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A Study on the Applicability of MICP for Stabilization of Platform Embankment of Angkor Ruins

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ABSTRACT

This study explores the potential of microbially induced carbonate precipitation (MICP) as a minimally invasive technique for stabilizing the weak platform foundations of Angkor Wat's masonry structures. The compacted soil and stone platform deteriorates during floods, compromising structural stability. MICP utilizes microorganisms to precipitate calcium carbonate within the soil matrix, enhancing its strength and reducing permeability. Laboratory tests confirmed the increased strength and reduced permeability of the platform materials following MICP treatment. This study proposes a novel "one-shot injection" method to minimize construction time. This method considers soil compaction and calcium carbonate precipitation rates to optimize the treatment solution for specific soil and microbial conditions. Finite element analysis of the Bayon Temple's central tower revealed significant stability improvements following MICP treatment, particularly under saturated soil conditions. Even with a shallower treatment depth (1.5 m), considering the reduced permeability achieved by MICP, sufficient stability was ensured. This study suggests that MICP offers a promising and sustainable approach to preserving Angkor Wat's cultural heritage while minimizing intervention in its historical structures.

INTRODUCTION

Many valuable historical sites and buildings, such as UNESCO World Heritage sites, hold significant importance in civil and architectural engineering history. Masonry, a standard structural style using stone or bedrock, has been utilized across ages and regions. Despite their historical value, many masonry structures have been damaged or deformed over hundreds to thousands of years and require repair and protection. The prevalence of foundation issues underscores the urgent need for effective geotechnical repair methods (JSA, 2005, 2011). For example, the Angkor site in Cambodia, a World Heritage site, features numerous masonry structures from the Khmer Dynasty (9th–15th century), including the renowned Angkor Wat. These structures rest on platforms made of slab masonry and stone. Over time, subsidence or tilting of these structures has occurred due to deformation in the underlying slab soil.

Flooding from rainfall infiltration is a major destabilizing factor. For instance, before the demolition of the Prasat Supra N1 tower, it was reported that its tilt increased rapidly after heavy rainfall in 1997. A flat-plate loading test revealed that the tower's bearing capacity decreased significantly after water infiltrated the base, likely due to reduced suction. Rising groundwater levels, primarily due to continuous rainfall, contribute to this issue. With climate change increasing rainfall intensity, similar problems could affect other structures, necessitating countermeasures.

To stabilize Angkor's masonry structures, preventing rainwater intrusion and enhancing each structure's base fill's strength is crucial. In historical building restoration, preserving the original structure and minimizing extensive repairs while ensuring safety are essential. This study explores the use of microbially induced carbonate precipitation (MICP) to improve the strength and imperviousness of base embankments without demolishing existing structures (Dejong et al., 2013; Whiffin et al., 2007; Kim D, 2024). MICP enhances soil strength and reduces hydraulic conductivity by increasing urease activity in microorganisms, injecting urea and calcium chloride to precipitate calcium carbonate.

This research involves experimental and analytical studies to assess MICP's effectiveness for Angkor's platform embankments. The experiments will analyze soil samples from the Angkor restoration to determine changes in permeability and strength. A three-dimensional (3D) finite element method (FEM) analysis will be adopted to evaluate the optimal MICP construction conditions for the Bayon Temple's base embankment.

EXPERIMENTAL MATERIALS AND METHOD

Physical properties of the testing soil

Soil samples used for the microbial solidification tests were the same samples used by the Japanese Government Angkor Site Salvage Team (JASA) for the restoration of the base fill. Preliminary tests were conducted to determine the physical properties of the soil samples before MICP treatment. In addition to testing the soil particle density, the soil samples were tested in a triaxial compression testing machine for different head permeability tests, followed by consolidated drained triaxial compression tests to determine the cohesion and the internal friction angle.

The soil particle density was determined according to the Japan Society of Geotechnical Engineers (JGS) standard, and it was obtained as 2.604 g/cm^3.

