New mitigation techniques for prevention of soil liquefaction by using microbial functions

Méthodes de traitement innovantes basées sur l'activité microbienne pour la prévention de la liquéfaction des sols

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ABSTRACT: This paper introduces new liquefaction disaster prevention techniques, which are cost-effective and have low-environmental impacts. This study explores two different methods to introduce bio augmentation/bio stimulation of the Toyoura sand. Type 1 involves a bio augmentation method that uses a high urease activity and high calcite precipitation potential species to maintain the short term construction. Type 2 is the low-cost and low-environmental impact method that involves the enhanced use of in-situ urease producing bacteria under the rational natural conditions of these species. The main findings of this study as follows: 1) Microbial carbonate precipitation can improve the physical properties of Toyoura sand under the bio augmentation/ bio stimulation conditions; 2) Urease producing bacteria from in-situ sediment can survive the high salinity conditions and produce calcite; 3) Microbial carbonate precipitation can increase the strength of the embankment surface as well as the soil strength in the embankment and change the no-failure condition in the event of an earthquake. These results show that the proposed method is suitable for use as an embankment maintenance method.

RÉSUMÉ : Ce document présente de nouvelles techniques de prévention des dommages dus à la liquéfaction.Ces techniques sont économiques et à faible impact environnemental. Cette étude explore deux méthodes différentes pour permettre l'augmentation bio/bio stimulation du sable Toyoura. Type 1 met en oeuvre une augmentation bio basée surune haute activité de l'uréase et la précipitation de calcite haut espèces potentielles pour maintenir une construction à court terme. Le type 2 est une méthode à faible coût et à faible impact environnemental méthode qui implique l'amélioration de l'utilisation de l'uréase in situ en produisant des bactéries dans le cadre de l'utilisation rationnelle des conditions naturelles de ces espèces. Les principales conclusions de cette étude sont: 1) la précipitation des carbonates microbiens peut améliorer les propriétés physiques du sable Toyoura grace à l'augmentation de la stimulation/bio bio conditions ; 2) des bactéries productrices de l'uréase à partir des de sédiments in-situ peuvent survivre à la forte salinité et produire de la calcite ; 3) la précipitation des carbonates microbiens peuvent augmenter la résistance de la surface du remblai ainsi que la résistance du sol dans le remblai et améliorer la sécurité en cas de séisme. Ces résultats montrent que la méthode proposée est adaptée à une stabilisation des remblais

KEYWORDS: Microbial Carbonate Precipitation (MCP), prevent liquefaction, earthquake response analysis.

1 INTRODUCTION.

Soil liquefaction occurred during the 2011 Great East Japan Earthquake, giving rise to severe damage in 96 cities, towns and villages in Tokyo, and six prefectures throughout the Kantō Plain area of Japan. Since Japan is very prone to earthquakes, and since severe temblors are expected in the future, there is an urgent need for technologies that can prevent liquefaction, which is a phenomenon integral to the destructive power of these disasters. This study presents the results of an investigation into the effectiveness of a new technology that improves the seismic resistance of soil by utilizing the metabolic activity of a microorganism that has high urease activity. This approach, which has the potential to reduce both expense and environmental loading in comparison with conventional technologies, was examined both in laboratory tests and via seismic response analysis.

2 MICROBIAL FUNCTIONS AND RESEARCH BACKGROUND

Previous research has revealed that *Bacillus(Sporosarcina) pasteurii* which was originally a terrestrial microorganism, is effective in strengthening liquefied soil because of its urease activity. Specifically, when this microorganism is present in sand, it precipitates calcium carbonate in the interstices of sand particles. Equations (1) and (2) show the mechanism of this precipitation(Hata, Kaneda 2015).

(hydrolysis of urea)

$$CO(NH_2)_2+2H_2O \rightarrow (urease) \rightarrow 2NH^{4+}+CO_3^{2-} \quad (1)$$

(precipitation of calcium carbonate)

$$Ca^{2+}+CO_3^{2-} \rightarrow CaCO_3 \quad (2)$$

The urea hydrolysis shown in Eq. (1) belongs to the general class of reactions employed in the supply of nitrogen to plants. Two approaches were taken in this study: the first was to seek effectiveness within a brief period by introducing foreign microorganisms with high urease activity into an existing embankment, the second was to seek effectiveness via "engineering" control over the reinforcement by utilizing In-situ microorganisms in the embankment in order to reduce costs.
The specifics of our study process will now be described. In addition to using *B. pasteurii*, which is a land-dwelling microorganism known to be effective as a quick-acting countermeasure against liquefaction, soil was exposed three times to a hardening solution containing a 0.3 mol/L concentration of urea and calcium chloride, and then subjected to a cyclic triaxial test to determine the deformation properties of the soil. A triaxial compressive test of consolidated drainage (CD) was conducted to determine the physical properties of the soil before and after hardening treatment.

