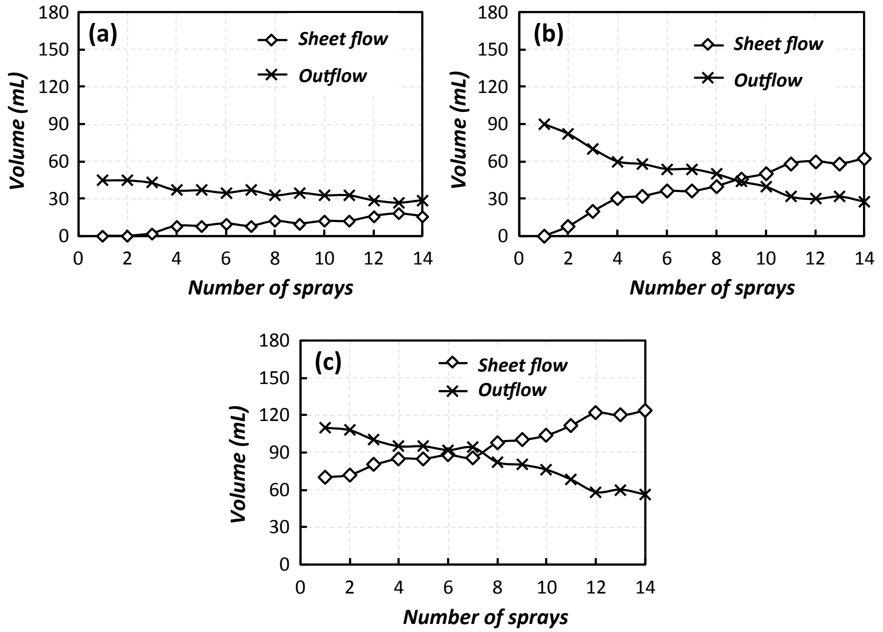


**Fig. 7** Supply volumes converted to sheet flow and outflow in slope **a** $0.25 \times P_v$, **b** $0.5 \times P_v$ and **c** $1 \times P_v$

is considered as contributor. Accordingly, at any ($n$th) number of supplies,

$$\text{Supplyefficiency (SE)} = \frac{\text{Cumulativeofinfiltrationquantity}}{\text{Cumulativeofsupplyquantity}} \times 100\% \quad (3)$$

$$\text{Infiltrationquantity} = \text{Supplyquantity} - \text{sheetflow} - \text{loss} \quad (4)$$

The spray loss was found to be around 10% of the supply volume. The supply efficiencies by the end of the treatment were around 71%, 52% and 42%, respectively, for the cases of $0.25 \times P_v$, $0.5 \times P_v$ and $1 \times P_v$, suggesting that high supply lessens the supply efficiency for the slope soil considered in this research work. The efficiency might vary depending on the spray rate, position of spraying and gradation of the soil as well; therefore, future studies should also consider other factors impacting SE.

## *3.2 Effect of Cementation Solution Concentration*

Figure 8 presents the comparison of near-surface UCS of the slopes treated with two different concentrations of cementation solution (0.5 and 1 mol/L). The observation reveals that the treatments using both concentrations were able to improve the surface

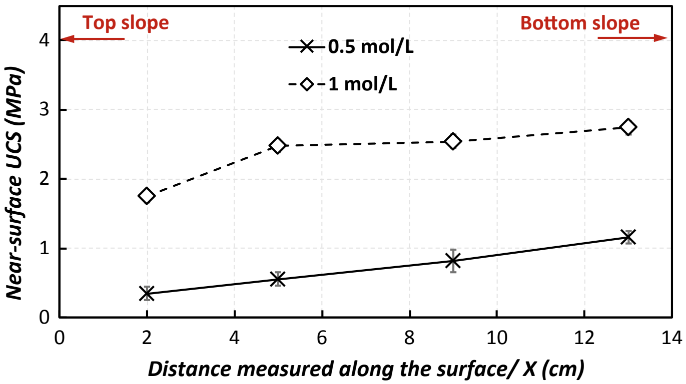


**Fig. 8** Near-surface UCS of the slopes treated using 1 and 0.5 mol/L cementation solutions

conditions; however, the concentration of the cementation solutions significantly governs the MICP improvement of near-surface. The near-surface treated by 1 mol/L shows the UCS values between 1.8 and 2.8 MPa. On the other hand, 0.5 mol/L resulted relatively low strength, UCS between 200 kPa and 1 MPa.