For the permeability tests and triaxial compression tests, cylindrical specimens with a diameter of 5 cm and a height of 10 cm were placed on a pedestal with a dry density of 1.60 g/cm^3 and covered with a rubber sleeve.

The triaxial tests were conducted following JGS-0524-2020, which outlines the method for consolidated-drained (CD) triaxial compression tests on soils. The effective confining pressures used for these tests were 50 kPa, 100 kPa, and 150 kPa, all maintained at a back pressure of 200 kPa. All tests were conducted three times to check the accuracy of testing results.

The permeability tests were conducted using a triaxial compression testing machine with a cell pressure of 20 kPa and a back pressure of 0 kPa, with the B value, which indicates saturation, being 0.95. Water flowed from the bottom to the top of the specimen at the water level difference through the permeable cylinder.

Table 1 summarizes the results of each test.

Table 1. Physical properties of the soil sample

Soil particle density (g/cm^3)	Permeability (cm/s)	Cohesion (kN/m^2)	Internal friction angle (deg)
2.604	2.38×10^{-4}	0.729	29.8

Outline of the MICP test

Three specimens were prepared for each of the three MICP treatments. Each specimen was treated with 100 mL of the bacterial culture solution and 100 mL of the solidification solution alternately, which means one cycle treatment includes two injections.

The measured volume of liquid (culture solution/solidification solution) was injected at a downstream flow with a head difference of 10 cm.

Table 2 shows the chemical composition of the cementation solution.

Table 2. Chemical composition of the cementation solution

Chemical composition	Value	
Nutrient Broth	0.3 g	0.3 g
NH_4Cl	1.0 g	1.0 g
$NaHCO_3$	0.212 g	2.12 g
$CO(NH_2)_2$	1.802 g	18.02 g
$CaCl_2$	3.329 g	33.29 g
Pure water	100 ml	100 ml
Mol Concentration of $CO(NH_2)_2$, $CaCl_2$	0.3 mol/L	3.0 mol/L

The cementation solutions consisted mainly of agricultural materials, such as urea applied as a fertilizer and calcium chloride used as a snow-melting agent. In this experiment, the urea and calcium concentrations were adjusted to 3 and 0.3 mol/L, respectively. Based on this, two testing cases were performed using different concentrations of cementation solutions. This time, each case involved three injections (three times bacterial solutions and three times cementation solutions), and each test applied duplicate specimens to focus on the reliability of the test results.

The concentrations of the cementation solutions were defined under two conditions: 3 mol/L of Urea and $CaCl_2$ and 0.3 mol/L of Urea and $CaCl_2$.

Permeability tests

After the prescribed number of treatment cycles, the specimens were frozen to allow them to stand independently. The permeability of the MICP-treated specimens with relatively poor permeability was determined using different head permeability tests. A triaxial compression testing machine was used to conduct the tests. The specimens were saturated using the double negative pressure method, in which de-aerated water was passed through under conditions of 120 kPa cell pressure and 100 kPa back pressure. After confirming that the B value exceeded 0.95, a permeability test was conducted under the condition that the back pressure was set to 0 kPa, and the hydraulic conductivity was measured with de-aerated water.

The hydraulic conductivity k_T (cm/s) was calculated using the following equation:

$$k_T = 2.303 \frac{aL}{A(t_2 - t_1)} \log \frac{h_1}{h_2},$$

where a is the cross-sectional area of the standpipe, L is the length of the specimen (cm), A is the cross-sectional area of the specimen (cm^3), $t_2 - t_1$ is the measurement time (s), h_1 is the water level difference at time t_1 (cm), and h_2 is the water level difference at time t_2 (cm).

Consolidated drained triaxial compression tests

The specimens subjected to the permeability tests were further subjected to consolidated drained (CD) triaxial compression tests. After measuring the volumetric strain during the consolidation process and determining the confining pressure in the normal consolidation region, the CD triaxial compression test (effective confining pressures of 50, 100, and 150 kPa) was conducted in the same way as for the specimens without MICP. After the test, the specimens were oven-dried, and the dry density of the specimens with soil particles and calcite was calculated.

