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NEW MICROBIAL-FUNCTION-BASED REINFORCEMENT METHOD FOR EMBANKMENT

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ABSTRACT: In recent years, erosion control has been increasingly implemented for land embankments of public roadways (e.g., express highways). In the field of geo-environmental engineering, it is important to develop an easy-to-use maintenance method for such embankments based on a natural process. This study aims to develop an eco-friendly and inexpensive maintenance method for embankment management. In this paper, the general concept of the newly proposed method is presented based on the results of laboratory tests and numerical simulations. The most important advantage of this method is the enhancement of urease activity in the in-situ microorganism community. Laboratory tests showed that microbial carbonate precipitation (MCP)-treated sand can increase the liquefaction strength. The numerical simulation results show that an MCP-treated embankment surface shows a rigid frame structure. These results show that the proposed method is suitable for use as an embankment maintenance method.

Keywords: Erosion control, Microbial function, Urease activity

1. INTRODUCTION

In Japan, the maintenance cost of infrastructure facilities has been increasing in recent years. At the same time, the amount of carbon dioxide emissions from construction and maintenance activities has been increasing. Therefore, low-cost eco-friendly maintenance techniques need to be developed in the near future. Toward this end, the authors have focused on easily available and inexpensive agricultural materials. One such example is urea, a very popular agricultural material used for supplying nutrients from soil to plants. Urea can be used to enhance tree planting on an embankment. In this study, we developed an embankment maintenance method that uses in-situ urease-producing bacteria. These bacteria live in normal soil (pH = ~7 and electrical conductivity = 0.6 mS/cm). The advantage of the proposed technique is that it is eco-friendly and inexpensive. Soil whose strength is enhanced using microbial functions is called "bio-soil." In previous studies, specific bacteria isolated from Yagaji island in Okinawa were found to enhance soil strength to up to 2 MPa after cultivation for 2 months [1]. In another study, potato extract solution was injected into a soil column to control the soil permeability; this served as an in-situ leakage repair method that uses in-situ microorganism activity [2]. The present paper presents the results of experimental tests of the physical properties of bio-soil and the effect of this soil on embankment stability based on numerical simulations.

2. OVERVIEW OF PROPOSED METHOD

In this study, we developed a new eco-friendly maintenance method to increase the surface soil strength based on microbial functions, namely, the hydrolysis of urea. The mechanism of the hydrolysis of urea and the precipitation of calcite are represented by equations (1), (2), and (3).

(Hydrolysis of urea)

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH^{+}_4 + CO^{2-}_3 \ \ pH (\uparrow) \tag{1}$$

(Precipitation of calcite (calcium carbonate))

$$CO_2 + H_2O \rightarrow HCO^{-}_3 + H^{+} \tag{2}$$

$$HCO^{-}_3 + Ca^{2+} + OH^{-} \rightarrow CaCO_3 (\downarrow) + H_2O \tag{3}$$

These reactions require urea, a calcium source (calcium chloride, calcium nitrate, etc.), and urease-producing bacteria [2], [3]. In this study, we used *Bacillus pasteurii* as it shows high urease activity and salt tolerance [4],[5]. Figure 1 shows the process of the proposed eco-friendly maintenance method and Fig. 2, a schematic diagram of the remediation system. Before initiating this type of maintenance work, treatability tests were performed using in-situ soil microorganisms. Then, another treatability test (large-scale cultivation) was performed in a laboratory to evaluate the urease activity with various combinations of nutrients and calcium sources.

A combination of nutrients and a calcium source was selected according to the results of the treatability test.

Then, this combination was sprayed on the

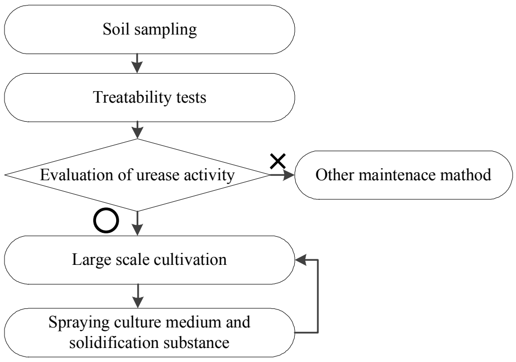


Fig. 1 Process of maintenance method

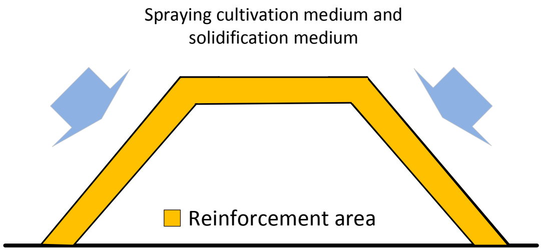


Fig. 2 Schematic diagram of maintenance work

embankment surface to accelerate the reinforcement activities of microorganisms. Finally, to maintain the surface of embankment covered with Calcite during the public service period