Next, in a separate process during which we evaluated a potentially inexpensive method with a low environmental loading, urease-positive microorganisms taken from the bottom sentiment of Toyama Bay were isolated from the sediment, evaluated, and then exposed to hardening treatment under the same conditions used in the quick-acting method investigation.

The liquefaction parameters ($R_{L=20}$, etc.) in undrained sediment samples exposed to hardening treatment in a cyclic triaxial test were then sought. Finally, we evaluated the effectiveness of both processes via seismic response analyses.

3 CYCLIC TRIAXIAL TEST OF DEFORMATION PROPERTIES OF TOYOURA SAND USING B. PASTEURII

Figure 1 shows a diagram of the application of this technology, which is expected to provide reinforcement of an embankment within a brief period through the use of microorganisms. Since the fluid containing *B. pasteurii* has low viscosity and high soil penetration, a single application of the fluid containing the foreign microorganism was made to the embankment surface. In the next step, an even layer of hardening solution was applied to the surface of the embankment and allowed to penetrate thoroughly in the expectation that it would facilitate solidification of the structure.

For the laboratory experiment, 5 cm diameter × 10 cm high samples were created of Toyoura sand and subjected to a cyclic triaxial test in order to identify the deformation properties of the soil. Triaxial CD compressive tests were also conducted. The ρ_d, C and φ found in the results of CD test are shown in Table 1.

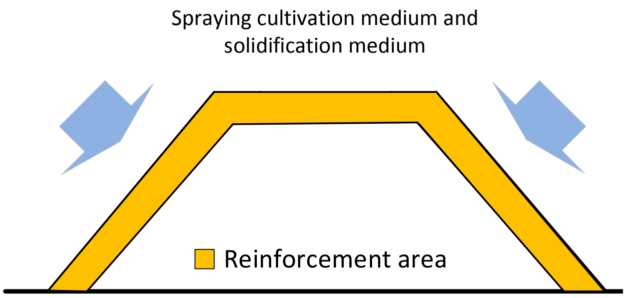


Figure 1. Diagram of the proposed method.

Table 1. Results of CD tests(*B.pasteurii*).

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

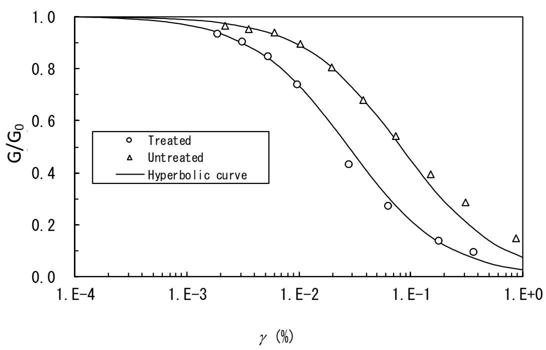


Figure 2. G／G$_0$～γ curve(*B.pasteurii*).

Table 2. Results of cyclic triaxial cell tests.

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

The results in the table indicate that the hardening treatment with *B. pasteurii* caused increases in ρ_d and C, while φ showed almost no change. Figure 2 provides the G/G$_0$-γ curve obtained from the cyclic triaxial test used to identify the soil deformation properties. Table 2 shows the parameters obtained. This table indicates that the hardening treatment with microorganism tends to increase G_0, the initial shear stiffness.

4 ISOLATION OF NATIVE UREASE-POSITIVE MICROORGANISMS AND VERIFICATION OF GROWTH DURING HARDENING

This study employed microorganisms newly isolated from bottom sediments of the Japan Sea near Toyama Bay as the native microorganisms used in our tests. The urease activity of these microorganisms was 111 U/L, 1/5 that of land-dwelling *B. pasteurii.* Since these organisms are sea dwelling, they should be able to grow in environments with ocean level salinity, but such growth was not demonstrated in environments containing calcium chlorite at 0.30 mol/L concentration, which is added in order to aid calcium carbonate extraction. However, since it is essential that the desired microorganisms be able to survive and grow in a hardening environment in order to carry out microorganism-induced strengthening of the liquefied soil, we carried out an experiment to verify that urease activity is maintained in an artificial seawater environment with an added hardening solution component (growth test).

