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Microbially Induced Calcite Precipitation (MICP) Biostimulation Reduces the Slope Angle Degradation of CL Soil Under Loading

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ABSTRACT
Landslides are among the most detrimental geotechnical hazards in Indonesia. Conventional stabilization methods can improve slope stability but are associated with high costs and environmental impacts. Microbially Induced Calcite Precipitation (MICP) offers an environmentally friendly approach through calcite precipitation that strengthens interparticle bonding. This study investigates the effectiveness of MICP biostimulation in reducing slope angle degradation under loading in low-plasticity clay (CL) soil. Two small-scale slope models (without treatment and MICP treatment) with an initial angle of 60° were subjected to a 125 kg loading test. Slope deformation was monitored for 160 minutes, and shear strength parameters were determined through a direct shear test. The results showed that the MICP-treated slope experienced an average angle degradation of only 2.24°, which was 47.17% smaller than that of the untreated slope (4.24°). The failure mechanism shifted from sliding to vertical cracking. The direct shear test confirmed an increase in cohesion of 90.15% and an increase in the internal friction angle of 37.05%. These findings demonstrate that MICP biostimulation can reduce slope angle degradation and modify failure patterns. The study highlights the potential of MICP biostimulation as an effective and sustainable slope stabilization technology.

Keywords: *MICP Biostimulation; Slope Angle; Slope Stability; Clay Low Plasticity*

1. Introduction

Landslides are among the most frequent geotechnical hazards worldwide, causing significant socio-economic losses [1]. Indonesia is classified as part of the global landslide-prone zone [2], with records from the National Disaster Management Authority (BNPB) indicating that in 2024, 207 landslide events occurred, resulting in 213 fatalities, 22 missing persons, and 123 injuries [3], [4]. In tropical regions, kaolinite is the most dominant clay mineral [5]. Clay with a high kaolinite content is generally classified as low-plasticity clay (CL) according to the Unified Soil Classification System (USCS) [6]. This soil is susceptible to strength loss with increasing water content, thereby reducing slope stability [7]. Therefore, various soil stabilization efforts have been undertaken as solutions to enhance slope stability.

Conventional stabilization methods, such as the use of cement, and fly ash, have been proven to increase soil cohesion by 677% and 213%, as well as the internal friction angle by 18% and 14%, through the additional bonding formed between the compounds generated from these materials and soil particles, thereby improving slope stability [8], [9]. However, the application of these materials is constrained by both economic and environmental limitations [10], [11]. Their use may also elevate soil pH to extreme levels, posing a risk of long-term residual contamination [12], [13]. These challenges have driven the development of biologically based stabilization approaches that emphasize sustainability and environmental compatibility.

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One environmentally friendly approach is Microbially Induced Calcite Precipitation (MICP) [14]. This process utilizes urease-producing bacteria to hydrolyze urea into carbonate ions, which subsequently react with calcium ions to form calcite ($CaCO_3$) [15], [16]. Calcite precipitates bind and strengthen interparticle contacts, thereby enhancing cohesion, reducing permeability, and improving the mechanical properties of the soil [17]. Two principal techniques are employed in MICP, namely bioaugmentation and biostimulation [18]. Bioaugmentation involves introducing exogenous bacteria, such as Sporosarcina pasteurii, into the soil; however, this method requires strict laboratory control [15], [16], [19]. In contrast, biostimulation is considered more practical and cost-effective, as it requires only nutrient solutions to stimulate the growth of indigenous soil bacteria, making it potentially more applicable at the field scale [17].

Previous studies have reported that biostimulation MICP can enhance soil shear strength parameters, such as cohesion by up to 153% [19], and the internal friction angle by 46.9% in expansive soils [20], while also reducing permeability by 50% [21]. Shear strength is the most critical parameter in determining slope stability [9]. A study found that cohesion plays a more dominant role than the friction angle in improving the safety factor of slopes with angles greater than 35° [22]. Furthermore, it was demonstrated that increasing soil cohesion by 200% can raise the safety factor by 53.8% [23]. An elevated safety factor indicates improved slope stability, thereby enabling steeper slope angles [22], [24]. Previous research incorporating various innovations, such as cement, nanosilica, and fly ash, has also shown that these innovations improve slope angles by enhancing soil mechanical properties [9], [25], [26].