3. LABORATORY TESTS

3.1 Material and methods

Toyoura sand was used as soil in the experiments. *B. pasteurii* (ATCC11859), an aerobic urease-producing alkaliphilic bacteria, was used as the microorganism in this study. Calcite precipitation was carried out using the following procedure. The bacterial culture medium (ATCC medium 1376) was infiltrated with a solidification medium. Table 1 shows the composition of the solidification medium. The soil columns (Dr = 50%) were infiltrated in a solution with 1 L of the solidification medium containing 0.30 M $CaCl_2$ and urea three times per 24 h. Figure 3 shows an overview of the column tests. The soil columns were then removed from the solution for one day before being used for strength testing. Cyclic triaxial tests and consolidated-drained (CD) triaxial compression tests were performed using a compression machine to test the physical properties of microbial carbonate precipitation (MCP) sand and the liquefaction strength. After the strength tests, the $CaCO_3$ weight was measured as follows: (1) After oven drying (110°C, 24 h), the weight of the soil samples was measured. (2) The soil samples were washed with 1 N HCl two or three times to dissolve precipitated carbonates. (3) The soil samples were rinsed with ion exchange water, drained, and oven dried (110°C, 24 h). (4) The weight of the rinsed soil samples was measured. Three samples each were prepared for MCP sand and control sand.

Table 1 Composition of the solidification medium [6],[7]

Item	Value	Unit
Nutrient Broth	1.50	
NH_4Cl	5.00	
$NaHCO_3$	1.06	g
$CO(NH_2)_2$ (0.3 mol/L)	9.01	
$CaCl_2$ (0.3 mol/L)	16.65	
Distilled water	500	mL

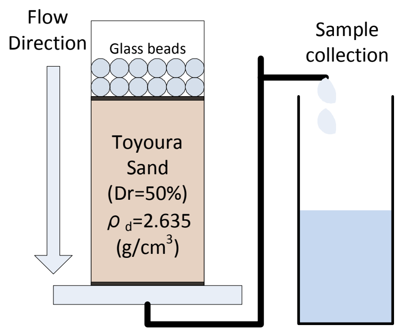


Fig. 3 Overview of column tests

3.2 Results of laboratory tests

Figure 4 shows the results of the CD triaxial compression tests (confining pressure: 100 kPa). The use of the MCP-treated sand increased the peak strength by ~20%. The result of the volumetric strain and axial strain curves shows that both Toyoura sand and MCP-treated sand properties have the behavior with plastic volume

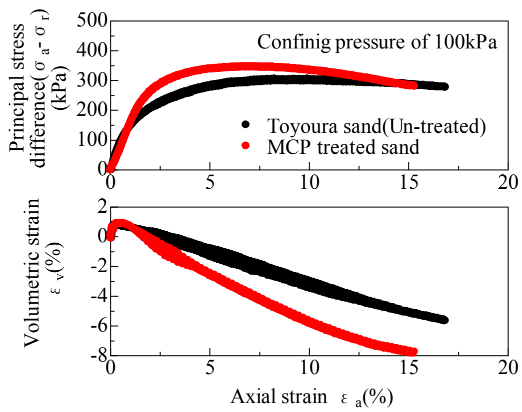


Fig. 4 Results of the CD triaxial compression tests (confining pressure: 100 kPa)