The results of the test revealed that the urease activity showed no significant change between before and after the growth test (total change was about +0.7%). The above findings indicate that we can expect the abovementioned Toyama Bay bottom sediment microorganisms to be effective for calcium carbonate extraction in an environment including hardening components.

5 VALIDATION BY CYCLIC TRIAXIAL TEST OF REINFORCEMENT BY NATIVE MICROORGANISMS OF CONSOLIDATED UNDRAINED SOIL DURING LIQUEFACTION

Prior to seismic response analysis, we conducted an undrained cyclic triaxial test to calculate $R_{L=20}$, for sand samples that had been hardened using native *B. pasteurii* obtained from bottom sediments of Toyama Bay. Toyoura sand was selected as the raw sand. Three hundred grams of Toyoura sand was packed into plastic molds in three layers. Each layer was tamped 20 times after insertion, and 100 mL (corresponding approximately to the interstitial volume) of liquid culture diluted 5-fold with pure water (bacterial concentration = 1.0E+07 cells/mL), was poured into the mold. Next, the sample was hardened by three exposures to hardening solution, thereby resulting in successful growth of the *B.pasteurii*. The interval between exposures was 72 h.

Next, an undrained cyclic triaxial test was performed to calculate $R_{L=20}$ for the soil, and the progress of the liquefied soil strengthening were examined. The dry density was found, after which the calcium carbonate extracted from the samples was acidolyzed in 0.50 mol/L hydrochloric acid in order to calculate the mass fraction of the sand accounted for by calcium carbonate. Table 3 shows the results of the cyclic stress amplitude ratio and mass fraction of calcium carbonate measurements. This shows that hardening treatment with *B. pasteurii* provided an increase in calcium carbonate of about 2% with respect to the mass of the sand. The higher the mass fraction of calcium carbonate was, the higher the cyclic stress amplitude ratio tended to be.

Figure 3 compares the test results of the untreated Toyoura sand with those of the hardened samples containing microorganism isolated from Toyama Bay bottom sediments. As can be seen in the figure, the solidified sand had a high cyclic stress amplitude ratio at low cycle numbers, but tended to approach the dense sand ratio at higher cycle numbers.

6 EVALUATION OF EFFECTIVENESS BY SEISMIC RESPONSE ANALYSIS

In keeping with the objective of the structure examined here, an analysis of the seismic response was performed using the analytical MuDIAN code in order to examine embankment surface layer safety improvements resulting from reinforcement by foreign microorganisms that have been shown capable of hardening soil, and to confirm the effectiveness of the enhanced functionality of native microorganisms that can be expected to have the ability to harden soil, via an inexpensive method that offers low environmental loading.

Figure 4 presents the mesh and Figure 5 presents the incident seismic wave used in our analyses. The same mesh and input seismic motion were used in two different types of analysis. The surface wave speed was assumed to be Vs = 150 m/s and the shear rigidity was increased, but was assumed to be dependent on the confining pressure. Liquefaction was expressed in the Ishihara-Yoshida soil model as the degree of cumulative damage(Ishihara, Yoshida and Tsujino 1985). Subsection 6.1 below examines reinforcement of the soil itself and subsection 6.2 examines countermeasures against liquefaction of the soil directly beneath an embankment.

6.1 *Effectiveness of reinforcement of embankment surface for improving seismic resistance*

The objective of this analysis was to validate the effectiveness of the staged distribution of soil-hardening microorganisms and hardening solution over an existing embankment by extracting calcite crystals from the interstices of sand in the embankment surface. Figure 6 shows the zone of reinforcement and the locations where the subsidence was estimated. The depth of reinforcement at the surface was only one element throughout the surface. The reinforced strengths of the embankment models were set at the levels given in Table 1 for Toyoura sand and for *B.pasteurii*-strengthened soil. Figures 7 and 8 present equivalent strain distributions and the subsidence distances of the embankment peak, respectively, when the embankment surface had been hardened.

Figure 7 indicates that high strains occur in the peak and the sides of the embankment when it has not been reinforced. However, significant suppression of these strains can be expected, even if the microorganism hardens just the surface. The compared subsidence distances of the embankment peak shown in Figure 8 also show suppression of subsidence due to the surface hardening. These results clearly indicate that distribution of the hardening components across the surface, rather than impregnating the entire embankment, was effective or improving the ability of an embankment to withstand an earthquake.