Several previous studies have examined the influence of MICP biostimulation on soil mechanical properties; however, its effect on slope angle (β) has received limited attention. This study aims to evaluate the effectiveness of MICP biostimulation in reducing slope angle degradation under loading conditions. A small-scale slope model was constructed, and loading tests were conducted, with observations of changes in β, failure slope patterns, and soil shear strength parameters. The findings are expected to provide insights into the reinforcement mechanisms of MICP-treated slopes and offer a sustainable and effective alternative for slope stabilization.

2. Material and Method

2.1. Materials

Soil samples were collected from the backyard of Universitas Kadiri at a depth of 80 cm to obtain undisturbed soil [27]. The soil was air-dried for 2 weeks at room temperature, without direct sunlight, until the water content reached approximately 10% to maintain the viability of indigenous bacteria [16]. The dried soil was then pulverized using a machine equipped with a 0.3 mm sieve. According to the USCS, the soil is classified as low-plasticity clay (CL) with the following characteristics: sand fraction 31.45%, silt 52.39%, clay 16.17%, coefficient of uniformity (Cu) 11.22, coefficient of curvature (Cc) 3.56, liquid limit (LL) 24.99%, plastic limit (PL) 10.93%, and plasticity index (PI) 14.06%.

2.2. MICP Solution

The MICP solution was prepared by mixing urea (0.333 mol/L) [18], $CaCl_2$ (0.3 mol/L), CH_3COONa (0.1 mol/L), NaOH (0.001 mol/L) [28], and sugarcane molasses (3 g/L) [19]. All components were weighed according to the specified composition, simultaneously dissolved in distilled water, and stirred until homogeneous. The prepared solution was immediately applied to the soil to prevent degradation of the active components.

2.3. Sample

This study employed two slope models: one treated with water and the other with the MICP solution. As illustrated in Figure 1, the slope model was constructed with a 60° slope angle, a height of 22 cm, and a base length of 26.7 cm, consisting of 11 layers with a vertical spacing of 2 cm. The samples were formed in a glass box measuring 60 cm in length, 14 cm in width, and 25 cm in height. Reference lines corresponding to the slope geometry and layer configuration were marked on the

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glass walls. Plastic-coated wooden formwork was used to create the slope angle, and plasticine was applied at the joints to prevent leakage.

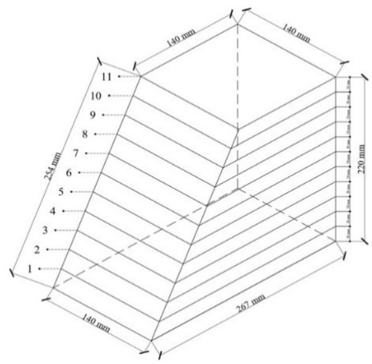

Figure 1. Slope Sample Dimensions

Soil was placed into the box using the air pluviation method for each layer [29]. After deposition, the surface was leveled with a brush without applying pressure to ensure uniform distribution. The soil volume of each layer was calculated to maintain density consistency. The wet unit weight of the soil was set at 1.61 g/cm³, with water or MICP solution added at 40% of the soil weight. A water or MICP solution was evenly poured onto each layer and allowed to infiltrate for approximately 2 minutes before the subsequent layer was added. The formwork was removed after 24 hours, followed by a 7-day incubation at room temperature, without direct sunlight, to preserve the viability of indigenous bacteria and enable optimal calcium carbonate precipitation. A 7-day incubation period was selected because calcium carbonate precipitation becomes effective in reinforcing the soil during this stage [19].

2.4. Loading Test

The testing was carried out using a small-scale apparatus developed by AIC Innovation. A total load of 125 kg was applied and uniformly distributed through a 16 mm thick wooden plate to prevent bending, while a spherical bearing was employed to minimize eccentricity. Before testing, the slope surface was leveled with a 2 mm layer of sand to ensure uniform contact. The detailed testing scheme is illustrated in **Figure 2**.