RESULTS AND DISCUSSION OF THE EXPERIMENTS

Permeability and consolidated drained triaxial compression test

Table 3 and shows the results of the laboratory tests. The results of CD tests indicate that the same number of injection cycles and a higher molar concentration of the cementation solution lead to a more pronounced improvement in cohesion value. This may be because the hydrolysis of the urea reaction from the cementation solution accelerates the microbial population or urease activity and enhances the production of bicarbonate and ammonium ions. Ammonium ions can maintain the rational pH condition of calcium carbonate precipitation, bicarbonate ion promoting mineral precipitation into the soil pore and increasing cohesion value related to concentration of urea and $CaCl_2$. This was also confirmed by the dry density results obtained from the comparison with the untreated and treated specimens.

On the other hand, the internal friction angle tended to increase rapidly with solidification treatment. This may be due to the precipitation of fine calcium carbonate crystals on the surface of the sand particles, which increased friction between the particles. The solidification process also contributed to the increase in friction between the sand particles.

These results indicate that when the amount of calcium carbonate based on the MICP treatment is low, the effect is mainly to increase the internal friction angle. As the concentration of the cementation solution increases, the cohesion value is expected to increase.

The permeability tests under the effective confining pressure was 20 kPa were applied to the specimens before the CD tests. The results of the hydraulic conductivity was in the order of $\times 10^{-5}$ cm/s in all cases. On average, the smallest hydraulic conductivity of 3.27×10^{-5} cm/s was obtained after three cycles at 0.3 mol/L, while the lowest hydraulic conductivity value of 1.4×10^{-5} cm/s was obtained after four cycles at 3 mol/L in individual specimens. This results indicates that the precipitation of calcium carbonate based on the MICP treatment contributes to the decrease in hydraulic conductivity.

Table 3. Results of the laboratory tests

Testing case	Cohesion (kN/m^2)	Internal friction angle (deg)	Dry density (g/cm^3)	Permeability (cm/s) (Effective confined pressure =20kPa)
Untreated	0.72	29.8	1.60	2.38×10^{-4}
3 cycles at 0.3 mol/L	1.02	34.2	1.71	3.27×10^{-5}

3 cycles at 3 mol/L	6.45	36.2	1.64	6.06×10^{-5}

3D FEM analysis with experimental data

The effects of MICP treatment on the stability of the central tower of the Bayon Temple base embankment were investigated based on the permeability and strength properties obtained from laboratory experiments. The treatment was assumed to be a solidification method from the surface layer (injection method), and several conditions were set up with different improvement depths. In this study, the effect of MICP treatment applied to the base embankment to improve stability during flooding and to reduce flooding in the interior of the embankment was investigated with numerical simulation. The bearing capacity analyses utilized the 3D FEM software PLAXIS 3D(Bentley), incorporating results from laboratory testing parameters such as cohesion and internal friction angle.

These analyses were conducted for both dry conditions and under the assumption that the base fill was completely saturated with water. A factor of safety was calculated for different improvement depths, and the results were then compared to confirm the effect of the MICP treatment. First, total stress analyses were conducted for the unsaturated state under normal conditions and the fully saturated state, assuming the entire embankment was flooded.

The mechanical response of soil under the interaction of water infiltration phenomena in saturated and unsaturated soils is analyzed by coupling the momentum conservation law for a mixture of solid and liquid phases, considering soil saturation, and the continuity equation for the liquid phase, with displacement of the solid phase and pressure of the liquid phase as unknowns. Suction effects are taken into account when assessing the effective stress of the soil. This study was used to evaluate rainfall infiltration behavior into the base embankment.