The precipitation content of calcium carbonate governs the mechanical response of the MICP soil [20, 21, 25, 26]. When the slope is treated using 0.5 mol/L, relatively lower precipitation of calcium carbonate occurs, leading to the weaker particle connections (see Fig. 9a), which is unlikely to be desirable for the stabilization of slope near-surfaces. On the other hand, stronger intergranular bridging could be observed in treatment using 1 mol/L (see Fig. 9b), which can be considered to be the major contributor to erosion resistance.

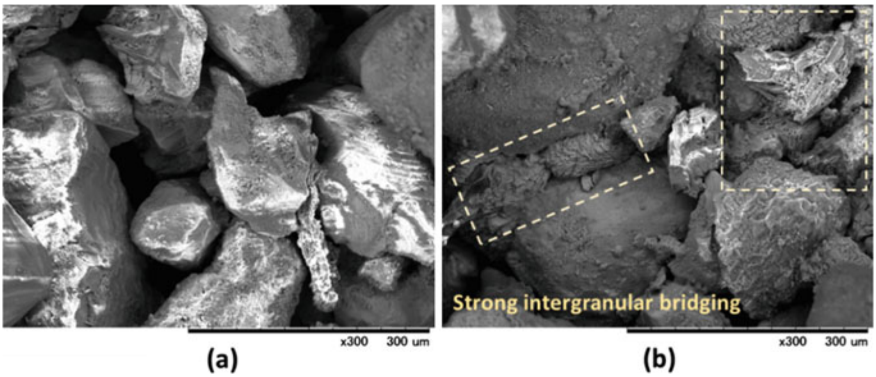


**Fig. 9** SEM images of soils treated by **a** 0.5 mol/L and **b** 1 mol/L cementation solutions

### 3.3 Profile of Cemented Slope

Based on the outcomes of the series of small-scale slope model solidification tests, the optimum treatment conditions were derived and implemented to a full bench-scale slope model in an open (temperature uncontrolled) environment (Case 5, refer Table 1) in order to demonstrate the applicability in real-field, promoting the technique.

Considering the application in Hokkaido (located in cold subarctic region, experiencing cold climate), the slope was subjected to cold climate for the treatment. The temperature during the treatment was monitored in real time by the sensors attached to the slope surface, and the measurements are plotted in Fig. 10. It can be seen that the average temperature was around 15 °C within the first 192, but the temperature dropped to the lowest value of 5 °C for the next 48 h, and then once again that increased at latter periods. Overall, the treatment temperature ranged between 5 and 20 °C. Diurnal fluctuations also could be observed; in night times, the temperature dropped by 5–6 °C. As per the biological response of the bacteria [17], the bacteria could precipitate $CaCO_3$ even at low temperatures; however, the effective performance has been reported to be between 15 and 25 °C. Accordingly, it can be understood that the bacteria were effectively performing during around 70% of the treatment process.

It was also found that the pH of the outflow solutions was between 8.0 and 8.5 in most of the times, suggesting the occurrence of MICP reactions that turned the solutions to alkaline condition. The $Ca^{2+}$ values indicated that the resources were utilized up to around 68%. Until the 11th number of treatments, the pH was found to be between 8.0 and 8.5; however, afterward, a drop could be seen, led the pH value to around 7.8. Similar tendency was also observed in $Ca^{2+}$ measurements, i.e., rapid increase was observed in $Ca^{2+}$ readings after 12th treatment. This could be probably attributed to the low temperature effect. When the temperature decreased below 10 °C, the MICP reactions were likely to be trivial within soil, resulted the decrease in pH and increase in leached $Ca^{2+}$.

Figure 11 presents the variation of near-surface UCS of the slope. It can be seen that relatively a marked improvement was achieved, and that ranged between 1.6