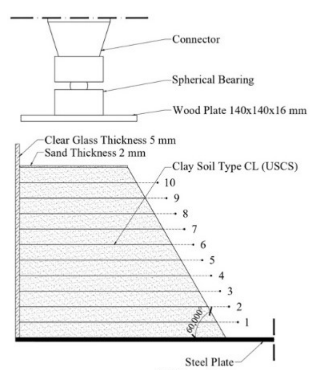

Figure 2. Loading Test Scheme

Lateral deformation of each layer (layers 1 to 10) was monitored using ruler stickers with a precision of 1 mm attached to the glass surface and recorded from a perpendicular viewing angle to minimize perspective distortion [30]. Observations were conducted three times at 10-minute intervals up to 160 minutes. Changes in slope angle (β) for each layer were calculated using the Pythagorean Theorem based on the deformation data and subsequently visualized with AutoCAD software. The slope failure after testing was documented using a digital camera.

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2.5. Direct Shear Test

Shear test specimens were also prepared using the water pluviation method with the same unit weight and addition of water or MICP solution as in the slope model samples, followed by a 7-day incubation period. The tests were conducted in accordance with ASTM D-3080 under three levels of normal stress, namely 1.097 kPa, 3.126 kPa, and 4.025 kPa, with a constant shear rate of 1 mm/min [31]. Each condition was tested in triplicate. The peak shear stress data were analyzed to determine the values of cohesion (c) and internal friction angle (φ).