expansion. Figure 5 shows the result of Mohr's stress circles. Table 2 lists the physical properties of the sand samples. The dry density of the two sand types was measured to be 1.364 and 1.472 g/cm^3. The experimental results showed that MCP-treated sand increased the dry density of Toyoura sand. In other words, the precipitation of calcite in the sand pore increased the soil density. The same results were obtained when the cohesion (C) value of MCP-treated sand was used. However, the internal friction angle (φ) remained constant after the MCP process. These results suggested that the increase in the sand strength increased the C value, similar to what happens in the case of cement-treated soil. The cyclic axial load of a sinusoidal wave with frequency of 0.1 Hz was applied to the soil. The cell pressure and water pore pressure were measured. Figure 6 shows the liquefaction strength curve (DA = 5%). This result shows that the liquefaction characteristics of MCP-treated Toyoura sand are improved. The improvement of the liquefaction strength of MCP sand caused an increase in the cohesion value as in the case of cement-treated sand. These results suggest that the improvement of the liquefaction strength is based on the microbial function during around 1 week. Photo 1 shows the SEM images obtained in both cases. These photos show that the surface of the MCP-treated sand was covered with small calcite crystals. Table 3 shows a comparison of the results obtained for MCP-treated sand and untreated sand. These results show that MCP-treated soil had higher E_0 and G_0 values than untreated (control) sand.

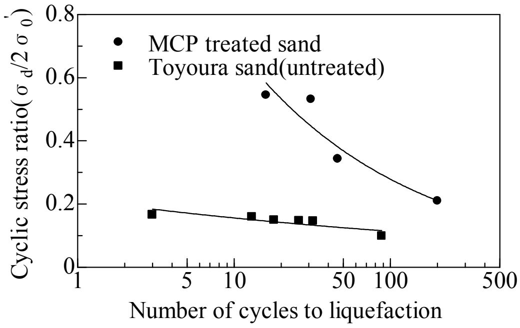
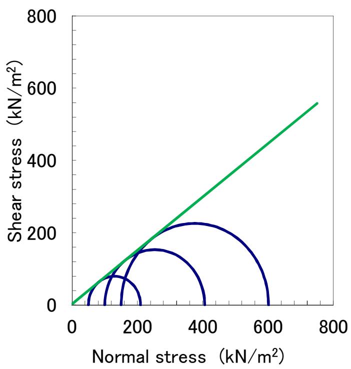
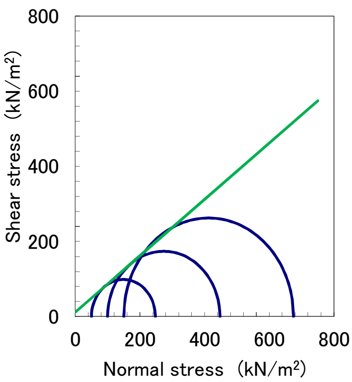


Fig. 6 Results of liquefaction strength curve



Toyoura sand (untreated)

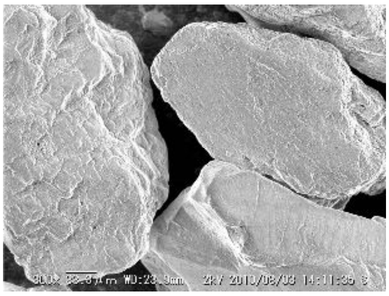


MCP sand

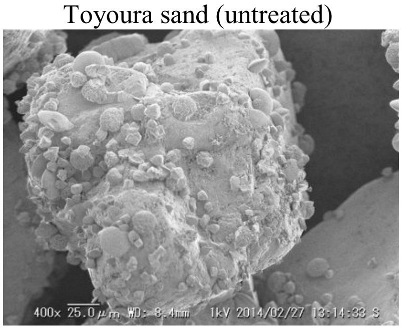
Fig. 5 Results of Mohr's stress circles

Table 2 Physical properties of sand sample

Item	ρ_d (g/cm^3)	C (kN/m^2)	φ (°)
Toyoura sand (untreated)	1.364	3.3	36.5
MCP sand	1.472	11.9	36.9



Toyoura sand (untreated)



MCP sand

Photo 1 SEM images

Table 3 Results of cyclic triaxial cell tests

	E_0 (MN/m^2)	ε_r (%)	G_0 (MN/m^2)	γ_r (%)
MCP sand	435.5	1.84E-02	145.4	2.76E-02
Untreated sand	106.0	5.43E-02	35.4	8.14E-02

E: calculated with H-D model under assumption of ε_a = 0.0001%.

ε_r: ε_a for E/E_{max} = 0.5

G_0: G of E_0 and ε_r for γ = 0.0001%

γ_r : γ of the G/Gmax=0.5 condition.