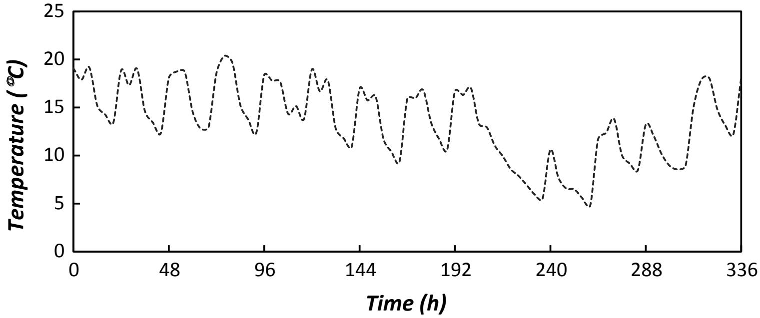


**Fig. 10** Temperature measurement from sensors, during the treatment

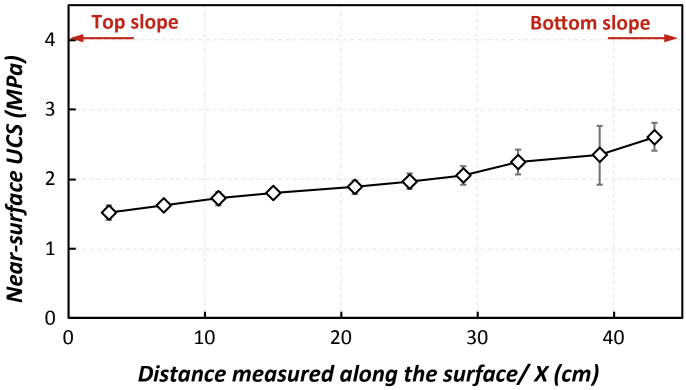


**Fig. 11** Variation of near-surface UCS of bench-scale slope

and 2.8 MPa. Similar to that observed in small-scale slope (Case 2), higher UCS was observed at bottom slopes, which could probably be attributed to the flow lines (i.e., sheet flow) and slight transportation of bacteria cells toward bottom slope. Previous studies have suggested that the sand should be treated to a UCS value of around 1.5 MPa to prevent the dynamic and liquefaction damage [28]. Therefore, the near-surface UCS achieved herein is considered to be sufficient enough to withstand against the sediment yield and to provide a reliable cover condition to the expressway slopes.

Subsequently, the mold was dismantled at vertical assembly, and the cementation was assessed along the vertical direction. To evaluate the spatial distribution of calcium carbonate, samples were collected from different depth positions of the slope and tested. Figure 12a presents the distribution of calcium carbonate with the depth measured from the slope surface. It can be seen that high cementation was achieved at surface zone, and the cementation decreased with the increasing depth. This could be possibly due to the distribution of the bacteria cells; as the soil investigated herein

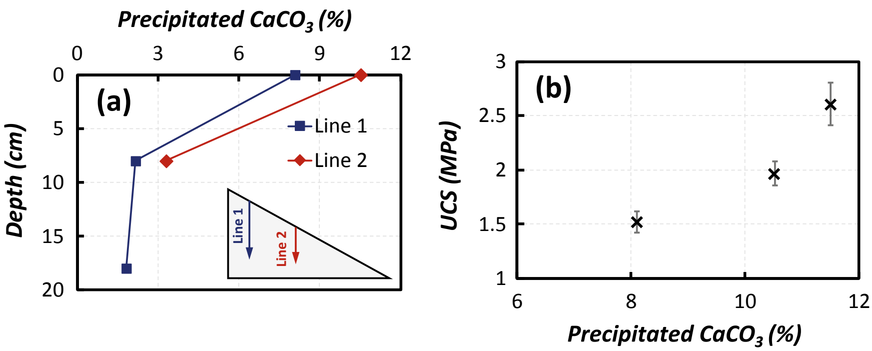


**Fig. 12** **a** Distribution of $CaCO_3$ with the depth and **b** plot of UCS against $CaCO_3$ measurements

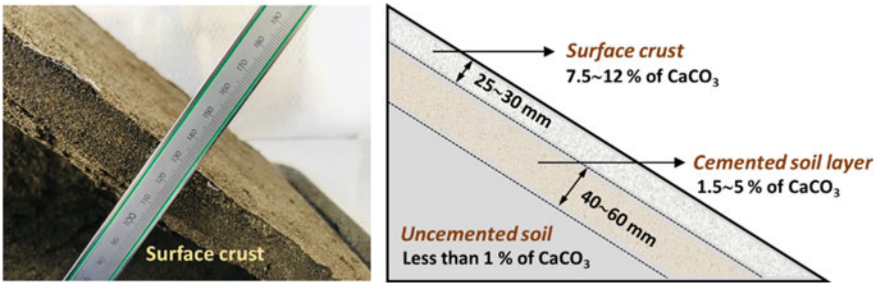


**Fig. 13** Cemented crust layer and categorization of treated slope profile

was fine sand, higher bacteria cells would be filtered at near-surface zone compared to that of deeper zones. In Fig. 12b, the measured calcium carbonate content is plotted against the UCS values. The results indicate that the UCS was highly governed by the precipitated $CaCO_3$, exponentially increasing with the increase in $CaCO_3$, and the tendency reported herein is in a good agreement with the plot reported in previous works [20].