6.2 *Benefit to soil beneath embankment of liquefaction countermeasures by B.pasteurii-induced hardening*

The objective of this investigation was to evaluate the effectiveness of this technology for improving seismic resistance by hardening soil with a native microorganism while using an inexpensive method that poses low environmental loading. The analytical region was that shown in Figure 5. The embankment itself and the region down to 10 to 20 m below

Table 3. Results of the cyclic stress amplitude ratio($R_{L=20}$) and mass fraction of calcium carbonate measurements.

$R_{L=20}$	$CaCO_3$ Pprecipitation rate (%)
0.37	2.027
0.50	2.051
0.23	2.012

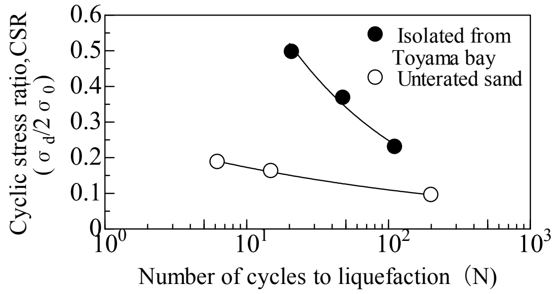


Figure 3. Compares the undrained cyclic triaxial tests.

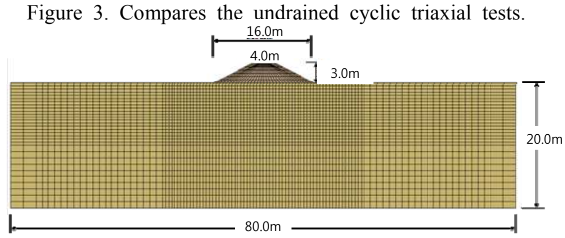


Figure 4. Analysis mesh.

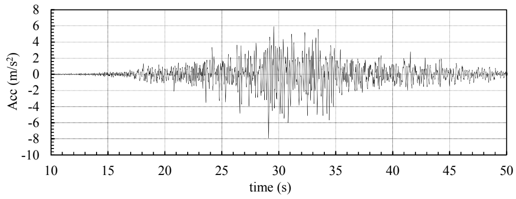


Figure 5. Input seismic wave.

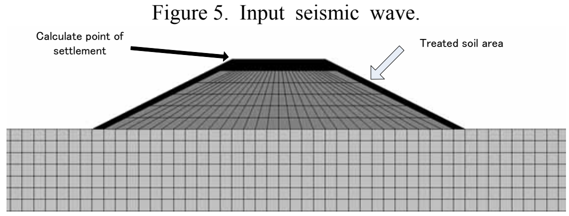
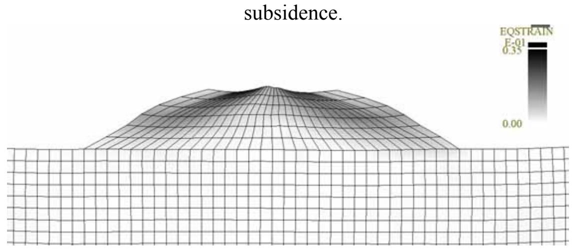
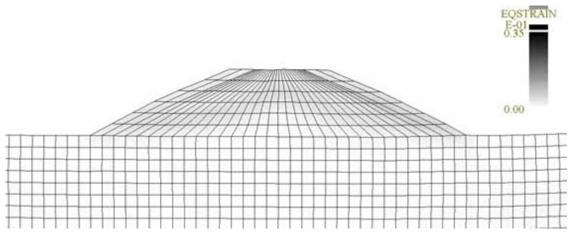


Figure 6. Zone of reinforcement and the locations where the subsidence.



(Untreated case)



(Treated case)

Figure 7. Equivalent strain distributions of both cases.

ground level (GL) were presumed to be stable, while the region between GL and -10 m was assumed to be prone to liquefaction. The liquefaction region was assigned the strength of liquefied Toyoura sand shown in Figure 3, and the liquefaction region after hardening treatment was assigned the corresponding