3. Result and Discussion

3.1. Slope Angle per Layer

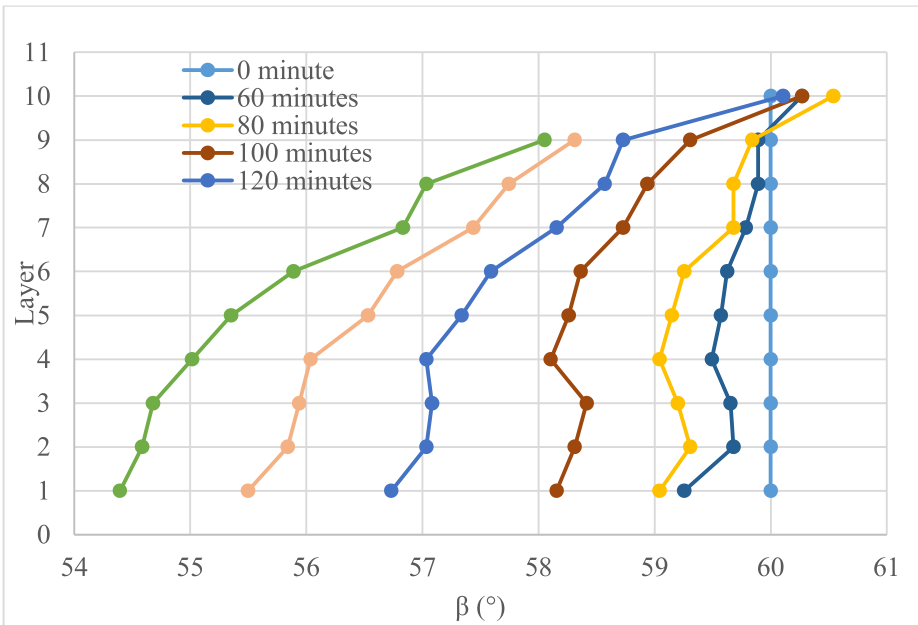

Figure 3. Untreated Slope Angle per Layer

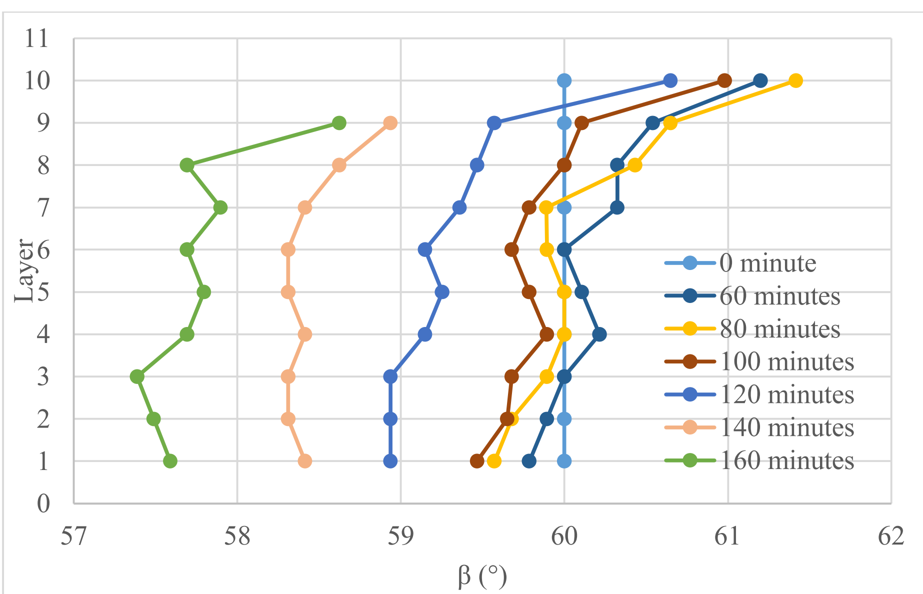

Figure 4. MICP-treated Slope Angle per Layer

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The observations revealed distinct differences between the untreated and MICP-treated slopes in maintaining β across layers during the 160-minute loading period (Figures 3 and 4). On the untreated slope, after 60 minutes of loading, a reduction in β was first observed in the lower layers (1–4), with the angle decreasing to 59.25°–59.49°. The reduction progressed significantly up to 160 minutes, at which point the lower layers reached angles of 54.39°–55.01°. The middle layers (layers 5–7) also exhibited a decrease, with final values of 55.35°–56.83°, whereas the upper layers (layers 8–9) remained relatively more stable, with final angles of 57.03°–58.05°. In contrast, for the MICP-treated slope, after 60 minutes of loading, the lower layers exhibited only a slight reduction, with angles of 59.79°–60.22°, while the middle and upper layers remained stable at 60.11°–61.20°. By 160 minutes, the lower layers of the MICP-treated slope reached final angles of 57.59°–57.69°, whereas the middle and upper layers remained within the range of 57.80°–58.62°.

The reduction in slope angle for the untreated slope reached 5.61–4.99° in the lower layers and 4.65–1.95° in the middle to upper layers. In contrast, the total reduction in slope angle for the MICP-treated slope was only about 2.41–2.31° in the lower layers and 2.31–1.38° in the middle to upper layers. These results indicate that MICP treatment reduced the decrease in slope angle by 3.2° in the lower layers and 2.34° in the middle layers. Furthermore, the stability of the middle and upper layers in the MICP-treated slope was considerably higher, with fewer minor deviations in the final angles than in the untreated slope.

3.2. Average Slope Angle

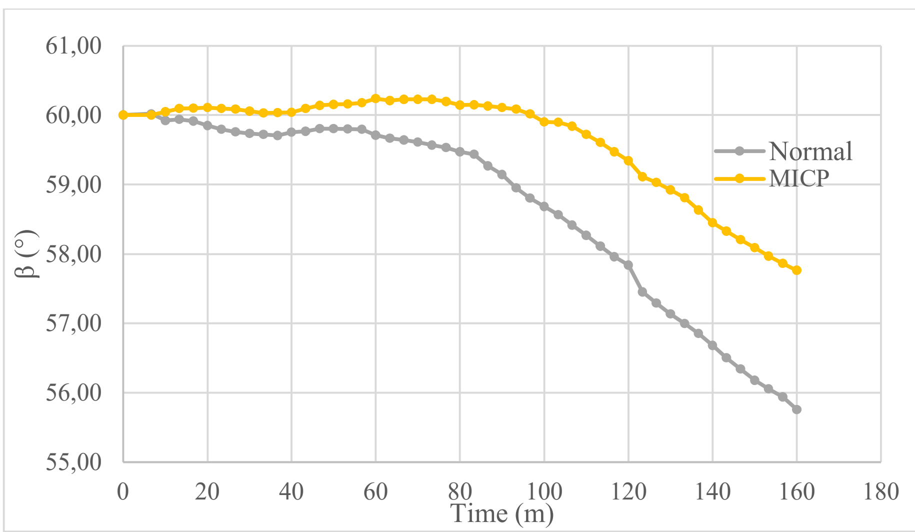
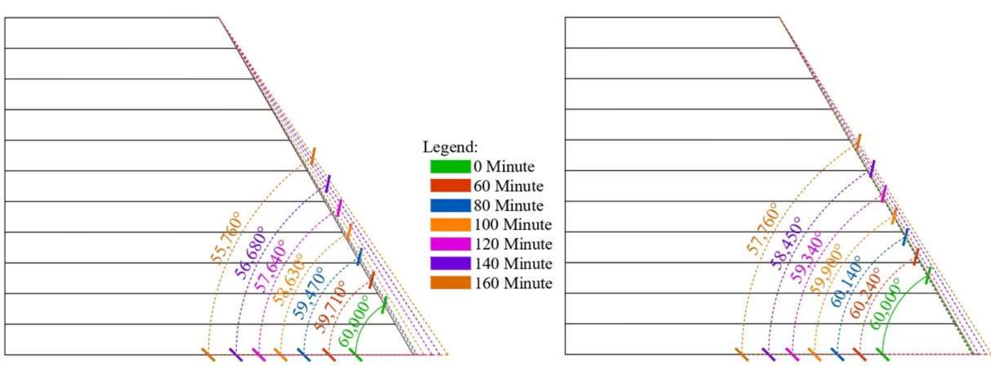