The assessment also showed that the surface crust layer was formed to a thickness ranging between 25 and 30 mm (see Fig. 13), and that primarily comprised of well-developed calcium carbonate bonds, wherein the calcium carbonate was found to be highly distributed, up to around 12%.

The assessment further demonstrated that the MICP-treated slope can be considered into three categories/ layers: (i) well-cemented surface crust, (ii) cemented soil layer and (iii) uncemented soil (as illustrated in Fig. 13). The near-surface crust was underlain by a cemented soil layer, and that was underlain by uncemented soils. The cemented soil layer was not be able to withstand the existed shape, as the formed calcium carbonate content was found to be low and was unable to facilitate strong connections. From the SEM analysis, the calcium carbonate crystals were found to be located on the surface of the grains. The thickness of this cemented soil layer was unable to measure exactly; but the measurement of calcium carbonate content of the soil sampled at various locations revealed that the thickness of cemented soil layer could be nearly around 40–60 mm. Below that, no considerable calcium carbonate deposits were found, remaining as same as untreated soil.

In the MICP treatment, the particle contacts are cemented by calcium carbonate, which leads to the aggregation of soil particles, resulting the increase in mean size of substrate. The surface crust layer achieved herein is a well-aggregated matrix and is unlikely to be considered as soil grains; hence, the probable mean particle size may be huge. Therefore, the crust formed on the surface can be expected to provide a protection through sort of armoring/ shielding mechanism and can be primarily responsible for surface erosion/ sediment yield resistance. The thicker the crust layer enable the better the cover condition, preserving the slope near-surface against the degradation processes. Moreover, the formation of calcium carbonate on the surface of the soils located in cemented soil layer is likely to increase the mean particle diameter. This suggests that the cemented soil layer (even slight crystallization on grain surface) can also be attributed to the increase in both internal and external erosion resistances. Therefore, the cemented soil layer can be potentially considered as secondary shield/ armor against erosion process.

Several studies witnessed that the MICP treatment responses are highly determined by the grain size distribution of the soil material [17, 27]. Coarse sands consist of large pores and facilitate high infiltration of sprayed solutions. On the other hand, the fine soils spaces pose limitations regarding the treatment depth. The less void spaces affecting the transportation of bacteria calls onto the soil and infiltration volume. Although sufficient MICP resources are supplied, the absence/ limited availability of the bacteria at depths leads to the formation of thin surface crust. As demonstrated, for the fine sand studied herein, the near-surface cover appears to be limited to the depth of around 30–60 mm. To expand the understanding on applicable range of MICP, similar works need to be performed in the future on different soil materials, and the efficiency needs to be correlated with the grain size distribution in terms of both resource utilization and effective treatment depth.

## 4 Conclusions

The bio-grouting responses have been found to be varying depending on volume of cementation solution supplied. High supply of solution develops a highly nonuniform profile compared with low supplies. For the near-surface stabilization of slope considered herein, 0.5 times the pore volume of target near-surface zone was found to be the optimum, and the corresponding supply efficiency appeared to be acceptable.

Treatment using 1 mol/L cementation solutions showed better response than that of 0.5 mol/L. When the slope is treated using 0.5 mol/L, relatively lower precipitation of $CaCO_3$ occurred (led to 200 kPa–1 MPa) compared to that achieved in treatment using 1 mol/L (led to 1.8–2.8 MPa). 1 mol/L treatment was found to provide strong intergranular bridging between soil particles.

The bench-scale model results revealed that the MICP treatment in an open environment, i.e., within 15–25 °C, insignificantly affected the microbial performance, demonstrating the feasibility for the applications in cold regions. The near-surface achieved the UCS of 1.6–2.8 MPa with acceptable uniformity. Measurement of calcium carbonate and assessment demonstrated that the treated slope profile can be considered into three layers: surface-crust layer, cemented soil layer and uncemented soil, suggesting that the application technique may enhance the cover condition of the slope via (i) the crust formed along the outer surface of the slope and (ii) cemented soil material formed on the interior.

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