4. NUMERICAL SIMULATIONS

4.1 Overview of numerical simulations

Figure 7 shows the numerical mesh and boundary conditions. The side and bottom of the ground were adopted as the repeated boundary and viscosity boundary, respectively. The embankment was 3.0 m in height, 16 m in width, and 4.0 m in width at the crest. First, self-gravity analysis was performed for both the ground and the embankment. Then, dynamic analysis was performed on one phase. The FEM program code MuDIAN developed by Takenaka Corporation (Shiomi et al., 1993) was used in the simulation [8]. Table 4 lists the material constants. Figure 8 shows the initial Vs, shear stiffness, yield stress, and reference strain after the self-gravity analysis at the area with no embankment. Assuming Vs = 150 m/s at the ground surface, the shear stiffness G is calculated from equation (4). The yield stress and reference strain are calculated from equations (5) and (6), respectively. The strength of the ground is given by the cohesion c = 50 kPa and friction angle φ = 40° (Table 4).

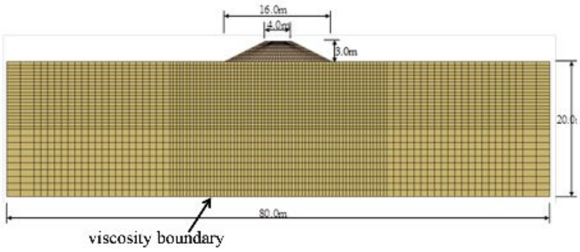


Fig. 7 Analysis mesh

$$G_0 = G_{ref}\left(\frac{\sigma'_{m0}}{\sigma_{ref}}\right)^n \quad (4)$$

where G_{ref} : initial shear stiffness for the test

σ_{ref} : initial constraint stress for the test

σ'_{m0} : mean effective stress at each element

n: material constant (n = 0.5)

$$\tau_y = \sigma'_m \sin\phi + c\cos\phi \quad (5)$$

$$\gamma_r = \frac{\tau_y}{G_0} = \frac{\sigma'_m \sin\phi + c\cos\phi}{G_{ref}\left(\dfrac{\sigma'_m}{\sigma_{ref}}\right)^n} \quad (6)$$

where c: cohesion

φ: friction angle

The dynamic deformation characteristic (G/G_0) and damping ratio h are calculated from equations (7) and (8), respectively. For the ground, h_{max} is assumed to be 20.0%.

$$\frac{G}{G_0} = \frac{1}{1+\dfrac{\gamma}{\gamma_r}} \quad (7)$$

$$h = h_{max}\left(1-\frac{G}{G_0}\right) \quad (8)$$

Figure 9 shows the $G/G_0, h\sim\gamma$ curve obtained using experimental data at the embankment for both treated and untreated soil at a constraint pressure of 50 kPa.

Figure 10 shows the embankment area with treated and untreated soil. There are two cases: (a) both the top and the side of the embankment are treated and (b) only the side is treated. The surface of the embankment is treated with urease.

Table 4 Material constants

Self-gravity analysis

	ρ (t/m3)	G_{ref} (kPa)	σ_{ref} (kPa)	ν	c (kPa)	φ
Embankment	1.95	70800	200	0.49	3.3	36.5
Ground	1.8	304934	500	0.49	50	40

Dynamic analysis

	ρ (t/m3)	G_{ref} (kPa)	σ_{ref} (kPa)	ν	c (kPa)	φ	α	β
Embankment	1.95	70800	200	0.3	3.3	36.5	0.595	0.000614
Treated-embankment	1.94	292000	200	0.3	11.9	36.5	0.595	0.000614
Ground	1.8	304934	500	0.3	50	40	0.595	0.000614