The van Genuchten model is described here as an item that requires parameterization in a fully coupled analysis. When considering steady groundwater flow and consolidation of saturated soil layers, only the saturated hydraulic conductivity of the soil is a relevant parameter. However, when dealing with problems involving porewater flow in unsaturated soils, it is necessary to describe the hydraulic parameters of groundwater flow in the unsaturated zone and introduce the Soil Water Characteristic Curve (SWCC), which describes the relationship between the volumetric water content (or saturation) of the soil and suction. Unsaturated hydraulic conductivity is generally lower than saturated hydraulic conductivity, which also requires a model to determine saturation as a variable. Among the many theoretical and empirical models for SWCC and unsaturated hydraulic conductivity that have been proposed, the most widely used model uses the van Genuchten equation for the SWCC model and the Mualem equation for unsaturated hydraulic conductivity. This model first relates saturation and pressure hydraulic head (ψ) by a function consisting of three parameters.

$$S(\psi) = S_{res} + (S_{sat} - S_{res})[1 + (g_a|\psi|)^{g_n}]^{g_c}$$

$$\psi = -\frac{\rho_w}{\gamma_w}$$

Where ρ_w is suction, γ_w is the unit weight of water, S_{res} is the residual saturation, S_{sat} is the volumetric water content, g_a is an empirical parameter related to the inverse of the air penetration value, g_n is the fraction of water extracted from the soil after exceeding the air penetration value, g_c is an empirical parameter, and Plaxis 3D makes the following assumptions

$$g_c = \left(\frac{1 - g_n}{g_n}\right)$$

g_a causes the SWCC to translate in the direction of the suction axis while maintaining the curve shape. The curvature of the curve is changed by g_a while maintaining the center position of the curve.

The Mualem equation, which describes the relationship between unsaturated hydraulic conductivity and saturation, is expressed by dividing S_{eff} by the next effective saturation.

$$S_{eff} = \frac{S - S_{res}}{S_{sat} - S_{res}}$$

as a function of the following effective saturation

$$K_{rel}(S) =_{max} \left[(S_{eff})^{g_l} \left(1 - \left[1 - S_{eff}{}^{\left(\frac{g_n}{g_n - 1}\right)} \right]^{\left(\frac{g_n - 1}{g_n}\right)} \right)^2, 10^{-4} \right]$$

Here, K_{rel} is the relative hydraulic conductivity, which is multiplied by the saturated hydraulic conductivity to calculate the unsaturated hydraulic conductivity.

The results of the total stress analysis for the unsaturated condition are as follows: The maximum vertical effective stresses after loading the weight of the central tower are 1028, 1340, 2506, and 7176 kN/m^2 for 0, 1.5, 3, and 4.5 m improvement depths, respectively. An increase in the maximum vertical effective stress was observed as the improvement depth increased. The results for the total stress at full saturation are as follows: The maximum vertical effective stresses after loading the weight of the central tower are 251, 666, 912, and 1653 kN/m^2 for the 0, 1.5, 3, and 4.5 m improvement depths, respectively. Compared to the unsaturated condition, the maximum vertical effective stresses at full saturation were lower, indicating that the embankment strength decreased. Table 4 shows the safety factors calculated for each case using the shear strength reduction method.

The safety factor is obtained by continuously decreasing the parameters of the shear strength of the ground, $\tan \phi$ (ϕ: internal friction angle), and the cohesion c, until the ground collapses. If the input values of each strength constant are ϕ_{input} and c_{input}, and the values when the calculation stops converging, and the ground collapses are $\phi_{failure}$ and $c_{failure}$, the factor of safety F_s is expressed by the following equation.

$$F_s = \frac{tan\varphi_{input}}{tan\varphi_{failure}} = \frac{c_{input}}{c_{failure}}$$

The safety factor is 1.326 for the unsaturated condition at 0 m improvement depth, which is consistent with the fact that the central tower of the Bayon has not shown any significant deformation from the foundation since its construction. In the fully saturated and unimproved case, the load from the structure would result in soil collapse, and it is assumed that if the base fill is completely flooded, ground deformation would occur, which would cause the structure to collapse. When the entire base is flooded, the required improvement depth is 3 m to satisfy the required safety factor 1.21. However, the MICP improvement is expected to satisfy the safety factor and reduce the extent of flooding with a smaller improvement depth due to the increased strength and reduced permeability.