Figure 5. Change in Average Slope Angle



(a) (b)

Figure 6. Visualization of Slope Angle Changes (a) Untreated; (b) MICP Treatment

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The average changes in β for the untreated and MICP-treated slopes are presented in Figure 5, while their visualizations are shown in Figure 6. At the initial condition (0 minutes), both slopes exhibited an average β of 60.0°. The untreated slope demonstrated a decrease in slope angle beginning at 20 minutes. By 60 minutes, the average β had decreased to approximately 59.71°, followed by further reductions to 58.68° at 100 minutes, and ultimately reaching 55.76° at 160 minutes. The total decrease in the average β of the untreated slope was about 4.3° relative to the initial condition. In contrast, the MICP-treated slope shows a different behavior. Between 20 and 50 minutes, β remained stable at around 60.0°, and subsequently increased to a maximum of 60.24°–60.14° at 60–80 minutes. Beyond this period, β gradually decreased, reaching 59.90° at 100 minutes, 58.45° at 140 minutes, and 57.76° at 160 minutes. The average reduction in β was 2.24° for the MICP-treated slope compared to 4.24° for the untreated slope. AutoCAD visualizations further highlight this distinction: the untreated slope shows greater displacement of the failure plane, whereas the MICP-treated slope maintains a relatively stable angle. These results indicate that MICP treatment reduced the average β reduction by 2°.

3.3. Slope Failure Type

(a) b)

Figure 7. Slope Failure at a Scale of 1:5.46 (a) Untreated; (b) MICP Treatment

The visual documentation of the slope failure revealed a clear distinction in failure patterns between the untreated slope and the MICP-treated slope. On the untreated slope (Figure 7a), the slope failure developed via a sliding mechanism, characterized by a shear plane extending from the toe to the crest. In contrast, in the MICP-treated slope (Figure 7b), the failure pattern did not exhibit a sliding mechanism but instead formed a vertical failure plane that initiated at the slope crest and propagated downward. Cracks predominantly appeared in the upper portion and extended vertically into the slope body. Most of the slope mass remained intact, indicating that the damage was localized along the vertical failure path.