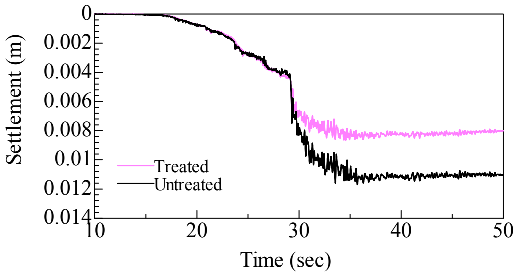
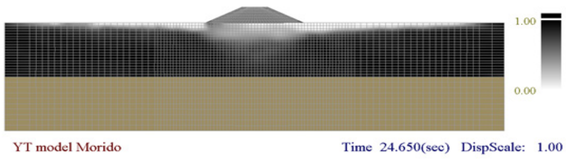
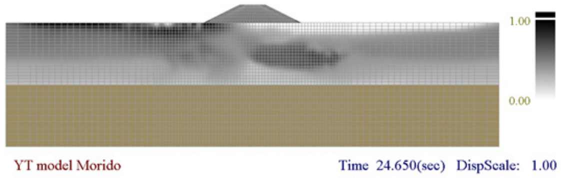


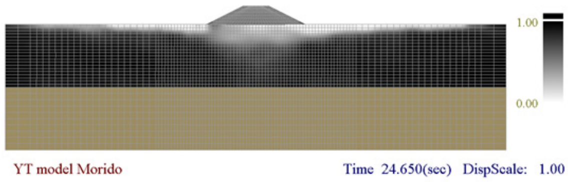
Figure 8. Suppression of subsidence due to the surface hardening. (Treated)



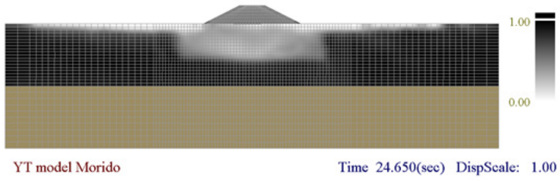
(Untreated)



(Improvement of entire liquefaction region)



(Improvement to 3 m depth under embankment)



(Improvement to 6 m depth under embankment)

Figure 9. Distribution of excess interstitial water pressure ratio at the time of maximum amplitude.

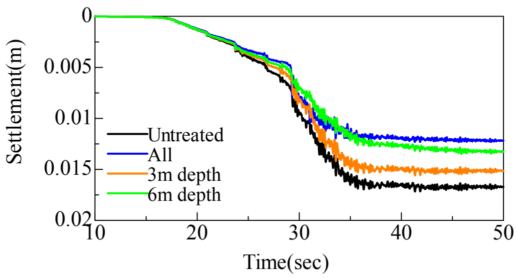


Figure.10 Compares the subsidence distances of the embankment peaks.

strength also shown in Figure 4, for the soil with added microorganism from Toyama Bay. The four cases selected for analysis were 1) no treatment, 2) hardening of entire liquefaction region by microorganism, 3) hardening of first three m depth below embankment by microorganism, and 4) hardening down to six m below embankment by microorganism. Figure 9 shows the distribution of excess interstitial water pressure ratio at the time of maximum amplitude (24.650 s). Our observations regarding these cases are as follows:

1) Untreated
Although the excess interstitial water pressure ratio fell in a few locations directly beneath an embankment because the ground density and increased under the weight of the embankment, this ratio remained at 1.0 overall throughout the liquefaction region.

2) Improvement of entire liquefaction region
When it was assumed that the entire liquefaction region should be treated using the liquefaction strength curves shown in Figure 4, the excess interstitial water pressure ratio exceeded 1.0 in part of the region, but overall, the treatment was successful in suppressing liquefaction.

3) Improvement to 3 m depth under embankment
Hardening was carried out with *B.pasteurii* down to a depth of three m in an attempt to reduce operational costs and time, but no particular reduction of the excess interstitial water pressure ratio with respect to the untreated case was found.

4) Improvement to 6 m depth under embankment
Hardening was carried out with *B.pasteurii* down to a depth of 6 m for the same purposes as in case 3), and a significant reduction in excess interstitial water pressure ratio with respect to the untreated case was found.

Figure 10 compares the subsidence distances of the embankment peak shown in Figure 7 in order to show the improvement in seismic resistance that can be provided by native microorganism-induced hardening, which is a method whose cost is low and poses only low environmental loading. The results for subsidence of the peak of the embankment showed that improvement of the soil to 6 m below the embankment provided about as much reduction of subsidence as improvement to the entire volume liquefaction region.

7 SUMMARY

This paper has presented a laboratory investigation and seismic response analysis of the effectiveness of a technology for improving soil using microorganisms. This study employed the addition of foreign microorganisms possessing the ability to harden the surface of an embankment in a short period of time, or native microorganisms, in an examination of hardening the soil beneath an embankment. The latter approach is low-cost and poses a low environmental load. Promising results were obtained, indicating the effectiveness of both foreign and native microorganisms for this objective.

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