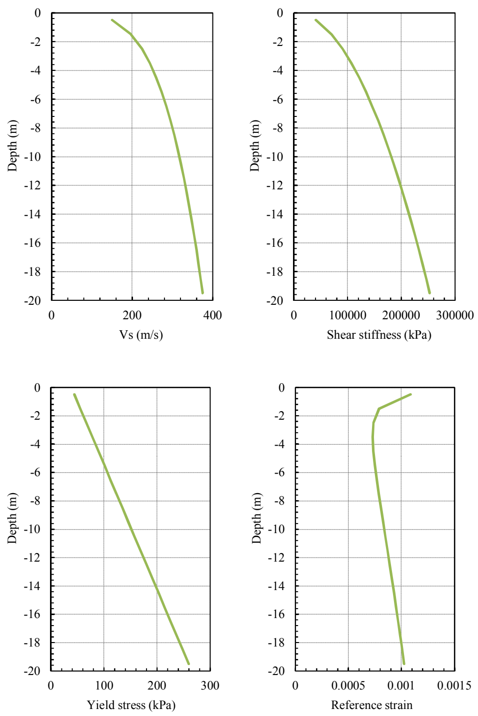


Fig. 8 Initial states after self-gravity analysis

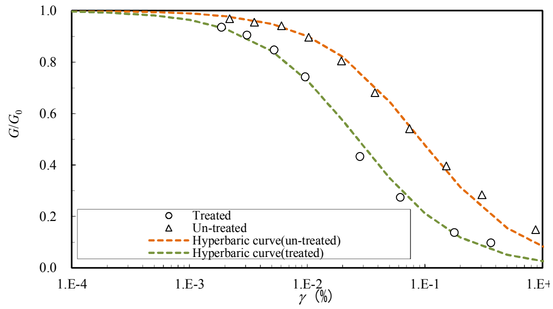
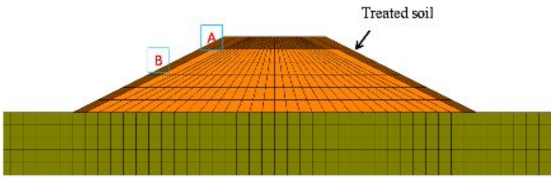
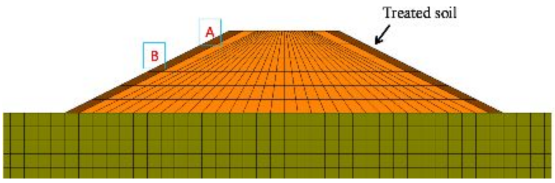


Fig. 9 $G/G_0, h\sim\gamma$ curves



(a) Treated case



(b) Treated case

Fig. 10 Treated and untreated soil at the embankment

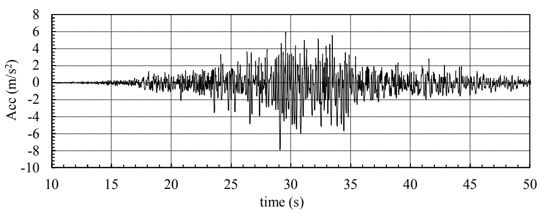


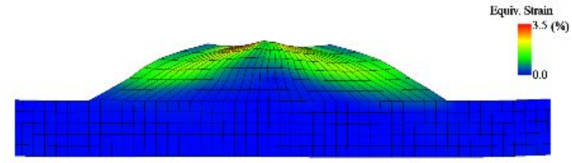
Fig. 11 Changes in input acceleration

Figure 11 shows the change in the input acceleration. The maximum acceleration is 7.95 m/s, and the time duration is 50 s. The earthquake wave is applied to the bottom as 2E.

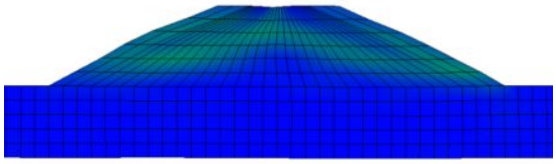
4.2 Numerical results

Figure 12 shows the distribution of the equivalent strain at 50.0 s. In the untreated case, failure is observed at the top of the embankment. On the other hand, in the treated case (a), no failure is observed even when the maximum input acceleration is ~8.0 m/s. In the treated case (b), high equivalent strain can be seen in the embankment.