Next, rainfall was applied to infiltrate the substrate surface, and a safety factor analysis was conducted. In this analysis, only vertical rainwater infiltration was considered, and groundwater flow coupling was not performed. The rainfall condition was given, assuming the maximum daily rainfall measured on site was 170 mm for 3 hours. The weight of the central tower was loaded after rainfall infiltration, and the safety factor obtained was 1.613. Therefore, stability can be maintained even at shallow improvement depths if the reduction in permeability due to MICP is considered. The effective stress distribution after loading the weight of the structure was compared among the unsaturated state, fully saturated state, and after rainfall infiltration. The maximum effective stresses are 1340, 666, and 1272 kN/m^2 for the unsaturated state, fully saturated state, and after rainfall infiltration. Effective stresses decreased due to the decrease in suction caused by rainfall. In all cases, the effective stress was low just below the main tower, which is a cause of concern because low strength may cause instability.

Table 4. Safety factors for each reinforcement condition.

Depth of MICP treatment (m)	Safety factor	
	Unsaturated	Saturated
0（Untreated）	1.326	Collapse（<1.0）
1.5	1.664	1.138
3	1.773	1.200
4.5	1.784	1.205

CONCLUSIONS

The findings of this study are summarized below.

- The results of the MICP treatment on the Bayon site restoration material indicate that MICP is expected to have a ground improvement effect.
- The improvement effect depends on the concentration of urea and calcium chloride in the solidification solution. The results suggest an optimum concentration of urea and calcium chloride in the solidification solution for efficient ground improvement.
- The results of 3D FEM analysis using the physical properties obtained from laboratory tests suggest that MICP is effective in improving the stability of the Bayon site.

RECOMMENDATIONS

The following are the issues to be addressed before applying MICP soil improvement technology to the base embankment of the Angkor site, which will improve its imperviousness and strength：

1) Optimum mix of solidification solution

If MICP treatment is to be used to improve the strength and imperviousness of the soil, it is essential to solidify the soil uniformly. From the results of experiment, it is clear that a large amount of calcium contained in the cementation solution precipitates as calcium carbonate at 0.3 mol/L. However, the precipitation efficiency of calcium carbonate is reduced at 3.0 mol/L. The calcium and urea content of the cementation solution at 3.0 mol/L is not efficient precipitated as calcium carbonate. In this reason. The precipitated calcium carbonate may cause clogging in the surface layer, preventing the MICP treatment from reaching the bottom and inhibiting the action of microorganisms, significantly reducing the percentage of calcium carbonate deposited to the injected volume. Since it is desirable to repair historical structures to the maximum necessary, further study is needed to determine the amount and concentration of solidification solution that will effectively increase the strength and imperviousness of the structure.

2) Understanding the unsaturated infiltration characteristics of MICP-treated soil

In conducting finite element analysis, the soil's unsaturated permeation characteristics were assumed from the literature because they had not been obtained in laboratory tests (Fredlund M.D.et al.,2002). Therefore, the same parameters were used for both MICP-treated and non-MICP-treated soils. Therefore, it is necessary to conduct water retention tests using embankment samples to understand their hydraulic properties.

3) Optimal improvement depth

Although not considered in this study, the upper terrace of the Bayon Temple is covered with sandstone blocks. As a result, part of the rainfall flows over the surface of the embankment and does not enter the interior of the embankment. The plasticity analysis performed in this study using MICP with an improvement at a depth of 1.5 m and a daily rainfall of 170 mm showed that the required safety factor was sufficiently satisfied. Therefore, we believe that the optimum improvement depth can be reduced to 1.5 m to minimize the extent of improvement and stabilization.

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