3.4. Shear Strength

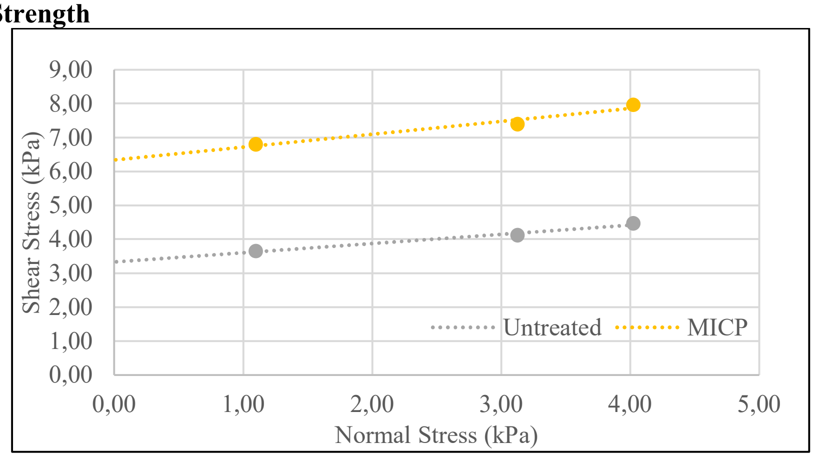

Figure 8. Results of Direct Shear Test

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The results of the direct shear test indicated a clear improvement in untreated soil compared with soil treated with MICP. In the untreated condition, the maximum shear stresses were 3.648 kPa, 4.120 kPa, and 4.465 kPa, yielding a cohesion of 3.332 kPa and an internal friction angle of 15.181°. In contrast, the MICP-treated soil exhibited a significant increase in maximum shear stress across all normal stress levels, with values of 6.792 kPa, 7.390 kPa, and 7.956 kPa. Consequently, the derived cohesion increased to 6.335 kPa, while the internal friction angle improved to 20.805°.

3.5. Discussion

The MICP-treated slope maintained β more effectively than the untreated slope. On the untreated slope, the average reduction in β reached 4.24° within 160 minutes, whereas on the MICP-treated slope it reached only 2.24°. This difference indicates that MICP biostimulation reduced slope angle degradation by 47.17%. The β values for each layer further support this finding: the reduction in the lower layers of the untreated slope ranged from 5.61° to 4.99°, whereas in the MICP-treated slope it was limited to 2.41°–2.31°. The effectiveness of MICP in reducing β degradation is attributed to the precipitation of calcium carbonate ($CaCO_3$), which acts as a particle-bridging agent and pore filler, thereby enhancing soil shear strength [32]. The results of the direct shear test corroborate this mechanism, with cohesion increasing significantly from 3.332 kPa to 6.335 kPa. The result is consistent with previous studies reporting that $CaCO_3$ enhances cohesion through microscale bonding [33]. The increase in cohesion plays a critical role in resisting slope deformation, thereby reducing slope angle degradation.

A distinct difference in slope failure patterns was observed between the untreated and MICP-treated slopes. On the untreated slope, failure developed more rapidly, following a sliding-type mechanism. In contrast, the MICP-treated slope exhibited a vertical failure that initiated at the crest and propagated downward. This alteration in the failure pattern is attributed to calcite precipitated by MICP, which acts as a particle-bridging agent and pore filler [34], thereby modifying the stress-concentration mechanism within the slope body. It was reported that MICP significantly reduces particle breakage and grain compressibility compared to untreated soil [35]. As a result, stress concentration that typically localizes along the shear plane is redistributed more uniformly throughout the slope body, leading to failure that occurs not directly along a shear plane but rather through vertically oriented cracking.

The results of the direct shear test demonstrated a significant improvement in soil shear strength parameters following MICP treatment. Cohesion increased by 90.15% after MICP biostimulation, whereas the internal friction angle increased by 37.05%. This rise in cohesion is attributed to calcium carbonate precipitates that reinforce interparticle contacts, thereby enhancing resistance to shear stress [36]. These findings are consistent with a previous study, which reported that $CaCO_3$ precipitation predominantly enhances cohesion rather than the internal friction angle [32].

This study confirms that the MICP mechanism through $CaCO_3$ precipitation not only enhances soil cohesion parameters but also directly contributes to reducing slope angle degradation. Furthermore, the findings demonstrate the potential of MICP as a sustainable stabilization technology for cohesive soil slopes, capable of mitigating landslide hazards. The application of biostimulated MICP at the field scale has the potential to enable steeper slope angles without additional reinforcement. This could provide greater construction cost efficiency and land use.

4. Conclusion

This study demonstrates that MICP biostimulation effectively reduces the slope angle degradation of low-plasticity clay (CL) under loading. The findings revealed that MICP reduced slope angle degradation by 47.17% and changed the failure pattern from sliding to vertical cracking. These results were validated by a 90.15% increase in cohesion and a 37.05% improvement in the internal friction angle. This confirms that MICP biostimulation has the potential to be an effective and sustainable stabilization technology for clay slopes. MICP biostimulation has the potential to be applied at the field scale to design steeper slopes without additional reinforcement, thereby achieving cost and land-use efficiency.

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This study is limited to a single soil type and does not account for environmental factors such as wet–dry cycles. Microstructural analysis was not conducted; thus, the presence of $CaCO_3$ can only be inferred from the increase in mechanical parameters and from previous research. Future research is recommended to include microscopic analyses, different soil types, and long-term evaluations of calcite bond durability under more complex environmental conditions.

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