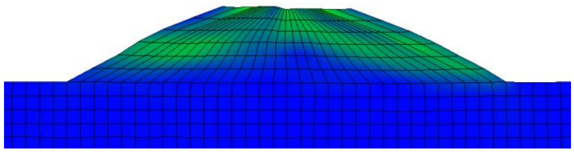
Figure 13 shows the time history of the settlement at the top of the embankment. One can see that the untreated and treated cases are the largest and smallest settlement cases, respectively. The importance of treating



Untreated case



(a) Treated case



(b) Treated case

Fig. 12 Distribution of equivalent strain (50 s)

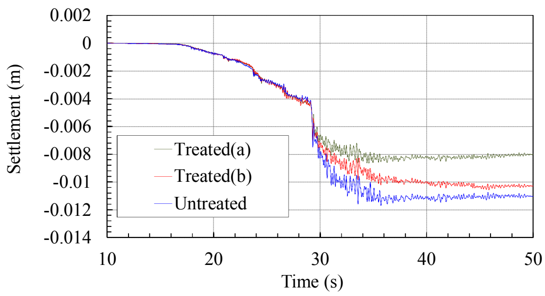


Fig. 13 Time history of settlement

the top of the embankment is indicated. Figure 14 shows the relationship between the shear stress and the shear strain during an earthquake with elements A and B in Figure 10. These are compared with the treated cases (a) and (b) against the untreated case. The behavior of element B is the same in both treated cases (a) and (b). On the other hand, in treated case (a), as element A has high stiffness, the shear strain is smaller than that in treated case (b). When both the top and the side of the embankment are treated, the embankment is reinforced by the effect of the rigid frame structure.

These results show that surface treatment of an embankment by urease is effective in suppressing the shear strain in an earthquake.

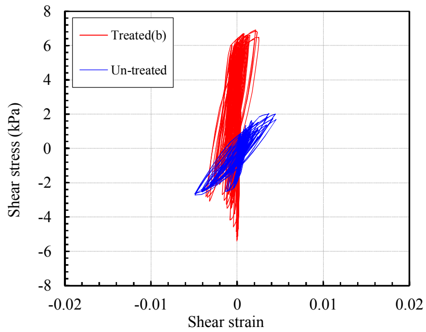
5. CONCLUSION

In this study, laboratory tests and numerical simulations were performed to investigate a new microbial-function-based embankment reinforce ment method. The main conclusions of this study are as follows:

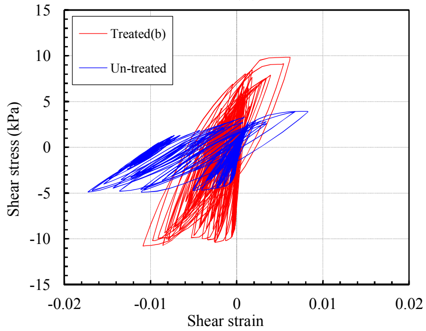
1) The MCP method can improve the physical properties of Toyoura sand.

2) MCP-treated Toyoura sand increases the peak strength by ~20% via the production of calcite in sand pores.
3) MCP can increase the cohesion value of Toyoura sand.
4) MCP treatment of the embankment surface can increase the surface soil strength and change the no-failure condition for an earthquake.

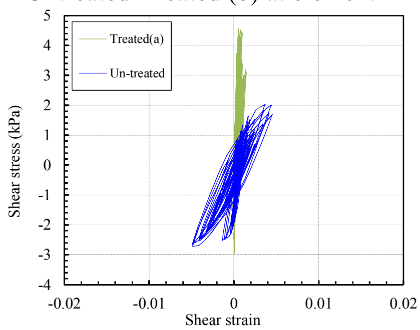
In this study, we performed laboratory tests and two types of numerical simulations. Some of our results show that the surface soil properties are improved.



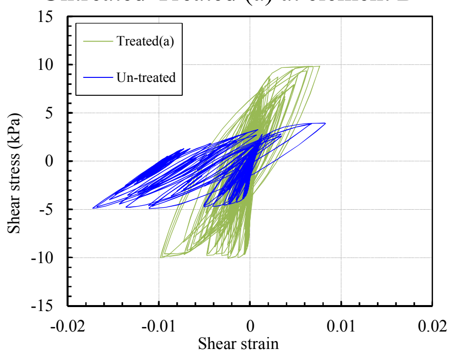
Untreated-Treated (a) at element A



Untreated-Treated (b) at element A



Untreated-Treated (a) at element B



Untreated-Treated (b) at element B

Fig. 14 Relationship between shear stress and shear strain

However, the application of specific microorganisms (such as *B. pasteurii*) to actual sites is difficult. Furthermore, the in-situ urease-producing activity of the bacteria should be enhanced by controlling the physical and chemical properties of the soil.

6. ACKNOWLEDGEMENTS

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